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Aquatic Barrier Prioritization in New England Under Climate Change Scenarios Using Fish Habitat Quantity, Thermal Habitat Quality, Aquatic Organism Passage, and Infrastructure Sustainability

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A Thesis Presented

By

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ABSTRACT

AQUATIC BARRIER PRIORITIZATION IN NEW ENGLAND UNDER CLIMATE CHANGE SCENARIOS USING FISH HABITAT QUANTITY, THERMAL HABITAT QUALITY, AQUATIC ORGANISM PASSAGE, AND INFRASTRUCTURE SUSTAINABILITY

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Improperly designed road-stream crossings can fragment stream networks by restricting or preventing aquatic organism passage. These crossings may also be more vulnerable to high flow events, putting critical human infrastructure at risk. Climate change, which emphasizes the need for suitable thermal habitat, and is also predicted to increase the frequency and magnitude of extreme floods, underscores the importance of maintaining stream connectivity and resilient infrastructure. Given the large number of road-stream crossings and the expense of replacement, it is important to prioritize removals and account for the multiple benefits of these management actions. I developed an aquatic barrier prioritization scheme that combines potential habitat gain, stream thermal resilience, aquatic organism passage, and culvert risk of failure. To assess relative thermal resilience, I deployed paired air-water thermographs in several New England watersheds and analyzed thermal sensitivity (relationship of water to air temperature) and exposure (duration, frequency, and magnitude of warm stream temperature episodes) among streams. These were combined into a single metric of thermal resilience corresponding with the distance of that stream’s sensitivity and exposure from the watershed median. To test the relationship between risk of failure, culvert dimensions, and stream connectivity, I developed a logistic regression to predict risk of failure using data from two watersheds that experienced extreme flooding from

Hurricane Irene (2011). Finally, I applied the resultant prioritization scheme to 66 road-stream crossings in the Westfield River watershed (MA).

Thermal habitat quality varied considerably within and among watersheds. Stream sensitivity was generally lower than the widely accepted 0.8˚C increase in stream temperature for every 1˚C increase in air temperature (Westfield median sensitivity = 0.44), with substantial differences among streams. Exposure also varied widely among streams, indicating that some headwater streams in New England are more thermally resilient than previously thought. Risk of infrastructure failure was predicted with a logistic regression using culvert constriction ratio and predicted aquatic organism passage as predictors (Likelihood ratio test, X2=59.1, df=3, p-value=9.2e-13), indicating that underdesigned culverts were more likely to be barriers to passage and more likely to fail in extreme flow events. To prioritize culverts, this study ultimately used a piecewise approach that identified culverts opening the longest reaches of thermally resilient habitat, and then ranked those culverts by infrastructure replacement need. In the Westfield River, the prioritization clearly identified crossing replacements most likely to yield multiple benefits. The scheme I developed can accommodate changes in the relative weights of the different criteria, which will reflect differences in management and conservation concerns in the confidence of inputs. In conclusion, increasing connectivity by removing barriers may be one of the most effective ways to mitigate the effects of climate change on aquatic systems, but it is important to remove the right barriers.

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1. BACKGROUND ON FRAGMENTATION AND BARRIERS IN AQUATIC SYSTEMS

1.1 Introduction

1.1.1 Fragmentation and barriers in streams and river systems

Streams and rivers are among the ecosystems most affected by human activities, and river infrastructure is a major cause of fragmentation (Forman and Alexander 1998, Dynesius and Nilsson 1994). Habitat fragmentation affects habitat diversity, metapopulation persistence, genetic resilience, and ecosystem dynamics. Habitat fragmentation caused by aquatic barriers is a major threat to stream fish abundance and diversity (Warren and Pardew 1998, Dunham et al. 1997, Slatkin 1985), and also disrupts ecosystem processes such as hydrology, sediment transport, and large woody debris transport (Jackson 2003). Road-stream crossings can be barriers when improperly designed (Clarkin 2008, Pess et al. 1998, Beechie et al. 1994), and put both ecosystems and transportation at risk (Nislow 2009).

One of the reasons streams are subject to so much fragmentation is because of their linear nature. In a linear system, organisms can only move in one dimension for spawning, feeding, predator avoidance, and environmental concerns such as lethal and near-lethal temperatures (Fausch et al. 2002). Headwater streams provide many of these services, and are disproportionately affected by road-stream crossings, as the crossing structure on a small stream is frequently a culvert, which is more likely to be a barrier than a bridge, ford, or other crossing type (Cafferata et al. 2004). Moreover, small streams cumulatively account for much more aquatic habitat than larger streams (Jackson 2003).

The implications of aquatic fragmentation on brook trout (*Salvelinus fontinalis*) populations have been widely studied. Brook trout are an excellent focal species for examining the interactive effects of climate change and connectivity in northern temperate streams, because their geographical distribution is strongly constrained by maximum temperatures (Wehrly et al. 2007, Mohseni et al. 2003, Keleher and Rahel 1996, Meisner 1990, Lee and Rinne 1980, Brett 1956), and populations are strongly dependent on interconnections between spawning habitats and foraging habitats (Petty et al. 2005). Due to poor land management, road development, and other human infrastructure, brook trout are restricted within highly fragmented habitats, with limited abilities to disperse to avoid unfavorable environmental conditions (Xu et al. 2010). Letcher et al. (2007) found that brook trout extinction probability was correlated with tributary and population size, and isolated populations could be rescued from extinction by restoring connectivity. Increased fish abundance and productivity have been observed within one year of barrier removal (Roni et al. 2002).

1.1.2 Culverts and road crossings

Road-stream crossings are ubiquitous and inevitable in any human-impacted landscape, and when improperly designed or maintained, can significantly impede organism passage and undermine the ecological integrity of river and stream systems, such as hydrology, sediment transport, and large woody debris transport (Clarkin 2008, Beechie et al. 1994, Jackson 2003). Culverts are extremely common because they are more cost-effective than bridges, especially on small headwater streams (Gibson et al 2005). Culverts are frequently barriers to fish passage, because of large outlet drops, insufficient water depths, and excessive water velocity (Blank et al. 2005, Warren and Pardew 1998, Stein and Tillinger 1996, Fitch 1995, Votapka 1991, Baker and Votapka 1990). Passage rate decreases with increasing water velocity (Haro et al. 2004), but the magnitude of this passage rate varies among species. Non-fish species, such as turtles and aquatic salamanders, take advantage of lower velocity sections of stream and boundary layers along the bank edges, which many culverts are lacking (Clarkin 2008). Maintenance of unfragmented stream bottom and bank-edge habitats is the best strategy for preserving continuous and interconnected populations for weak-swimming species (Clarkin 2008).

Fish passage through barriers is important because interconnections between spawning and foraging habitats are vital for metapopulation persistence. Letcher et al. (2007) found that isolated populations of brook trout (*Salvelinus fontinalis*) could be rescued from extinction by restoring connectivity, and this can be done effectively by culvert retrofitting or removal (Kemp and O'Hanley 2010, Roni et al. 2002).

The passability of aquatic barriers can vary temporally, be deemed binary, or viewed as a proportion. Negative impacts of various barrier types on different types of fish is highly variable, ranging from short delays to complete obstruction, and the impacts are dependent on the nature of the barrier, the river hydrology, and the species (Northcote 1998). While a dam may always be a barrier, road-stream crossings frequently vary in their passability depending on discharge, time of year, time taken to pass the barrier, presence of predators, and temperature (Kemp and O'Hanley 2010). Poplar-Jeffers et al. (2009) found that overall fish movement was an order of magnitude lower through culverts than through other crossing types or natural reaches. When culverts are partial or temporal barriers, they block the movements of a proportion of the population that are weaker swimmers or in younger life stages, or reduce access at certain times (Kemp et al. 2008). A barrier that can pass adult salmonids is still a barrier to juvenile salmonids and other less-athletic fish species (Blank et al. 2005).

It has been suggested that undersized culverts, due to their effects on flow conditions and local streambed morphology, are both more likely to be barriers to fish passage and more likely to fail in extreme flow events (Nislow 2009). Culverts fail less often from flood flows than from accumulations of wood and sediment that often accompany heavy flows (Cafferata et al. 2004). One can estimate flows using relationships between precipitation and watershed characteristics, but it is difficult to directly predict the sediment loading and wood debris at a given crossing

(Furniss et al. 1998, Cafferata et al. 2004). Inadequate design is frequently the reason for road-stream crossing failures, and the best way to reduce failure is to locate roads to avoid or minimize stream crossings (Cafferata et al. 2004).

1.1.3 Stream thermal regimes

The point of removing aquatic barriers is to open high-quality fish habitat, and one way to measure habitat quality is through a stream’s thermal regime. Summer stream temperatures directly affect brook trout distributions and abundance (Meisner 1990, MacCrimmon and Campbell 1969). Brook trout must be able to disperse to avoid lethal stream temperatures, which occur around 25˚C (Brett 1956), and they prefer temperatures at or below 20˚C (Picard et al. 2003), with growth rates affected at temperatures as low as 17˚C (Xu et al. 2010, Lund et al. 2002). The ability to disperse will be particularly important in the context of climate change, as finding higher quality habitat may be critical for species persistence (Nislow 2009, Mohseni et al. 2003, Keleher and Rahel 1996, Rahel et al. 1996, Meyer et al. 1988).

In the context of climate change, suitable thermal habitat for brook trout will shrink. Under some climate change projections, coldwater species will experience a nearly 50% reduction in suitable thermal habitat (Eaton and Scheller 1996). At higher elevations, even modest increases in temperature predict a 9-76% loss of existing thermally suitable habitat for coldwater fish (Rahel et al. 1996). However, water temperature does not vary linearly with air temperature, especially at a local scale, and different habitats will vary in their resilience to temperature increases (Trumbo et al. 2010).

Brook trout habitat is already highly fragmented, threatening metapopulation persistence even without the threat of climate change. Letcher et al. (2007) found that brook trout extinction probability was correlated with tributary and population size, but that isolated populations could be rescued from extinction by restoring connectivity. Roni et al. (2002) found that removing barriers to brook trout movement resulted in a nearly-immediate biological benefit when compared with other restoration techniques, and increased fish abundance and productivity were observed within one year of barrier removal. From a management standpoint, maintaining healthy brook trout populations means removing barriers between existing habitat allowing for potential escape route to high quality thermal habitat.

1.1.4 Climate change effects on river fragmentation

The ability of aquatic organisms to move and disperse will be particularly important in the context of climate change, as finding higher quality habitat may be critical for species persistence (Nislow 2009, Keleher and Rahel 1996, Rahel et al. 1996). Cold water species such as brook trout are good indicators of climate change effects because they rely heavily on having access to high quality thermal habitat, and are highly vulnerable to the potential effects of climate warming (Keleher and Rahel 1996). Under some climate change projections, these species will experience a nearly 50% reduction in suitable thermal habitat (Eaton and Scheller 1996). At higher elevations, even modest increases in temperature predict a noticeable decline in thermally suitable habitat for coldwater fish (Rahel et al. 1996). Xu et al. (2010) used climate change scenarios representing different stream flow and water temperature conditions over 100 years, and found that an increase of 0.5-2˚C in water temperatures greatly increases extinction probability in brook trout. Over the past 150 years, the global average air temperature has increased nearly 1˚C, and is expected to continue to increase by 1-3˚C by the middle to end of this century because of greenhouse gases (IPCC 2007).

Predictions of more flow variability and a higher frequency of extreme events due to climate change (Moore et al. 1997) will influence the capacity of existing culverts to protect road infrastructure. Culverts that are currently undersized with respect to their watersheds will be even more vulnerable to failure under predicted climate change scenarios (Nislow 2009, Moore 1997). Recently, there was much damage wrought by Hurricane Irene (2011) in the northeastern United States.

As flood risk changes under climate change scenarios, road-crossing infrastructure will need to keep up with higher flows that happen more frequently. On August 27, 2011, Hurricane Irene ravaged the state of Vermont, flooding four major rivers, killing 6 people, causing 117,000 power outages, and causing $733 million in damage (Leader 2012). More than 500 miles of roads and dozens of bridges were damaged or destroyed by the 3-7” of rain in the most devastating natural disaster since flooding in 1927 (Pealer 2012). Approximately 960 culverts were damaged in Vermont (Dillon 2011), and 34 bridges (Lunderville 2011). In Massachusetts, Hurricane Irene caused extreme flooding, with multiple culvert failures. If some climate change predictions hold true, this storm will not remain an isolated event, and a post-Irene assessment could be a valuable look into the future.

Climate change is an urgent issue, and updating existing infrastructure is a long process that needs to start now. In the face of existing climate change projections, it would behoove managers to consider prioritizing barriers that will open thermally resilient habitat for the sake of their coldwater residents. Moreover, improving road crossings would offer immediate and future ecological and infrastructure benefits, but it is important to direct efforts to where they will be most effective.

1.1.5 Multiple criteria in barrier assessment and prioritization

The very large number of road-stream crossings has underscored the need to identify which of these are likely to be barriers (Olivero and Anderson 2008, Jackson 2003, Jackson and Griffin

2000). Given limited time and resources, there is a strong interest in developing prioritization protocols to identify which removals and replacements will be effective in restoring habitat and stream connectivity to high-quality upstream habitats. Most road-stream crossing structures are already in place, and it is unlikely that an existing road will be moved, so it is practical to focus remediation efforts on restoration of the best areas. Because not all culverts are gateways to high-quality thermal habitat, it is important to be able to identify and prioritize which of these should be removed or repaired first.

At the state level, there are several road crossing barrier assessments currently in progress. In Washington State, the Department of Fish and Wildlife runs the Salmonid Screening, Habitat Enhancement, and Restoration (SSHEAR) fish passage barrier screening. They locate the structure, record its location, and determine if the stream is fish bearing. If it is not a fish bearing stream, they collect measurements and stop there, but if the stream does have fish, or is unknown, they conduct an A level assessment. If the culvert is deemed a barrier, they conduct a habitat assessment, then prioritize the barrier for correction (Bates et al. 2003). Massachusetts has stream crossing standards in place for new crossings, that culverts must be 1.2 times the bankfull width, but these are recommendations rather than regulations (MA River and Stream Crossing Standards 2006). In 2009, both Vermont (Bates and Kirn 2009) and New Hampshire (UNH 2009) developed guidelines for aquatic organism passage, though again these are not regulatory documents.

There is a wide range in how barrier passability is defined. It is frequently more convenient for mangers to consider crossings as either passable or not passable, hence the preponderance of binary barrier passability rankings (Clarkin 2005). One also must deal with cumulative passability, as there is rarely just one aquatic barrier in a river system. Moreover, the swimming abilities of the large number of species that make up river and stream communities are not well known, so it is impractical to use a species-based approach for designing or prioritizing stream crossings (MA River and Stream Crossing Standards 2006). Current methods to prioritize barriers generally include some measure of the following attributes: habitat quantity, habitat quality, degree to which a barrier impairs movement, and cost of repair (O'Hanley and Tomberlin 2005), but the simplest and most common prioritizations focus on stream miles added (habitat quantity) only (Kemp and O'Hanley 2010, Olivero and Anderson 2008). Most prioritization schemes begin with a barrier assessment, often at a watershed scale. Blank et al. (2005) used a tiered approach to assess fish passage, using the FishXing program, upstream and downstream population sampling, and direct-passage assessment. They found that the direct-passage study results suggested better passage at low flows than the other methods. They also found that upstream and downstream population sampling was not very useful for identifying the barrier status of a culvert.

At the nationwide level, aquatic fragmentation and river continuity has worked its way into the mission of many governmental and non-governmental organizations. The River and Stream Continuity Project (2009) emphasizes fish and aquatic organism passage, river and stream continuity, and wildlife passage in some watersheds in the northeastern United States. Trout Unlimited, American Rivers, Massachusetts Riverways, The Nature Conservancy, and others have all listed aquatic fragmentation as a conservation priority. Federally, the U.S.D.A. Forest Service developed *Stream Simulation*, an approach to designing crossing structures that are physically as similar as possible to the natural channel, such that the simulated channel allows free and unrestricted movements to any aquatic species (Clarkin 2008). The purpose of the Stream Simulation guide is to help national forests achieve their goal of maintaining the physical and biological integrity of the stream systems they manage.

Using multiple criteria when ranking barriers yields a more adaptable, in-depth and ecologically significant prioritization scheme than looking at river miles alone. Two major types of barrier prioritization being used are rank and score metrics, and optimization models, both of which can account for multiple decision criteria (Kemp and O’Hanley 2010). Ranking and scoring involves moving down an ordered list of prioritized barriers until the budget has been expended, and is easy to implement, but its major weakness relates to the fact that removal decisions are made independently of each other (Kemp and O’Hanley 2010). Optimization schemes allow more flexibility in the decision-making process and can account for real-world complexities (O’Hanley and Tomberlin 2005). Ideally, one assesses the potential environmental benefits gained from the removal of a barrier after assigning a passability score to each barrier (Kemp and O’Hanley 2010). Incorporating risk of barrier failure as an element in prioritization, as well as the ecological considerations, under both current and predicted future climate scenarios, would give a more inclusive perspective on overall benefits of removal or replacement.

1.2 Study Objectives

On a regional level, conservation managers are looking to have resilient populations, diverse communities, and productive ecosystems, as well as safe, reliable, cost-effective infrastructure due to improved or replaced culverts. In this study I built a prioritization scheme for the removal of aquatic barriers that considers fish habitat quantity, thermal habitat quality, aquatic organism passage, and infrastructure sustainability (Figure 1). This prioritization scheme can contribute to the larger, regional goal of conservation managers.

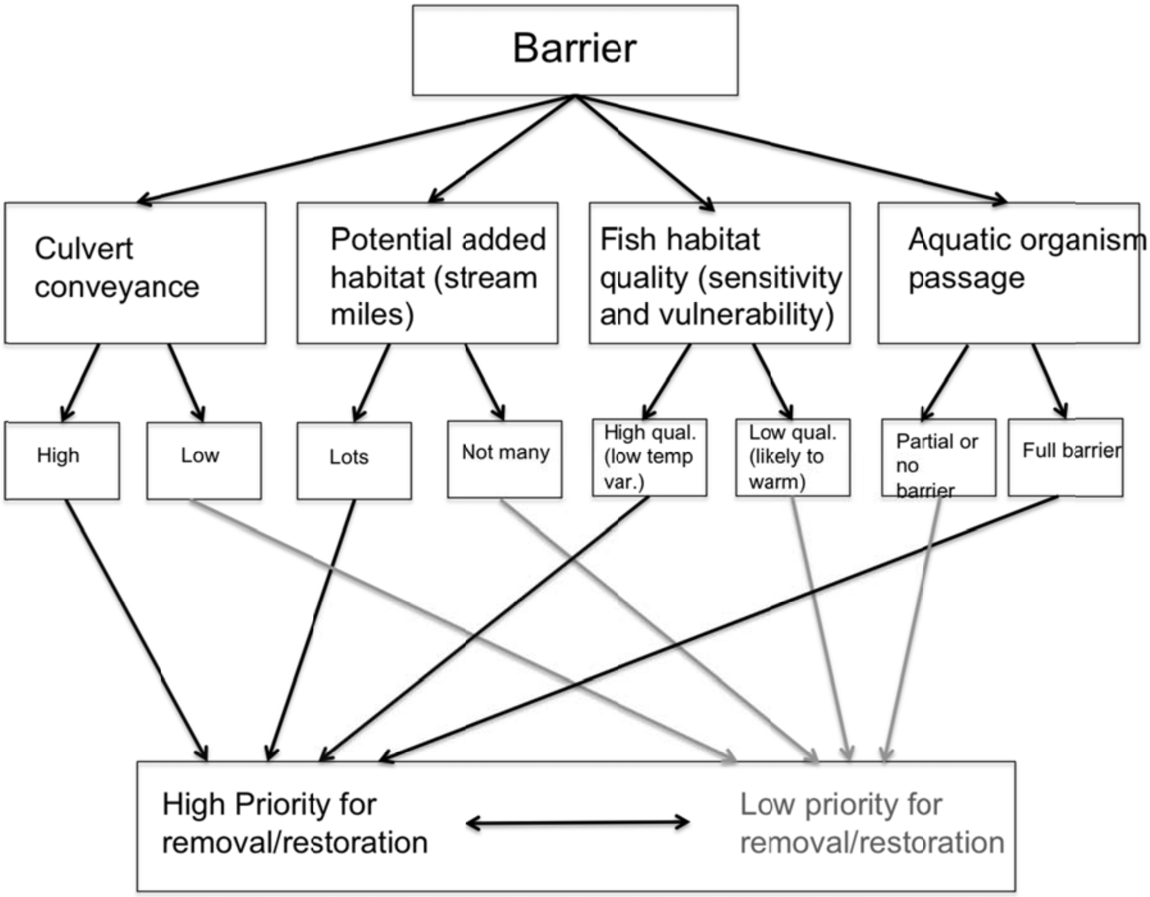


Figure 1. Conceptual model of a barrier prioritization scheme including habitat quantity, thermal habitat quality, aquatic organism passage, and infrastructure sustainability.

The objective of this study was to expand upon existing habitat quantity barrier prioritization models, by extending our understanding of the role of barriers and stream networks in two dimensions: fish thermal habitat and culvert/infrastructure sustainability, in the context of climate change in New England.

1.2.1 Thermal resilience: Sensitivity and exposure

One measure of habitat quality is the thermal regime of a river. Stream temperature is one of the parameters in stream ecology that determines the overall health of aquatic ecosystems (Coutant 1999, Smith and Lavis 1975), and temperature is a major determinant for the growth rate and development of fish (Elliot and Hurley 1997). Summer stream temperature is the single most important factor influencing brook trout distributions (MacCrimmon and Campbell 1969). Stream temperature varies not only as a function of air temperature, but also as a function of associated landscape variables (Trumbo et al 2010, Allan 2004, Cassie et al. 2001 Smith and Lavis 1975). Identifying thermally resilient coldwater habitats is an important step in prioritizing barriers for brook trout habitat restoration and conservation (Hudy et al. 2005). Thermal resilience in this study is defined as a combination of stream sensitivity and exposure: stream sensitivity is the relationship between paired air and water temperatures, and exposure is a standardized measure of the frequency, duration, and magnitude of water temperatures above a predetermined threshold. These two variables can be combined to get the thermal resilience of a stream.

1.2.2 Infrastructure sustainability: culvert opening relative to its upstream watershed size

It has been suggested that undersized culverts are more likely to fail in an extreme flow event, while acknowledging that frequently it is culvert angle or debris buildup and blockage that causes the actual failure. Hurricane Irene (August 2011) caused extreme flooding in western Massachusetts and all through Vermont, and multiple culverts failed because of the hurricane. Using data from the River and Stream Continuity Project (2009), I used this opportunity to test if undersized culverts relative to their upstream watershed areas failed more frequently than adequately sized culverts, and developed a logistic regression to predict the risk of culvert failure based on culvert characteristics and upstream watershed size.

1.2.3 Barrier prioritization

This study developed a barrier prioritization scheme that considers potential habitat gained by barrier removal, thermal resilience of a stream, aquatic organism passage, and culvert risk of failure. Potential miles gained are the added miles if a barrier were to be removed. These four ranking criteria can be combined in countless ways to prioritize road-stream crossings for removal in sample watersheds. Using brook trout as an indicator species because of their thermally dependent existence in highly fragmented habitats, I studied three HUC8-size watersheds in New England to examine these three ideas in greater depth.

2. STREAM THERMAL RESILIENCE IN THE CONTEXT OF CLIMATE CHANGE

2.1 Introduction

Water temperature is one of the parameters in stream ecology that determines the overall health of aquatic ecosystems (Coutant 1999, Stoneman and Jones 1996, Smith and Lavis 1975), and temperature is a major determinant for the distribution, migration timing, growth rate and development of fish (Xu et al. 2010, Elliot and Hurley 1997, Johnston 1997, Jensen 1990). Fish, especially salmonids, discriminate among thermal regimes strongly enough that many fisheries management systems classify fish habitat based on temperature (Wehrly et al. 2009). Higher water temperatures affect salmonids during spawning, incubation, and rearing stages of their life cycles (Battin et al. 2007, Petty et al. 2005).

At a watershed scale, stream temperature varies not only as a function of air temperature, but also as a function of associated landscape variables (Trumbo et al. 2010, Allan 2004, Cassie et al. 2001, Vannote et al. 1980, Hynes 1975, Smith and Lavis 1975) (Figure 2). Solar radiation in a stream's watershed is responsible for most of the increase in water temperatures (Cassie et al. 2001). On a finer scale, shading by banks and riparian vegetation can cause significant variability of water temperatures (Webb et al. 2008). A buffer zone can maintain water temperature within the normal warming trends of fully covered streams (Cassie 2006). Other important factors affecting water temperature include the altitude of a stream, the distance from the source of the stream, the temperature of the incoming water, the air/water interface, and anthropogenic factors (Allan 2004, Morrill et al. 2005). At a reach scale, much variability exists in the relationship between stream and air temperatures. The majority of large streams show an increase in water temperature of 0.6-0.8˚C for every 1˚C increase in air temperature (Morrill et al. 2005), but the response is more varied in small streams, which are at higher elevations, experience less solar exposure, and have a smaller thermal capacity than larger rivers (Trumbo et al. 2010, Cassie 2006).

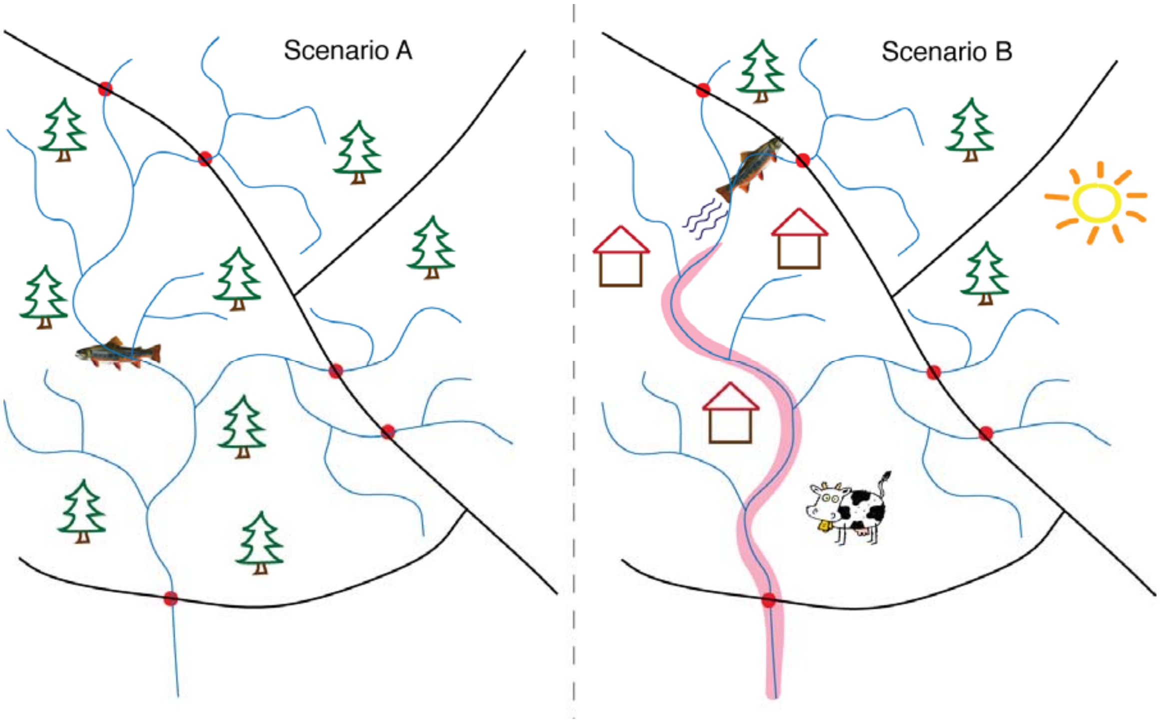


Figure 2. The downstream culvert (red dot) in both scenario A and scenario B opens the same number of stream miles, but the culvert in scenario A opens up higher quality thermal habitat than scenario B. Scenario B depicts a stream highly vulnerable to changes in air temperature, where removing or repairing one of the upstream culverts would offer an escape route for the brook trout in unfavorable conditions downstream, even though the downstream culvert would open the greatest number of stream miles.

Different timescales of measurement lead to different relationships between stream and air temperatures at a local scale. Previous research shows that weekly and monthly averages of air temperature are better correlated with water temperatures than daily values (Morrill et al. 2005, Cassie et al. 2006, Erickson and Stefan 2000, Pilgrim et al. 1998, Stefan and Preud'homme 1993). For these longer time scales, one can use a linear regression without addressing the lag time, but for a short time scale in larger rivers, it is necessary to account for the lag time (Pilgrim et al. 1998). The daily maximum and minimum are more significant than a weekly average from an ecological standpoint (Cassie et al 2001, Smith and Lavis 1975), though daily maximums have a higher variability than weekly averages (Cassie 2001, Pilgrim et al 1998). However, it is those same variations that from a fisheries perspective make it important to model the maximum temperatures on a short time scale. Maximum temperature provides the best fit in predicting brook trout presence/absence (Picard et al. 2003). The slope and intercept of stream/air temperature relationships are a function of the stream type, as a groundwater-dominated stream will have a shallower slope with a relatively high intercept (Cassie 2006).

Mohseni and Stefan (1999) found that there were four ranges to the stream/air temperature relationship. The first is at very low air temperatures, when there is ice covering the stream, so no surface heat exchange. The second range is at slightly higher air temperatures, but still below 0˚C, when the stream temperature is somewhere between groundwater and equilibrium temperatures. The third range is at moderate air temperatures (0-20˚C), as the stream varies between upstream temperatures and the equilibrium temperatures. This range changes linearly. The fourth range is at high temperatures, and the stream temperatures rise slowly compared to the air temperatures. When lumping all four ranges together, a linear regression does not project that leveling off well enough, and leads to erroneous predicted stream temperatures at the highest air temperatures, but when considering the different stages separately, a linear model is an appropriate representation (Morrill et al. 2005). Other heat fluxes that are not being taken into account are stream inflow and outflow, groundwater, snowmelt water, and anthropogenic effects (Bogan et al. 2003).

When modeling stream temperatures, one approach is to use a series of predictive environmental variables, such as the canopy cover in the local catchment, summer mean air temperature, network catchment slope, and soil permeability (Wehrly et al 2009). Another option for modeling stream temperatures is to rely on the stream/air temperature relationship. If broken out into seasonal components, this is an efficient way to model daily water temperatures (Cassie 2006). Smith and Lavis (1975) admit that a first approximation about the range of thermal behavior of a stream could be based on air temperature, but emphasized the complexity of thermal variations in small streams. Trumbo et al. (2010) modeled both the stream/air temperature relationship, hereafter referred to as sensitivity, and used a predictive model including landscape variables to predict said sensitivity in a different year.

2.2 Study Objectives

Variation in stream sensitivity and exposure to warm summer temperatures, combined with the negative effects of warm temperatures on brook trout growth and survival, suggests that stream thermal regimes should be considered in barrier removal plans. In this study, I identified areas of high quality thermal habitat for brook trout, as part of a larger barrier prioritization scheme that considers habitat quantity, thermal habitat quality, aquatic organism passage, and infrastructure sustainability. This chapter follows the idea of thermal habitat quality in more depth. I directly measured paired air and water temperatures in 67 streams over three HUC8-sized watersheds in New England from November 2010-October 2011, to classify brook trout habitat in these streams with respect to their thermal resilience, using stream sensitivity and exposure. Stream sensitivity describes the reaction of stream temperatures to a change in air temperature, and exposure is the average frequency, duration, and magnitude of stream temperatures that exceed a predetermined temperature threshold. I also developed a model using landscape characteristics to attempt to predict stream sensitivity and exposure. My overall goal was to add a habitat quality component to existing habitat quantity barrier prioritization models in the context of climate change.

2.3 Methods

2.3.1 Study area

The study area consisted of four regions in New England: three Hydrologic Unit Code (HUC) 8 scale watersheds, and a group of thirteen HUC10-scale watersheds in the White Mountain National Forest (Figure 3). The West River watershed (VT) and the Westfield River watershed (MA) are both subwatersheds in the Connecticut River, the biggest river in New England. The

Sandy River watershed (ME) is a subwatershed of the Kennebec River. The seven HUC10-size watersheds in the White Mountain National Forest (WMNF) of NH are slightly smaller: the Ammonoosuc River, Swift River, Mad River, South Branch Israel River, Peabody River, and the Hancock River. The WMNF data were collected and shared by Mark Prout, U.S.F.S. In each HUC8 watershed, 10-25 sample streams were chosen to directly measure air and water temperatures. Sample streams were chosen that support brook trout breeding habitat (identified by expert opinion).

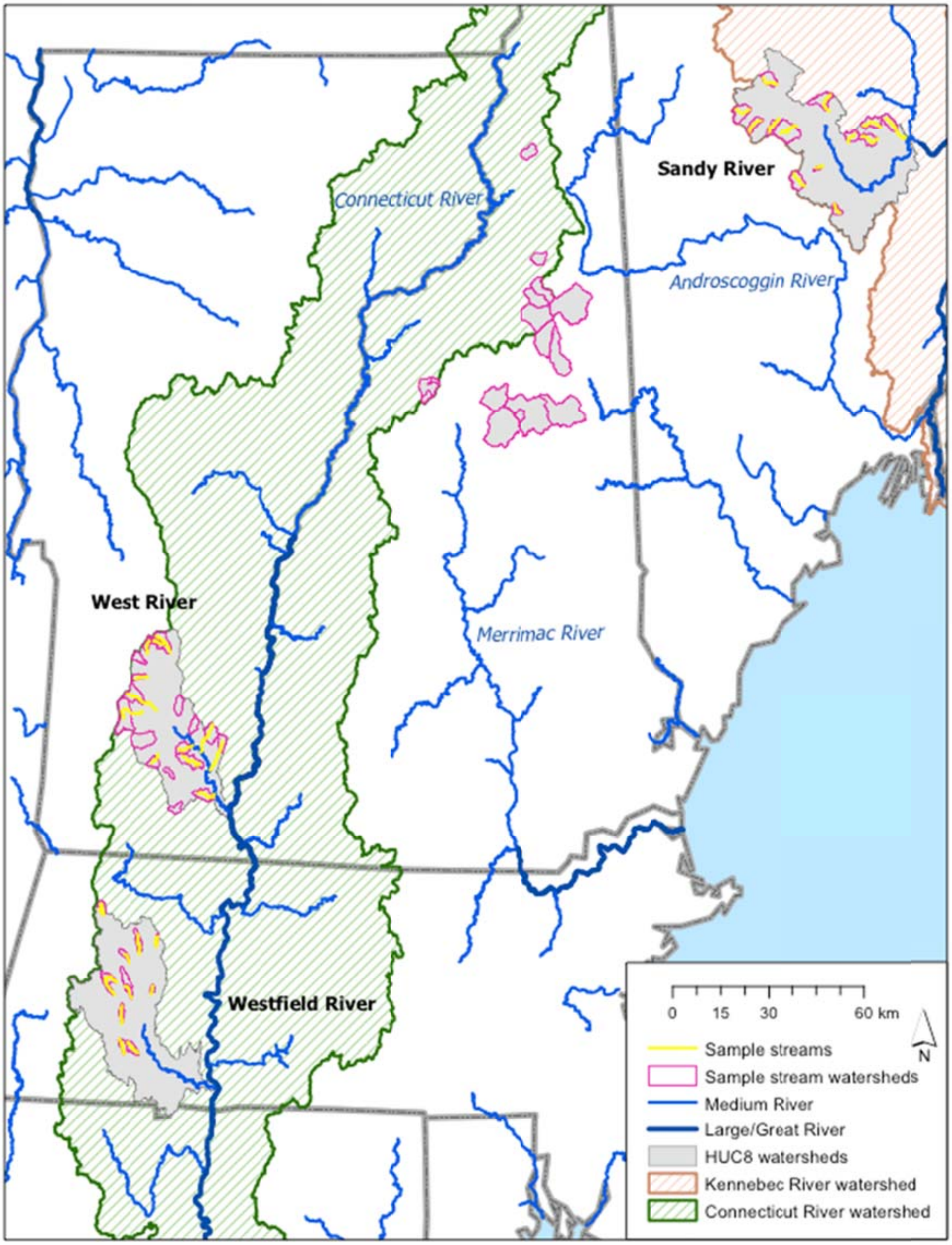


Figure 3. HUC8 watersheds and sample streams in New England. HUC8 watersheds are represented by gray polygons, and sample streams are represented by yellow lines inside of a pink polygon representing their individual watersheds.

2.3.2 Sampling protocol

I directly measured the air and water temperature of each stream with paired air and water temperature loggers (HOBO Watertemp Pro v2). For each sample stream I placed two sets of paired temperature loggers, one at a downstream location on the sample stream, which corresponded with a road-stream crossing, and one at an upstream site, which was as far upstream as I could feasibly get to and properly deploy a temperature logger. This redundancy in temperature loggers was to prevent data loss due to spring ice-out or other storms. The temperature loggers recorded every 30 minutes for one year, from November 2010 to October 2011. The HOBO Watertemp Pro v2 temperature loggers are accurate to 0.2˚C, and drift <1˚C annually (Onset Computer Corporation 2008). Temperature loggers were shielded from direct sunlight and physical damage using a perforated PVC cage. Water temperature loggers were cabled to the nearest sturdy root, placed in the deepest available pool, and covered with rocks to avoid detection and sunlight. Air temperature loggers were attached to a tree <30m away, in the shadiest area available, as recommended by Dunham et al. (2005).

2.3.3 Statistical analysis

All statistical analyses were done in R. The temperature data collected from the paired air and water temperature loggers were used to rank streams in terms of two important components of thermal habitat resilience: sensitivity and exposure. The sensitivity and exposure analysis only used summer data (July 1 – Sept. 30), because of its relevance to brook trout stress, but there is a dearth of year-round temperature monitoring in the Northeast, so the loggers also recorded data through the winter. Data were screened for outliers, which frequently corresponded with high flow events washing the logger onto the shore. Scatter plots of air and water temperatures were drawn to evaluate the relationships, and to look for discrepancies in the daily maximum values.

Sensitivity is the response of stream temperature to a change in air temperature, measured as the slope of a linear regression for those data between 21-30˚C maximum daily air temperatures. As discussed earlier, small streams do not have a linear temperature response to increasing air temperatures across their entire range of above-zero temperatures, but when solely considering temperatures in the 21-30˚C range, the stream temperature response is linear (Mohseni and Stefan 1999). I used daily maximum air temperatures in this study because the daily maximum temperatures have the highest probability of increasing in various climate change scenarios (IPCC 2007). I compared a variety of timescales of measurement, listed in Table 1. I also calculated the stream sensitivity using a Beverton-Holt model (Beverton and Holt 1957), to compare the fit to that of a linear model.

Table 1. Description of the different timescales of measurement used to calculate stream sensitivity.

Timescale of air temperature	Timescale of water temperature
Daily maximum	Daily maximum
Weekly median of daily maximums	Weekly median of daily maximums
Daily maximum	One-day lag of daily maximum
Daily maximum	Average temperature of the past week

Exposure to stress associated with increased temperatures was characterized by an average of three standardized measures: Frequency, duration, and magnitude. Frequency is the number of days where the water temperatures exceeded a given temperature threshold. Duration is the longest string of consecutive days where the water temperatures exceeded that temperature threshold. Magnitude is the average temperature of those days where the water temperature exceeded that threshold. These three measures of exposure were each range standardized, then averaged to a single metric, after being screened for outliers. Because there are arguments both for and against standardizing the three measures, I tested each of the exposure measures separately and compared correlation coefficients, and in the end only used the composite measure. Exposure metrics were calculated at a threshold of 21˚C, the point at which thermal stress may begin to affect distribution and survival (Brett 1956, Picard et al. 2003), and at a threshold of 17˚C, the point at which thermal stress begins to affect growth rates (Xu et al. 2010, Lund et al. 2002). Stream exposure informs managers about the biological stress on brook trout populations (Smith and Lavis 1975, Cassie et al. 2001). Using exposure at 17˚C also increased the available sample size, because more streams had instances where they were exposed at 17˚C than at 21˚C.

Using sensitivity and exposure, I classified the sample streams based on their thermal resilience for use in a prioritization ranking scheme. I codified the classification process by assigning each stream a value that corresponded with the deviation of that stream’s sensitivity and exposure from the median sensitivity and exposure of each HUC8 watershed, thus standardizing the sample stream rankings by region. The median sensitivity and exposure was represented by a line representing the balance of sensitivity and exposure, with a slope of -1 and an intercept of 0.5, on a plot scattering exposure against sensitivity: $y = (-1)*x + 0.5$, where 0.5 represents the median exposure (Figure 4). The deviation was measured as the perpendicular distance from the point to the median line. Both exposure and sensitivity were standardized to range from 0-1. This classification codification allowed me to combine sensitivity and exposure into a single thermal habitat quality metric in my overarching prioritization scheme. This classification codification can be a useful tool to managers who need to prioritize streams quickly and effectively based on their thermal resilience.

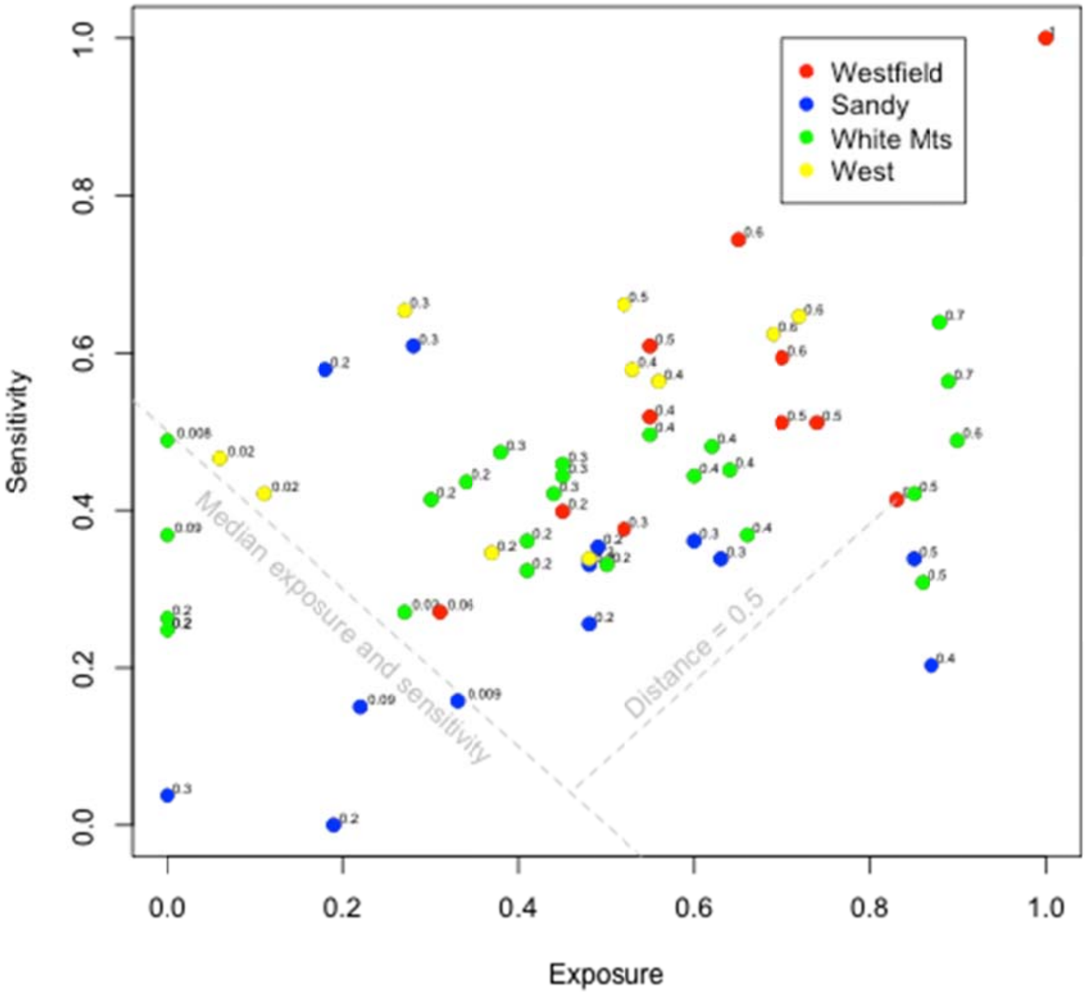


Figure 4. Graphical demonstration of the thermal resilience classification using sensitivity and exposure. The line y=(-1)*x + 0.5 represents the balance between exposure and sensitivity.

2.3.4 Landscape predictive model

It would be convenient to be able to predict sensitivity and exposure using landscape characteristics rather than directly measuring temperatures. I used ArcGIS10.0 to calculate candidate landscape metrics for the watershed upstream of each pour point, and for a 100m riparian buffer around sample streams. Candidate landscape metrics used in the final analysis are listed in Table 2. These landscape variables were used in a predictive model to explain the variation in the sensitivity and exposure of each stream.

Table 2. Candidate landscape metrics summarized for each sample stream watershed. The riparian buffer referred to is a 100m radius from the 1:100k NHD+ flowlines.

Metric	Units	Source
Watershed area	Km^2	Derived from DEM
Solar radiation corrected for % canopy	kWh/30m pixel	Derived from DEM and NLCD
Average watershed elevation	Meters	Derived from DEM
Average daily maximum temperature over past 30yrs	Degrees C	PRISM 2007
% Forest in watershed	Proportion	NLCD 2006
% Open land	Proportion	NLCD 2006

Because of low sample sizes of study streams, I used a fixed effects model, including the HUC8 region as a predictor variable rather than a factor, and created separate models for the response variables of sensitivity and exposure, using landscape variables to explain the variation in each stream's sensitivity or exposure. Because the sample streams were nested within larger HUC8 watersheds, I also tested a mixed model. I tested the model using all three exposure measures as response variables separately from the range-standardized composite exposure metric (described above under *statistical analyses*), to see if one measure could account for the others. I ran the model for both 17˚C and 21˚C exposure thresholds. For the sensitivity predictive model, I weighted the sensitivities by a vector of their R^2s, such that streams with a better-fitting sensitivity regression were given more weight in the landscape model. I fit all possible models, calculated model weights based on AIC, and chose a final model based on the lowest AIC by at least 2 points.

2.4 Results

Because of extensive damage and loss to the water temperature loggers after winter 2010 ice-out and Hurricane Irene (late August, 2011), paired temperature data were sparser than originally planned. Thanks to the redundancy of having two sets of paired temperature loggers at each sample stream, I still had enough data to classify streams based on their thermal regimes. The White Mountain National Forest (WMNF) watersheds had 25 sample streams of paired air- and water-temperature loggers with reliable data from July 1 to September 30. The Sandy River Watershed had 13 sample streams with useable temperature data. The West River Watershed had 10 sample streams of temperature loggers with useable data after extensive damage and loss due to Hurricane Irene. The Westfield River Watershed had 11 sample streams with useable data, having lost one water logger after 2010 winter ice-out.

2.4.1 Sensitivity

The strength and relationship between directly-measured air and water temperatures varied when sensitivity was calculated using different timescales (Table 3 and Figure 5). Daily maximum temperatures yielded the smallest confidence intervals, but a moving window of daily maximum air temperatures to the weekly mean of daily maximum water temperatures yielded the best R^2 values. Table 4 and Figure 6 show the relative ranks of streams using the different timescales of measurement, where a less sensitive stream is ranked higher (low numbers). The daily maximum temperatures did not have a great fit to the regression (mean watershed $R^2 = 0.36$) compared to the rolling window of one day's water temperature regressed against the average temperature of the past six days air temperatures (mean watershed $R^2 = 0.42$), and using a rolling window allows the sample size to remain high, unlike the weekly median of daily maximum temperatures (mean watershed $R^2 = 0.49$). The moving window of sensitivity calculations makes maximum use of the data with no arbitrary decisions.

Table 3. Sensitivity and its R^2 and confidence intervals calculated on a variety of time scales. R^2 and confidence intervals are displayed for sample streams in the Westfield River watershed for three different timescales of measurement: 1) Daily maximum temperatures, 2) weekly median of daily maximums, and 3) a 6-day rolling window of water temperatures to the daily maximum air temperatures. Also calculated but not shown was a 1-day, 2-day, and 3-day time lag of air to water temperatures.

Stream name	Daily max. slope	Weekly median of daily max slope	Week-long rolling window slope	Daily max R2	Weekly median of daily max R2	Week-long rolling window R2	Daily max CI	Weekly medians CI	Week-long rolling window CI
Abbott	0.55	0.86	0.76	0.30	0.57	0.56	0.34 - 0.76	0.34 - 1.38	0.60 - 0.92
Bedlam	0.26	0.26	0.35	0.24	0.27	0.33	0.14 - 0.39	-0.07 - 0.59	0.21 - 0.49
Center	0.75	1.09	0.92	0.43	0.68	0.49	0.51 - 0.98	0.42 - 1.76	0.67 - 1.17
Chauncy	0.29	0.24	0.42	0.3	0.3	0.44	0.17 - 0.41	-0.04 - 0.52	0.30 - 0.54
Gibbs	0.44	0.66	0.59	0.39	0.65	0.45	0.29 - 0.58	0.23 - 1.09	0.41 - 0.78
Glendale	0.44	0.5	0.60	0.34	0.52	0.50	0.28 - 0.59	0.14 - 0.86	0.46 - 0.75
Kinne	0.12	-0.07	0.09	0.05	0.03	0.02	-0.02 - 0.26	-0.43 - 0.28	-0.06 - 0.24
Meadow	1.09	1.41	1.36	0.52	0.82	0.67	0.83 - 1.36	0.94 - 1.88	1.13 - 1.59
Powell	0.45	0.59	0.60	0.37	0.54	0.46	0.30 - 0.61	0.18 - 1.00	0.43 - 0.76
Taylor	0.31	0.34	0.22	0.29	0.27	0.12	0.18 - 0.45	-0.16 - 0.84	0.05 - 0.39
Tuttle	0.57	0.63	0.72	0.67	0.8	0.59	0.47 - 0.67	0.39 - 0.86	0.57 - 0.87

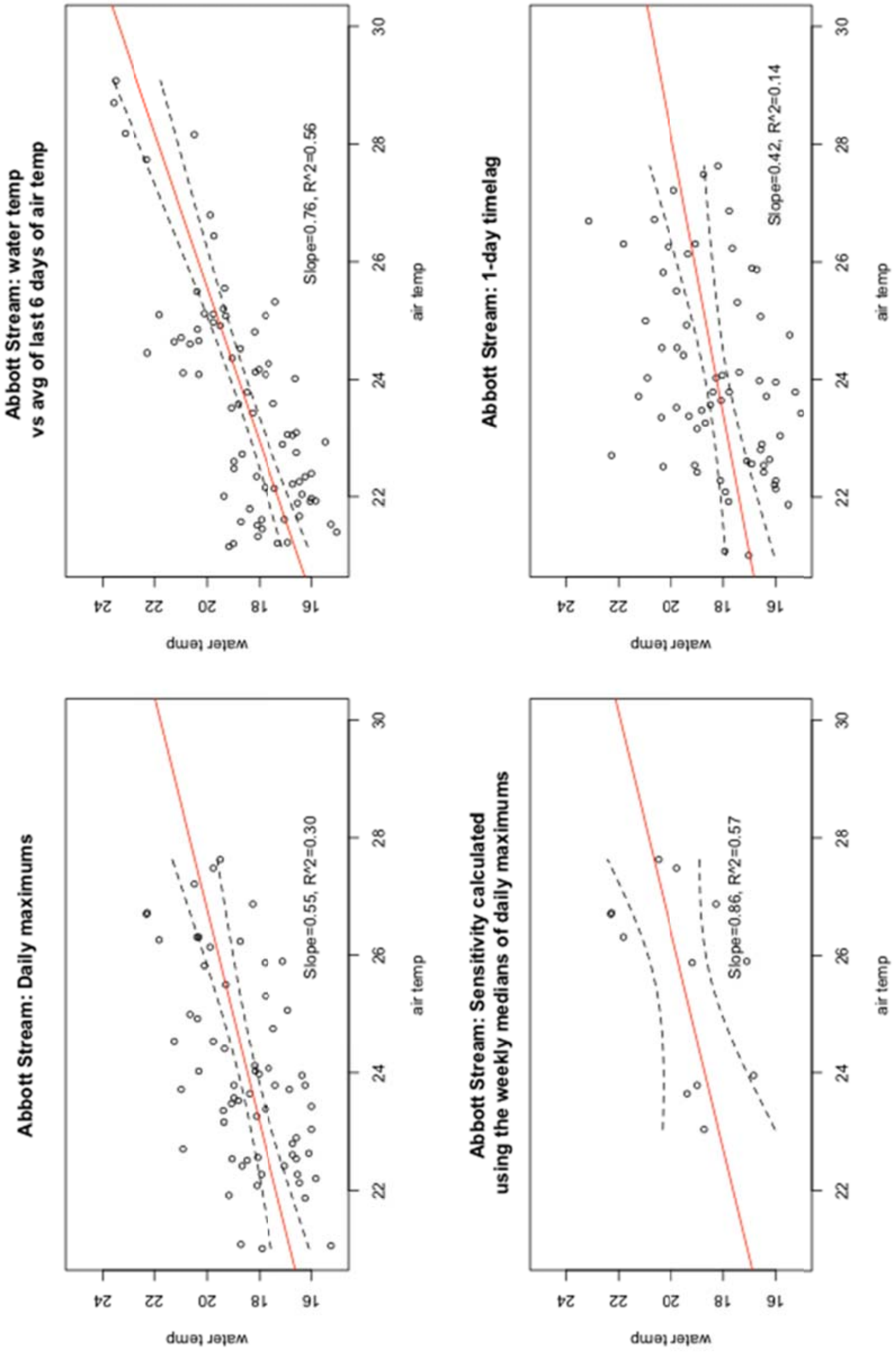


Figure 5. An example of one stream in the Westfield River watershed showing the air temperature-water temperature relationship when measured using daily maximum air temperatures, the weekly median of daily maximum air temperatures, a one-day timelag, and the reaction of water temperature to the average of the past six days of air temperature.

Table 4. Relative ranking of stream sensitivity in the Westfield River Watershed study streams, when using four different timescales of measurement: 1) daily maximum air temperature to daily maximum water temperature, 2) weekly median of daily maximum air and water temperatures, 3) a rolling window of one day of maximum air temperature to the average temperature of the last six days of maximum water temperatures, and 4) a one-day time lag of air to water maximum temperatures. This table shows that there is not much change in the stream rankings, regardless of how one measures sensitivity.

Stream name	Relative ranking using daily maximum	Relative ranking using weekly median of daily max	Relative ranking using week-long rolling window	Relative ranking using 1-day timelag
Abbott	8	9	9	9
Bedlam	2	3	3	2
Center	10	10	10	10
Chauncy	3	2	4	3
Gibbs	5	8	5	7
Glendale	6	5	7	4
Kinne	1	1	1	1
Meadow	11	11	11	11
Powell	7	6	6	5
Taylor	4	4	2	6
Tuttle	9	7	8	8

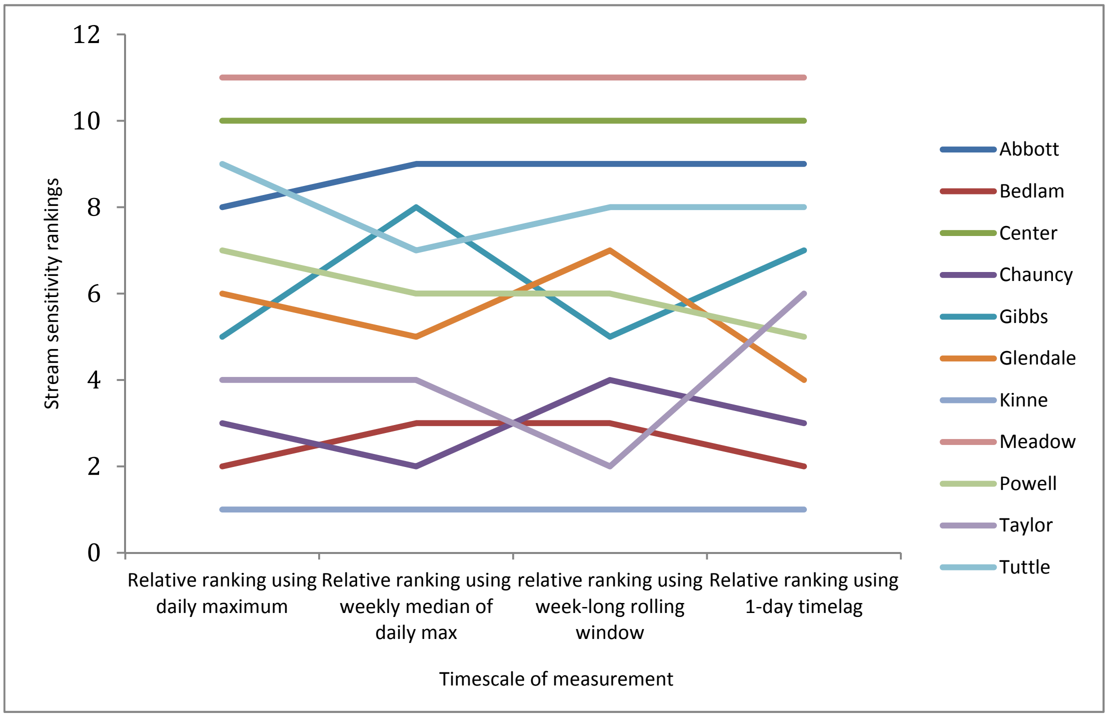


Figure 6. Relative rankings of stream sensitivity in the Westfield River watershed when different timescales of measurement are applied to the sensitivity calculations. A straight line indicates that there was no change in that stream's sensitivity relative to the other measured streams, regardless of the timescale used to calculate sensitivity.

The strength and relationship between directly-measured air and water temperatures varied across sites and across regions (Table 5). Using a moving window of time for air to water relationships, the median sensitivity in the Westfield River watershed was 0.44, the Sandy River watershed was 0.20, the median sensitivity in the WMNF was 0.32, and the median sensitivity in the West River watershed was 0.52 (Table 5). Of note, the minimum sensitivity value in the Sandy River watershed had a negative slope, though with a poor R^2 value (0.08), indicating that there was no observable relationship between air and water temperatures for that stream. This could be due to extreme sandiness of the watershed, or high rainfall during the summer I measured stream temperatures. There were no outstanding outliers that would have indicated a logger washed up on shore.

Table 5. Minimum, maximum, mean, median, and standard deviation for sensitivity in each HUC8 watershed. Sensitivity is the change in water temperature in relation to the change in air temperature, represented by the slope when water temperature is regressed against air temperature.

Sensitivity	Min	Max	Mean	Median	Std. Dev.
Westfield	0.12	1.09	0.48	0.44	0.27
Sandy	-0.24	0.57	0.14	0.20	0.24
WMNF	0.09	0.61	0.30	0.32	0.13
West	0.21	0.88	0.50	0.52	0.20

2.4.2 Exposure

Stream exposures varied between regions. Because the three exposure metrics – frequency, duration, and magnitude – were highly correlated (Table 6), exposure is reported on the range-standardized average of these three metrics for each stream (Table 7). Exposure metrics were calculated for both 17˚C and 21˚C (Table 7). At 17˚C, median exposure in the Westfield River watershed was 0.52, median exposure in the Sandy River watershed was 0.33, median exposure in the WMNF was 0.46, and median exposure in the West River watershed was 0.53. At 21˚C, median exposure in the Westfield River watershed was 0.37, median exposure in the Sandy River watershed was 0.44, median exposure in the WMNF was 0.00, and median exposure in the West River watershed was 0.35 (Table 7). The correlation between exposure at a 17˚C versus 21˚C exposure thresholds was 0.80.

Table 6. Correlation coefficients between the three standardized exposure metrics at 17˚C for all data lumped together, and calculated for each region separately.

	All regions	Westfield	West	Sandy	WMNF
Proportion x Magnitude	0.75	0.78	0.75	0.73	0.92
Proportion x Duration	0.73	0.93	0.82	0.83	0.96
Magnitude x Duration	0.84	0.83	0.88	0.62	0.90

Table 7. Minimum, maximum, median, mean, and standard deviations for exposure in streams at both 17˚C and 21˚C for each HUC8 watershed.

	Min	Max	Mean	Median	Std. Dev.
Exposure 17˚C					
Westfield	0.00	1.00	0.45	0.52	0.27
Sandy	0.01	0.80	0.38	0.33	0.25
WMNF	0.00	0.98	0.49	0.46	0.29
West	0.02	0.96	0.51	0.53	0.27
Exposure 21˚C					
Westfield	0.00	1.00	0.38	0.37	0.26
Sandy	0.00	0.82	0.48	0.44	0.22
WMNF	0.00	0.78	0.21	0.00	0.25
West	0.00	0.98	0.33	0.35	0.28

The correlation between sensitivity and exposure at 17˚C was 0.46. The correlation between sensitivity and exposure at 21˚C was 0.37.

2.4.3 Sample stream classification for prioritization

Streams are scattered as exposure against sensitivity for each HUC8 watershed, and the deviation of those sample streams from the median sensitivity and exposure, represented by the line y=(-1)*x + 0.5, was the thermal vulnerability value (Figure 7). Because sensitivity and exposure had been scaled before classification, I could subtract the thermal vulnerability value from 1 to get a thermal resilience value, so that a higher number represents a higher thermal resilience.

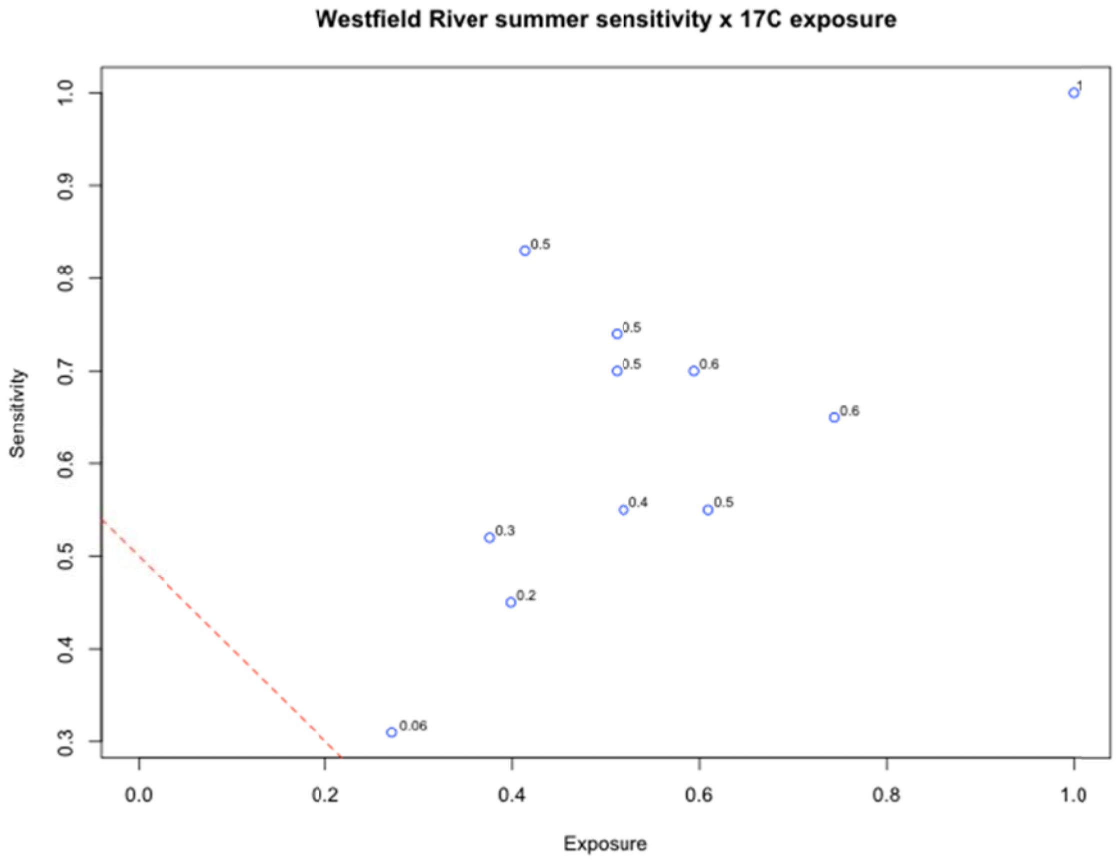


Figure 7. Classification of sample streams for prioritization in the Westfield River watershed, classified at a 17˚C exposure threshold. The dotted line represents the median sensitivity and exposure for that HUC8 watershed. The number next to each sample stream's point represents the distance of that point from the line y=(-1)*x+0.5.

After assigning a thermal resilience value to each sample stream, I ranked the sample streams based on their thermal resilience. I ranked sample streams for both a 17˚C exposure threshold and a 21˚C exposure, and ran a correlation to see how the rankings changed depending on which exposure threshold was used (0.741). A perfect correlation indicates no change in stream ranks at the different exposure thresholds.

2.4.4 Landscape predictive models

Variation in exposure and sensitivity was associated with landscape variables, but a lot of unexplained error remained in even the best model. I did not include landscape variables that were closely correlated with others (cutoff >0.7 correlation) (Table 8). I did not have a large enough sample size to justify using a mixed model, with HUC8 watershed ("region") as the factor. The AIC for a fixed effects model was lower than the AIC for a mixed model, for both sensitivity and exposure predictions (Table 9).

Table 8. Correlation coefficients for variables in the landscape models. Max temp refers to the average daily maximum temperature in the past 30 years, and sol.rad. % canopy is the solar radiation, corrected for % canopy cover.

	elev	% Forest	max. temp	Area	Sol.rad	Sol.rad. %canopy	% Open	winter temp
elev	1							
% Forest	0.25	1						
max. temp	-0.82	-0.32	1					
Area	0.32	0.03	-0.45	1				
Sol.rad.	0.68	0.22	-0.55	0.36	1			
Sol.rad. %canopy	0.68	0.37	-0.53	0.31	0.96	1		
% Open	-0.14	-0.78	0.33	0.10	-0.07	-0.23	1	
winter temp	-0.39	0.26	-0.19	0.23	-0.35	-0.36	-0.23	1.00

Table 9. Using AIC to compare the fit of a mixed model with that of a fixed effects model for sensitivity and for exposure.

	DF	AIC	BIC	Loglikelihood
Sensitivity				
Fixed-effects GLS model	6	62.18	71.51	-25.09
Mixed model	7	64.14	75.03	-25.07
Exposure				
Fixed-effects GLS model	4	131.20	137.64	-61.60
Mixed model	5	133.20	141.25	-61.60

The model using sensitivity as a response variable had the lowest AIC when using the average winter temperature and HUC8 region, with a weighting vector of the sensitivity R^2 values (Multiple R^2 = 0.1454, p-value = 0.2446, residual SE = 0.1284 on 26 DF).

For exposure I ran the models at 17˚C because of higher sample sizes and the strong correlation between exposures at 17˚C and 21˚C (0.80). The model using exposure as a response variable had the lowest AIC when using average elevation of the upstream watershed, area of the upstream watershed, and HUC8 region as predictor variables ($R^2 = 0.402$, p-value = 4.71e-05, residual standard error = 0.217 on 52 DF).

2.5 Discussion

Models based on simple air temperature – water temperature relationships can highlight potential threats to coldwater dependent species, such as brook trout. Direct measurements of paired summer air and water temperatures revealed much variation in stream thermal regimes at a local and regional level, directly relevant to brook trout persistence. These direct measurements resulted in a measure of habitat quality as a part of a larger barrier prioritization scheme in the context of climate change. Using stream sensitivity and exposure, I identified stream habitat that was relatively resilient or particularly vulnerable to climate change, and these stream rankings could be useful to managers looking to prioritize streams for conservation or restoration.

2.5.1 Sensitivity

Brook trout distribution and abundance is heavily influenced by maximum daily stream temperatures (Meisner 1990, MacCrimmon and Campbell 1969), but other time periods of measurement result in a better fit to the model. A rolling window of daily maximum water temperatures compared to the average of the last six days of air temperatures allows for a good fit without sacrificing data or making arbitrary decisions, and includes those temperatures that are most harmful to brook trout. More recently, Trumbo et al. (2010) did a similar study calculating stream sensitivity and exposure in the state of Virginia, and also pointed out that daily maximum air temperature fluctuations have the highest probability of occurring in climate change scenarios.

Mohseni and Stefan (1999) found that when modeling stream – air temperature relationships, a logistic model fit the data best for a full year of data. However, when only considering summer temperatures, where brook trout are at the most risk of encountering lethal temperature limits, Morrill et al. (2005) found that a linear regression is an acceptable model. I used a linear model because I only considered summer temperatures, and the median sensitivity among all sample streams was considerably lower than the accepted 0.8˚C rise in water temperature for every 1˚C rise in air temperature in larger rivers (Morrill et al. 2005, Allan 2004). This lower sensitivity in headwater streams implies that brook trout will have more high quality habitat available than previously thought under climate change scenarios. Other studies that use the 0.8˚C rise are estimating massive losses in coldwater habitat (Eaton and Scheller 1996, Rahel et al. 1996).

2.5.2 Exposure

Under climate change scenarios, exposure may be a more useful measure of stream thermal regime resilience or vulnerability than sensitivity, because exposure measures how vulnerable a stream already is to warming. Streams that have high exposure should probably not be considered as top priority for barrier removal, because no matter how low the sensitivity, that stream will always exceed ideal brook trout temperatures. Sensitivity and exposure were correlated, but not significantly so, and this is in part because you could have multiple streams with the same sensitivity, but that reaction of water temperature to air temperature change was happening at different parts of the water temperature range.

Using an exposure threshold of 17˚C can give managers a sneak preview of streams under climate change scenarios, because streams that have low exposure at 21˚C, but high exposure at 17˚C, are likely to become highly exposed in the future. Brook trout growth rates begin to be affected as low as 17˚C, though 21˚C is considered the distribution limit (Xu et al. 2010, Picard et al. 2003, Lund et al. 2002, Brett 1956). When ranking the sample streams in this study based on sensitivity and exposure, the ranks did not change significantly when using 21˚C exposure threshold compared to 17˚C exposure threshold, further justifying the use of a 17˚C exposure threshold.

Exposure is potentially more applicable for managers than sensitivity because it is the sheer exposure to high stream temperatures that ultimately affects fish.

Trumbo et al. (2010) categorized streams into four classes for prioritization – low exposure/low sensitivity, high exposure/high sensitivity, low exposure/high sensitivity, and high exposure/low sensitivity. The problem with this categorization scheme is that there is no clear way to differentiate between low exposure/high sensitivity and high exposure/low sensitivity. In this study I used the deviation from the line representing median sensitivity and exposure to assign a ranking value to each stream, which is a more intuitive way to rank sample streams, and makes more biological sense. These stream quality rankings can be used to prioritize streams for barrier removal or restoration, because not all streams are created equal with regards to thermal suitability for brook trout. Exposure tells you about the state of the stream today, while sensitivity describes the potential vulnerability of the stream, and though there is uncertainty associated with both measures, it would behoove managers to prioritize streams where both the exposure and sensitivity indicate a resilient stream. Stream sensitivity and exposure represent a simple, direct, cost-effective way to rank coldwater streams for prioritization.

2.5.3 Landscape Models

It would be convenient if one could use landscape-scale variables within each sample stream’s watershed to determine that stream’s sensitivity and exposure. Unfortunately, I had very low confidence in applying the predictive model I developed across regions, most likely because we lack information about groundwater inputs at an appropriate scale for headwater streams. For larger rivers, it has been well documented that stream temperature is a function of landscape-scale variables, such as solar radiation, shading by banks, altitude of the stream, and anthropogenic factors (Trumbo et al. 2010, Webb et al. 2008, Allan 2004, Cassie et al. 2001, Vannote et al. 1980, Smith and Lavis 1975). Because the landscape predictive model was not applicable in headwater streams, this underlines the point that direct measurements of paired air and water temperatures are a reliable and cost-effective way for managers to prioritize small headwater streams for brook trout conservation.

Climate change will affect the timing and amount of precipitation, amount of streamflow at any given time, and the air temperature (Battin et al. 2007, IPCC 2007). When looking at the risk to high quality brook trout habitat, temperature rise is the most predictable effect of climate change, justifying this focus on stream temperature response to rising air temperatures. This sensitivity and exposure classification should provide a useful framework for managers to protect and restore brook trout habitat to high quality areas. In long term planning and habitat prioritization, managers should use site specific air – water temperature measures rather than relying on regional or landscape models for small headwater streams. Not all reconnections of habitat are likely to be equally valuable, due to differences in current and future thermal habitat quality at the within-watershed scale.

3. INFRASTRUCTURE SUSTAINABILITY

3.1 Introduction

Road-stream crossings, such as culverts, are ubiquitous and inevitable in any human-impacted landscape, and when improperly designed, can significantly impede organism passage (Clarkin 2005, Gibson et al. 2005). The very large number of road-stream crossings has emphasized the need to identify which of these are likely to be barriers (Olivero and Anderson 2008, Jackson 2003, Jackson and Griffin 2000), because it has been shown that restoring connectivity is an effective way to maintain healthy fish populations and ecosystem processes (Kemp and O'Hanley 2010, Letcher et al. 2007, Roni et al. 2002). It has been suggested that undersized culverts both block fish passage and are more likely to fail in extreme flow events.

Under some climate change scenarios, storm flows are predicted to become more variable and more frequent (Betts 2011, Frumhoff et al. 2007). These higher flows will influence the capacity of existing culverts to protect road infrastructure, because culverts that are currently undersized with respect to their watersheds will become even more vulnerable to failure under predicted climate change scenarios (Nislow 2009). Moreover, undersized culverts, due to their effects on flow conditions and local streambed morphology, may be more likely to be barriers to fish passage (Nislow 2009, Clarkin 2005). The very large number of road-stream crossings has underscored the need to identify which of these are likely to be barriers to fish passage, and which culverts are likely to be a threat to our infrastructure sustainability (Olivero 2008, Jackson 2003, Jackson and Griffin 2000). Economically, designing culverts for fish passage may be more expensive in the short term because the culverts are bigger, but because failure risks are reduced, structural life is optimized, maintenance levels are reduced, and replacement frequency declines, these culverts may be more cost-effective in the long run (Freiburger and Fulcher 2013).

Road-stream crossings vary in their passability depending on time of year, time taken to pass the barrier, presence of predators, discharge, temperature, and the type of species attempting to pass (Kemp and O'Hanley 2010, Northcote 1998). Adult salmonids can pass culverts that are barriers to juvenile salmonids and other weaker-swimming species (Blank et al. 2005). Thus, culvert passability is not a binary variable, but is highly variable. Poplar-Jeffers et al. (2009) found that overall fish movement was an order of magnitude lower through culverts than through other crossing types of natural reaches.

Regulations about new culverts exist in six New England states, to ease aquatic organism passage. In a more comprehensive set of instructions, the USDA Forest Service's *Stream Simulation* provides guidelines to design crossing structures that are physically as similar as possible to the natural channel, such that the simulated channel allows free and unrestricted movements to any aquatic species (Clarkin 2005). Although these regulations are nominally in place to help with fish passage, they may also assist structures in their resistance to the effects of climate change. Because the Stream Simulation guide aims to maintain the physical and biological integrity of stream systems, the Stream Simulation crossings are more robust in the face of higher, more frequent flows predicted in climate change scenarios. Climate change is an urgent issue, and updating existing infrastructure is a long process that needs to start now.

3.2 Study objectives

I built an aquatic barrier prioritization scheme including habitat quantity, habitat quality, aquatic organism passage, and infrastructure sustainability, in two HUC8-scale watersheds in the Connecticut River watershed (Figure 8). This chapter develops a risk of culvert failure model for use in this overarching prioritization scheme. Specifically, I tested whether culverts that were undersized relative to their contributing watersheds were more likely to fail during the Irene event, and whether these undersized culverts were likely to be predicted barriers to fish movement.

3.3 Methods

3.3.1 Study area

I predicted culvert risk of failure in two Hydrologic Unite Code (HUC) 8-scale watersheds in New England (Figure 8): the Westfield River watershed and the West River watershed, both subwatersheds of the Connecticut River watershed. Hurricane Irene ravaged both the watersheds, providing ample data for analyses. These analyses were focused on the HUC14-scale watersheds nested within the HUC8s where I was able to obtain the most complete culvert failure datasets.

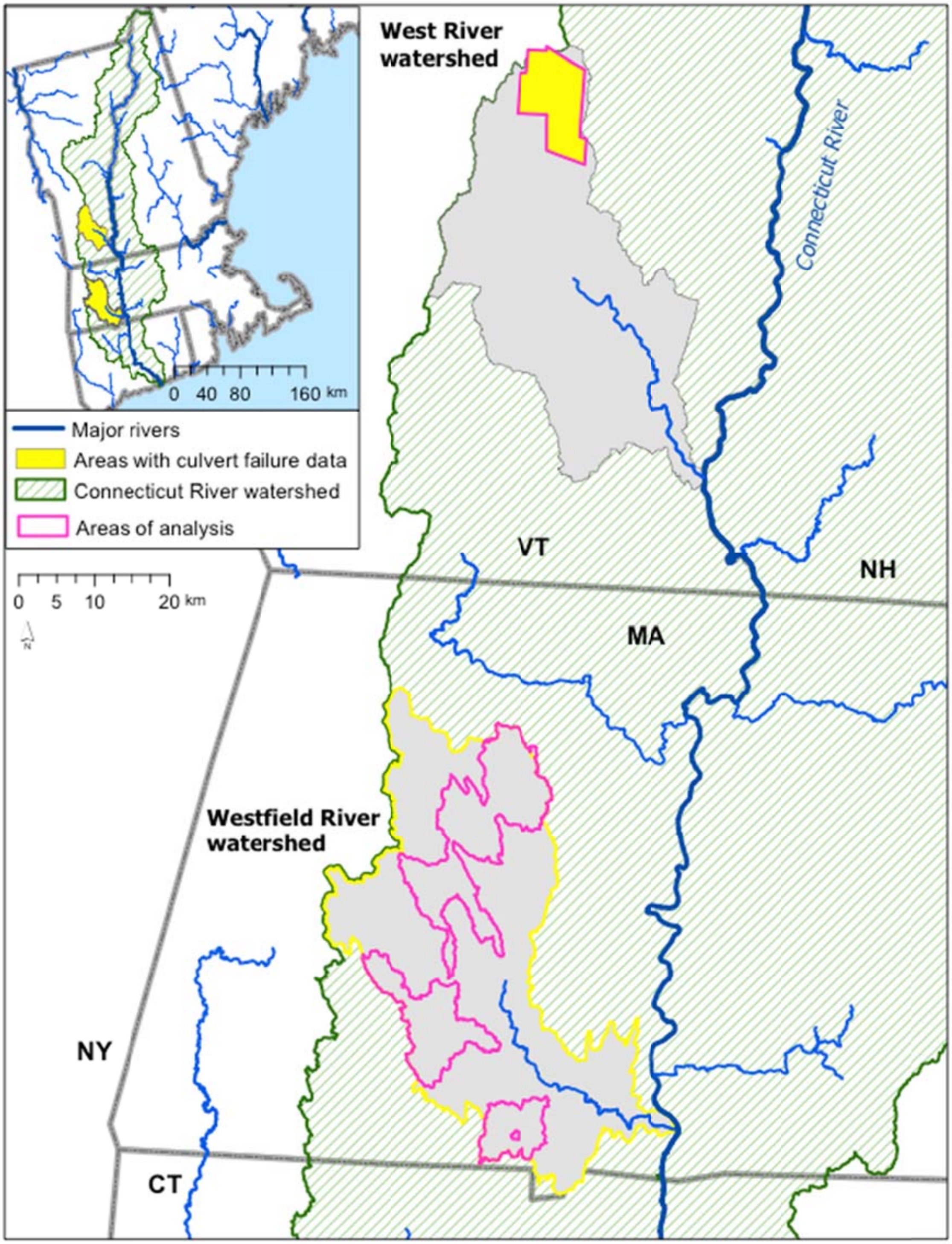


Figure 8: The model to predict risk of failure was based on culverts from the Westfield River watershed, MA, and from the town of Weston, VT that failed during Hurricane Irene. These watersheds are major drainages in the Connecticut River watershed, which drains most of New England, represented by green hatching in the map above. Pink outlines represent the HUC14-scale sub-watersheds where culverts were reported as having failed, and the culvert failure model focused on those sub-watersheds. Yellow indicates study areas.

3.3.2 Data collection

Culvert failure data after Hurricane Irene was collected by Carrie Banks of Massachusetts Riverways for the Westfield River watershed, and by Mark Falango of the Town of Weston for the West River watershed. Because in the West River watershed I only had culvert failure data for the town of Weston, the sample size was too low to give much power to the statistical analyses, so I combined the data from Weston and the Westfield, using state as a factor.

It is possible to model aquatic organism passage at a culvert using its physical characteristics, and many types of culvert surveys for fish passage are in use in the United States (Bates and Kirn 2009, River and Stream Continuity Project 2009, Blank et al. 2005, Bates et al. 2003). The River and Stream Continuity Project (2009), which works in New England and specifically the West and Westfield watersheds, developed an aquatic score metric, that assigns a proportional value to each culvert based on its physical characteristics meant to represent how much of a barrier that culvert is to aquatic organism passage (Appendix A). Bankfull width was not recorded in the River and Stream Continuity surveys, so I calculated bankfull width using the Regional Hydraulic Curves for Vermont, and the USGS Streamstats tool to calculate upstream watershed size (Jaquith and Kline 2006, U.S.G.S. 2011).

3.3.3 Statistical analyses

I created a risk of failure model for culverts using the ratio of culvert width to its bankfull width, and aquatic score, though I also tested models that included culvert openness (Appendix B) and upstream watershed size. Aquatic score is a weighted combination of outlet drop, physical barriers, water velocity, water depth, inlet drop, crossing span, crossing substrate, crossing embedment, openness, scour pool, tailwater armoring, and height, and was one of the measures calculated by the River and Stream Continuity Project (Figure 9, Appendix A) (River and Stream Continuity Project 2009). Culvert openness is the cross sectional area of the culvert, calculated with a complex formula that is specific to the opening type (Appendix B). All statistical analyses were done in R.

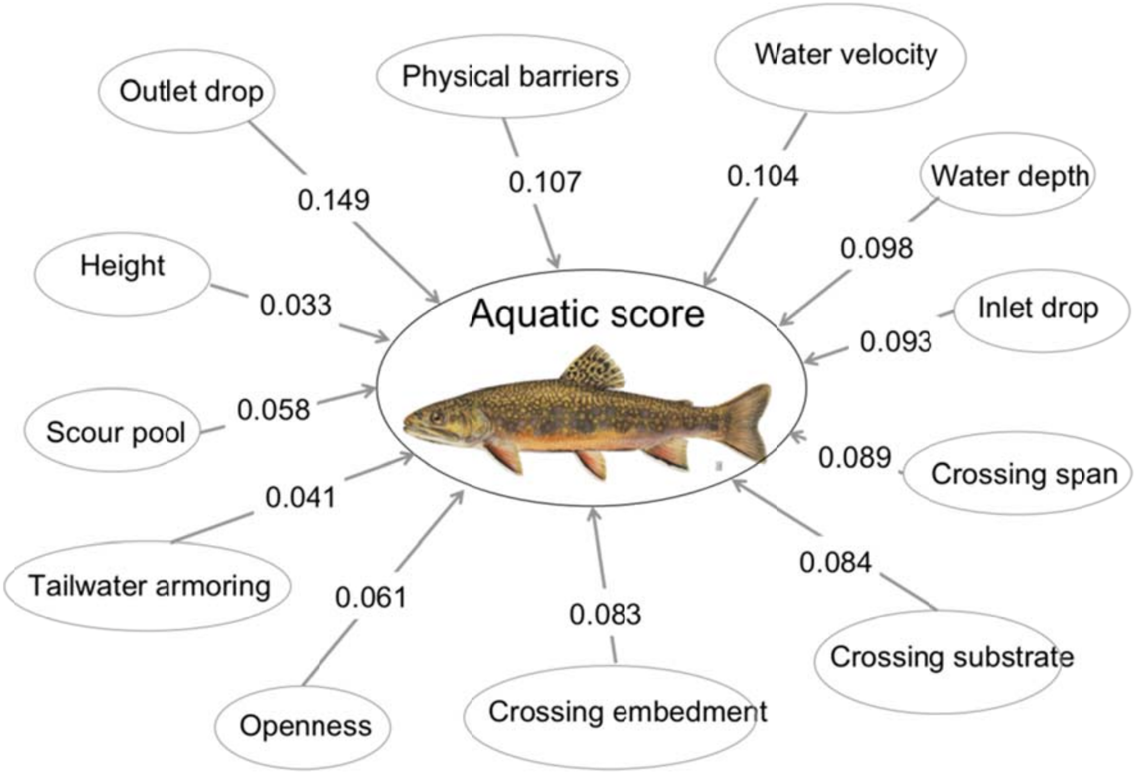


Figure 9. Aquatic score is a weighted combination of physical characteristics that can be measured about a culvert, and was calculated by the River and Stream Continuity Project (2009) in both the West River and Westfield River watersheds.

I ran t-tests to determine if there were any significant differences in the means of failed culverts versus those that did not fail for the ratio of culvert width to bankfull width and for aquatic score. Finally, I conducted a binary logistic regression using failure (yes or no) due to Hurricane Irene as the response variable, and culvert ratio, aquatic score, opening, upstream watershed size, and various interactions as predictors. I chose the best model using the lowest AIC by two points.

3.4 Results

In the Westfield River watershed, there were 1308 crossings, of which 17 failed during Hurricane Irene. Using only culverts from the HUC14-sized watersheds where I knew culverts had failed, I narrowed the sample size to 145 culverts (Figure 10). The town of Weston in the West River watershed had 20 culverts that had been surveyed, 7 of which had failed. I analyzed all culverts in the town (Figure 11).

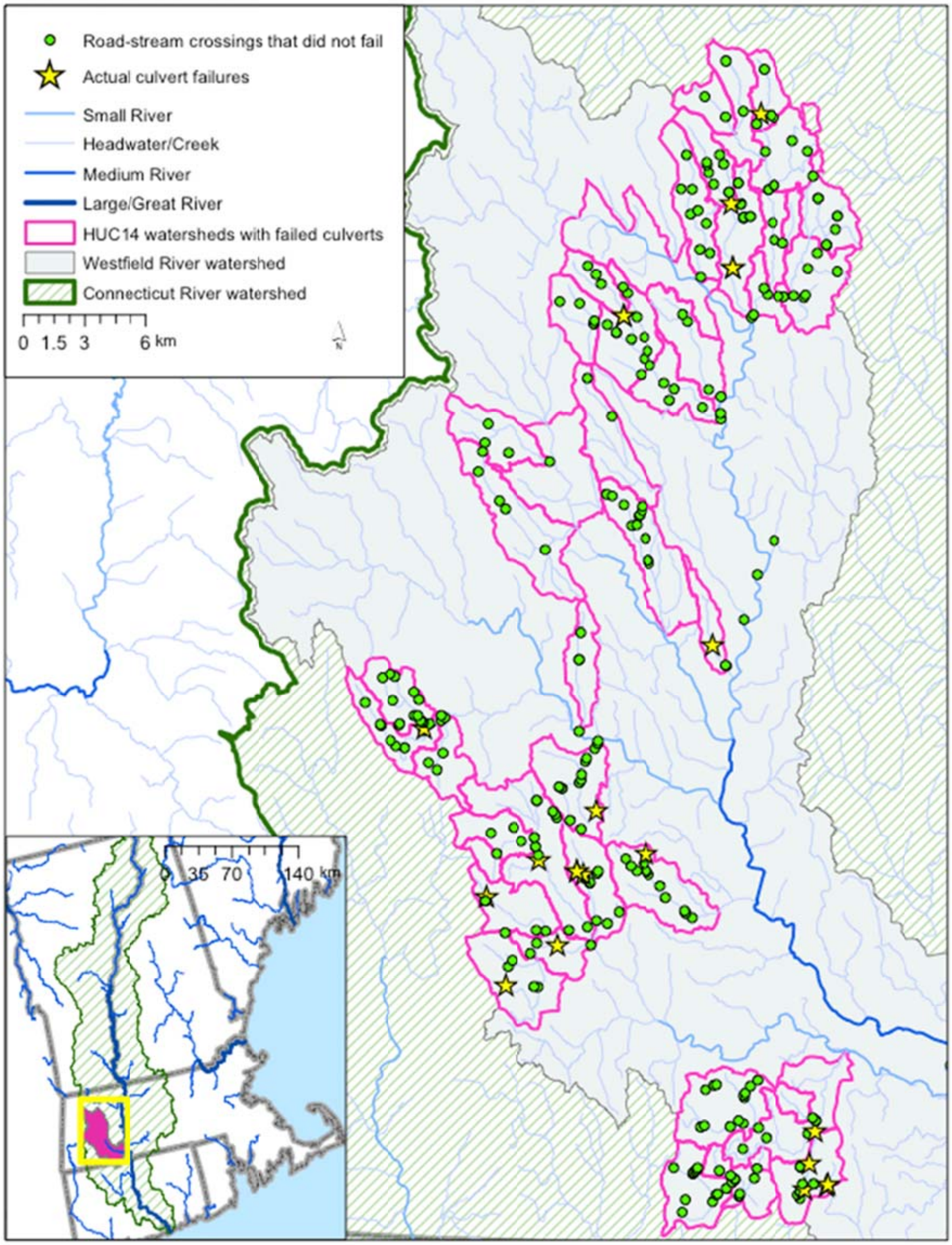


Figure 10. Spatial distribution of failed culverts in the Westfield River watershed, and spatial locations of all culverts included in this study. Yellow stars represent culverts that failed and green dots represent culverts that did not fail.

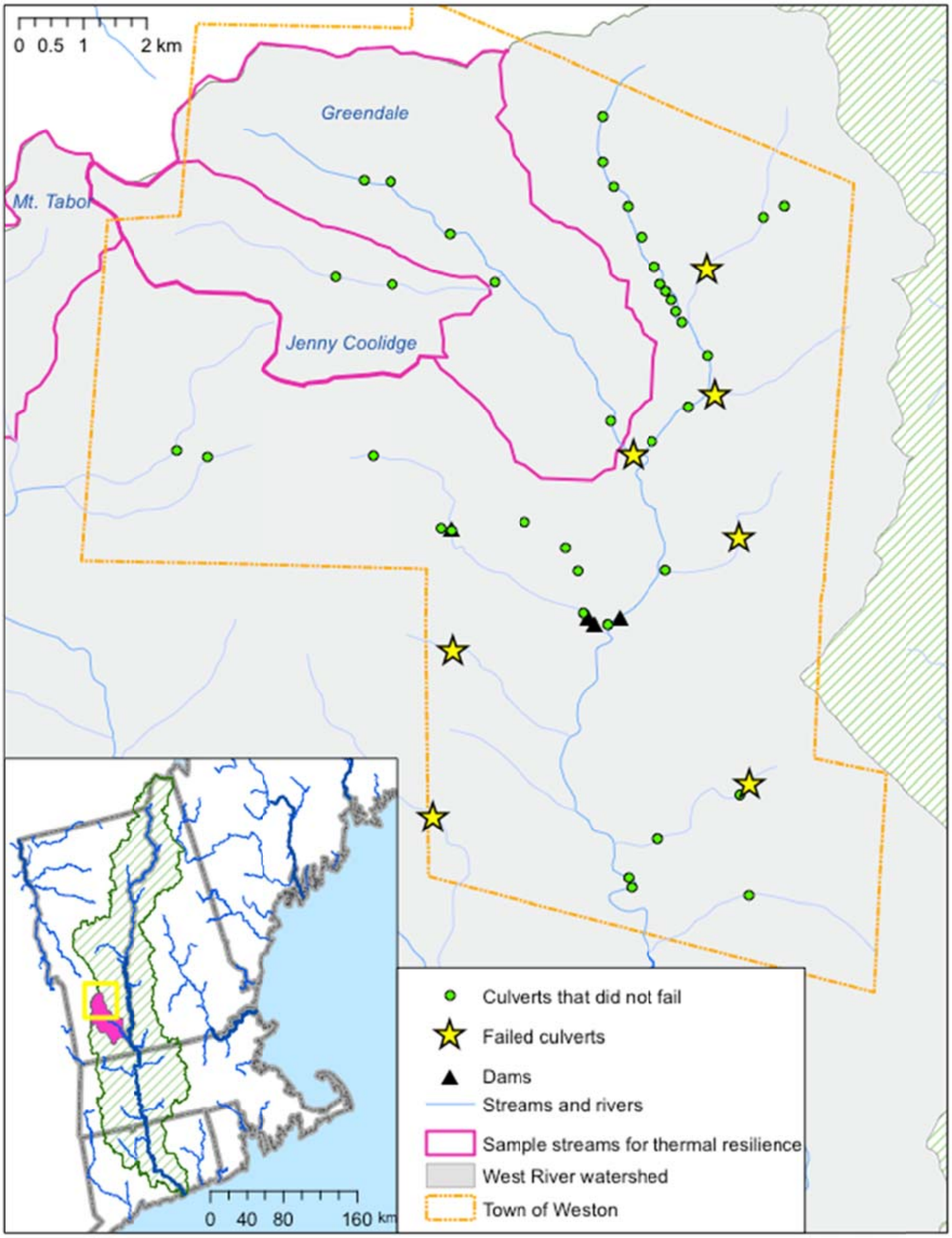


Figure 11. Spatial distribution of failed culverts in the town of Weston, in the West River watershed, after Hurricane Irene. Yellow stars represent culverts that failed, and green dots represent culverts that did not fail. The orange outline is the boundary of the town of Weston.

The median ratio of culvert width to bankfull width for data from both the Westfield River watershed and the town of Weston for culverts that did not fail was 0.44, and for culverts that did fail, was 0.34. The median aquatic score for culverts that did not fail was 0.71, and for culverts that did fail, was 0.64 (Table 10).

Table 10. Summary statistics for the ratio of culvert width to bankfull width and for aquatic score for data from both the Westfield River watershed and the town of Weston.

Not-failed culverts	Min.	Max.	Mean	Median	Std. Dev.
Culvert ratio	0.02	1.98	0.51	0.44	0.33
Aquatic score	0.26	0.99	0.69	0.71	0.18
Failed culverts					
Culvert ratio	0.02	0.82	0.38	0.34	0.22
Aquatic score	0.25	0.84	0.63	0.64	0.16

T-tests between failed and not-failed culverts showed a significant difference for the ratio of culvert width to bankfull width (t-test, t=2.61, DF = 42.56, p-value=0.013), and a significant difference at the 10% level for aquatic score (t-test, t=1.71, DF = 33.63, p-value=0.096) (Figure 12, Table 11).

Table 11. Statistical test results for comparing the distributions of failed culverts to those that did not fail. Distributions were tested using t-tests.

	Test statistic	DF	p-value
T-test: Ratio	2.61	42.56	0.013
T-test: Aquatic score	1.71	33.63	0.096

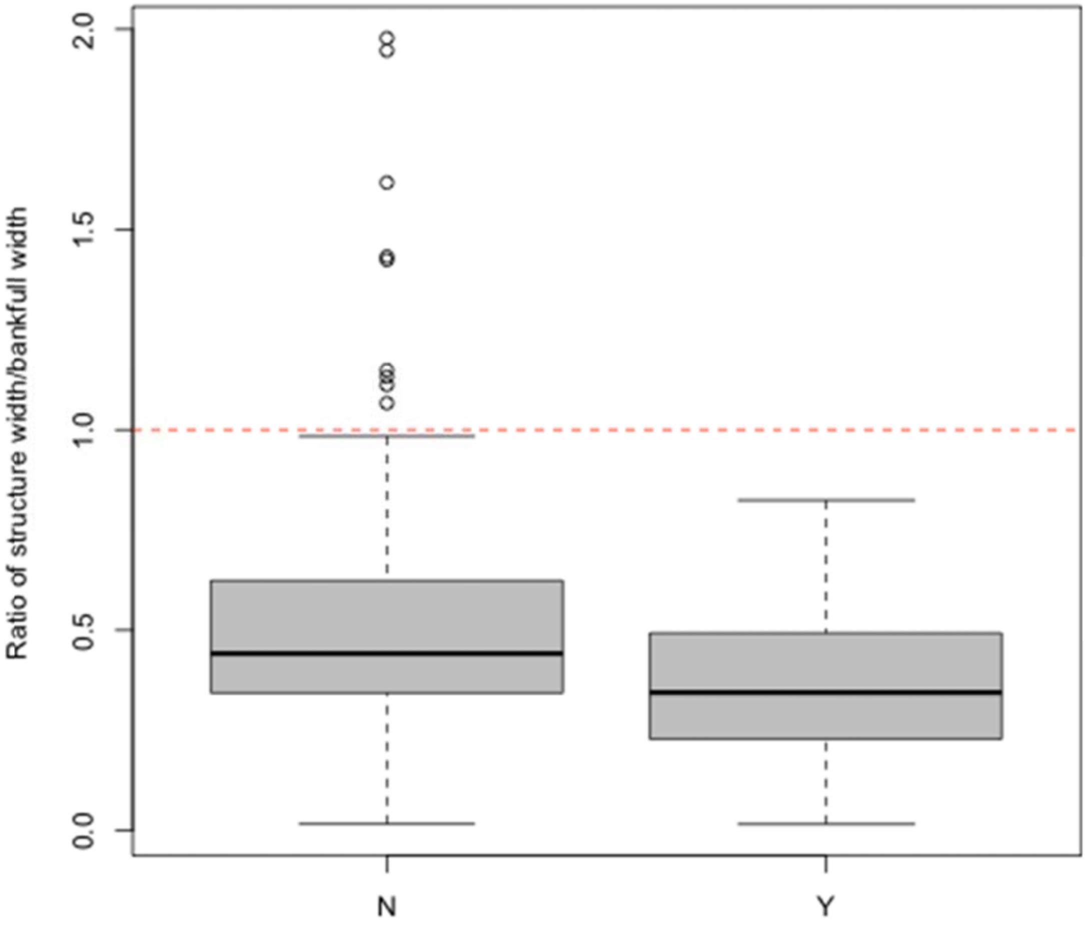


Figure 12. Boxplot distributions of culvert ratio. Note that none of the culverts that did fail had a ratio >100% of bankfull width.

A logistic regression using culvert ratio and aquatic score as predictor variables and culvert failure as a response predicted culvert failure based on data from both the Westfield River watershed and the town of Weston (Likelihood ratio test, X2=59.1, df=3, p-value=9.2e-13). The logistic regression using culvert ratio and aquatic score had an AIC of 136.51, while the regression using just culvert ratio had an AIC of 135.93 (Table 12). It is customary to use the model with the lowest AIC by two points, and the best two models only differed by 0.58 AIC.

The model using just culvert ratio performed best, but barely so. Table 13 shows the coefficient weights from the model including aquatic score and culvert ratio.

Table 12. Comparison of the delta AIC for each model tested in the logistic regression.

Degrees of freedom	**Delta AIC**	**Model**
2	0	Ratio
3	0.58	Ratio + aquatic score
3	1.85	Ratio + opening
2	2.47	Aquatic score
4	2.57	Aquatic score + ratio + opening
2	3.17	Opening
3	3.77	Aquatic score + opening

Table 13. Model coefficient weights for logistic regression that included aquatic score and culvert ratio.

	Estimate	Std. Error	z value	Pr (> |z|)
Intercept	0.08	0.93	0.09	0.93
Aquatic	-1.55	1.30	-1.19	0.23
Ratio	-1.93	1.06	-1.82	0.07

3.5 Discussion

The objective of this study was to test if culvert risk of failure could be predicted using previously-measured culvert characteristics, as part of a larger prioritization scheme that includes habitat quality, habitat quantity, aquatic organism passage, and infrastructure sustainability, in two HUC8 scale watersheds in New England. This study created a logistic regression that significantly predicted culvert risk of failure using the ratio of culvert width to bankfull width and aquatic score, which is a measure of aquatic predicted passage through a culvert defined by physical culvert characteristics. Hurricane Irene (August 2011) caused enough culverts to fail in the Westfield and West River watersheds to use failure due to that hurricane as a response variable.

The culverts that failed due to the extreme flows and associated debris buildup after Hurricane Irene were too small relative to their upstream basin sizes in the Westfield and West Rivers. None of the culverts that did fail were >100% of bankfull width, although there were instances of culverts that did not fail and were still <100% of bankfull width (Figure 12). Bankfull width stands in for bankfull discharge, which is the dominant channel forming flow, and thus affects stream-crossing structures. Cafferata et al. (2004) found that utilizing culverts that were as wide as bankfull width minimized culvert failures due to wood and sediment accumulation. Cafferata et al. (2004) also found that culverts at high risk from wood-related plugging had a culvert diameter divided by bankfull width (culvert opening ratio) less than 0.7, while in this study, the median ratio of culvert opening to bankfull width for failed culverts was 0.34. This difference in culvert ratio may be that to qualify as a failure in this study, a culvert would not only have to accumulate debris and sediment, but either overtop the road or have some road damage related to the plugged culvert. Although many states already have suggestions that culverts be built to 100% or greater of bankfull width, this study provides yet more justification for larger culverts.

Culverts with a higher aquatic score, which is a combination of physical characteristics related to aquatic organism passage, were less likely to fail than those with a lower aquatic score. The aquatic score of a culvert addresses the ability of that culvert to act similar to a natural streambed, and a culvert with properties of a natural streambed is more resilient to higher storm flows. Thus, culverts that were less of a barrier to aquatic organisms were also less likely to fail in extreme flow events. This convenient correlation serves the interests of both highway departments and conservation managers.

The logistic regression used to predict culvert failure when combining data from the Westfield River watershed and the town of Weston, VT can be used to predict culvert failure in extreme flow events. This could be a useful tool for managers in the face of climate change, allowing a crossing to be identified as high- or low-risk based on its structure characteristics relative to its upstream watershed size. The logistic regression used to predict culvert failure was significantly better at predicting failure than a null model. One consideration is that the ratio of culvert width to bankfull width is already taken into account in the aquatic score calculations, as constriction, though the constriction was a categorical variable in aquatic score, rather than continuous. Although the logistic regression using both aquatic score and culvert ratio was a better model than a model using only aquatic score, it is a simpler task to create a model using only aquatic score, which may appeal to time-stressed managers. Based on the failure model I developed in this study, existing methods of culvert assessment are adequate for predicting culvert failure in extreme flow events.

If this study were to be repeated in an un-surveyed watershed, the question arises as to whether both ratio and aquatic score are necessary to predict relative risk of failure. It would be considerably fewer man-hours to collect only one of these two parameters. Aquatic score requires less expertise, as unskilled data collectors can simply measure physical characteristics of the culvert. Culvert ratio requires a data collector to be able to ascertain bankfull width, and to properly measure it. However, the logistic regression using only ratio performed as well as the model using both ratio and aquatic score, whereas models with only aquatic score were not as well supported as models with only ratio, leading to the conclusion that one could survey culverts only for their constriction ratio, and come to the same results in terms of ranking culverts for removal or repair prioritization.

One limitation of using culvert ratio was that I only considered culvert dimensions in relation to the size of a given culvert’s upstream watershed, disregarding factors such as debris accumulation, slope of the culvert, average slope of upstream watershed, and angle of approach, that have all been shown to affect culvert failure (Furniss et al. 1998). Flood discharge alone is rarely the primary cause of crossing failures (Cafferata et al. 2004), but in this study I was interested in a coarse measure of culvert characteristics that could stand in for a more detailed approach to culvert failure, to provide a less cumbersome method of assessing relative risk of failure across large watersheds with many crossings.

Hurricane Irene was a 100-year magnitude flood, causing massive devastation in the Westfield and West River watersheds. The US Geological Survey reported record discharges for eight stream gauges in Vermont, including the Saxtons River (Rockingham), Little River (Waterbury), Ayers Brook (Randolph), Williams River (Rockingham), Walloomsac River (North Bennington), Otter Creek (Middlebury), Dog River (Berlin), and Mad River (Moretown) (VT FWS 2012). This culvert failure model successfully predicted culvert failure for flows of this magnitude, but does not necessarily hold true lesser or more severe floods. However, if one shifts perspective away from absolute risks and toward the relative risk, this model can be robust across flood magnitudes. The risk of failure relative to a crossing with different dimensions is less variable in a watershed.

It is important to be able to predict culvert failure for more than just infrastructure sustainability, but also for the long-term investment in stream stability and aquatic resources. Culvert passability is an important step in maintaining resilient populations, diverse communities, and productive ecosystems. As part of an overarching prioritization scheme that includes habitat quality, habitat quantity, aquatic passage, and infrastructure sustainability, it is important to be able to predict the risk of failure in culverts on headwater streams. This study provided a framework for doing just that, and should prove useful on its own as well as in the larger view of aquatic barrier prioritization.

4. BARRIER PRIORITIZATION IN NEW ENGLAND UNDER CLIMATE CHANGE SCENARIOS USING FISH HABITAT QUANTITY, THERMAL HABITAT QUALITY, AQUATIC ORGANISM PASSAGE, AND INFRASTRUCTURE SUSTAINABILITY

4.1 Introduction

Small-scale barriers, such as culverts at road-stream crossings, are one of the major threats to the ecological integrity of a watershed (Clarkin 2005, Pess et al. 1998, Beechie et al. 1994), and put both ecosystems and transportation at risk (Nislow 2009). Aquatic organisms need to move upstream and downstream through river systems for spawning, feeding, avoidance of unfavorable environmental conditions, and for population viability (Fausch et al. 2002, Rieman and Dunham 2000).

The very large number of road-stream crossings has emphasized the need to identify which of these are likely to be barriers (Jackson 2003, Jackson and Griffin 2000). Given limited time and resources, there is a strong interest in developing prioritization protocols to identify which removals and replacements will be effective in restoring habitat and stream connectivity to high-quality upstream habitats, thus allowing brook trout (*Salvelinus fontinalis*) and other coldwater fish an escape route from unfavorable environmental conditions (Xu et al. 2010, Petty et al. 2005). It has been shown that restoring connectivity is an effective way to maintain healthy fish populations and ecosystem processes (Kemp and O’Hanley 2010, Letcher et al. 2007, Roni et al. 2002). Climate change predictions of warmer summer temperatures and more variable extreme flows (Frumhoff et al. 2007, IPCC 2007, Moore et al. 1997) underscores the urgent need to restore connections to high-quality thermal habitat for brook trout and to update undersized infrastructure.

When prioritizing aquatic barriers for removal, a multiple criteria approach results in a broader, more adaptable, and more practical application of barrier prioritization schemes. Many prioritization approaches use a habitat-gained approach (Kemp and O'Hanley 2010), but this approach may miss the larger picture of ecosystem health and road infrastructure sustainability, because not all road-stream crossings are created equally with regards to the passability of the barrier, the amount of habitat on the other side of the barrier, the quality of the habitat on the other side of the barrier, and the ability of the crossing to withstand extreme flow events.

In this prioritization scheme, habitat quality refers to the thermal regime of a stream, measured by sensitivity and exposure and discussed in Chapter 2. Sensitivity is the response of stream temperature to a change in air temperature, and exposure is a standardized metric of the frequency, duration, and magnitude of temperatures above a predetermined water temperature threshold. Summer stream temperatures directly affect brook trout distribution and abundance, thus the thermal regime of a river is a good measure of habitat quality for brook trout. Chapter 2 follows a thermal habitat quality classification scheme for brook trout habitat, combining stream sensitivity and exposure to develop a thermal resilience value, for use in the overarching prioritization scheme. Although it would be convenient to be able to predict a stream's sensitivity and exposure using existing GIS landscape variables, the predictive model I created was too specific to its given watershed, thus was not applicable to other regions. This is likely due to the absence of appropriately-scaled groundwater input data in New England for headwater streams. Without a predictive model, it is necessary to directly measure paired stream and air temperatures in the streams of interest.

One of the important questions when assessing a culvert is how much of a barrier that culvert actually is to aquatic organism movement. Often road-stream crossings are considered full barriers, when in reality they vary greatly in their passability to fish and other aquatic organisms depending on time of year, type of species and life stage of the individual attempting to cross, discharge, temperature, and existence of predators (Northcote 1998, Kemp and O'Hanley 2010).

The River and Stream Continuity Project surveyed culverts in the two HUC8 watersheds that I used in my prioritization scheme and measured a series of physical characteristics of each culvert to calculate an aquatic score, which is a measure from 0-1 of how passable that culvert is to all aquatic organisms (River and Stream Continuity Project 2009, Appendix A). A score of 1 indicates full continuity, while a score of 0 represents a complete barrier to passage. Aquatic score is a weighted combination of outlet drop, physical barriers, water velocity, water depth, inlet drop, crossing span, crossing substrate, crossing embedment, openness, scour pool, tailwater armoring, and height (Figure 9, www.streamcontinuity.org 2009).

It has been suggested that undersized culverts, relative to their upstream watersheds, are more likely to fail in extreme flow events (Nislow 2009). Culverts usually fail because of debris and sediment accumulation rather than flow volume alone (Cafferata et al. 2004), but debris accumulation is often associated with high flows, which is a justification for using a coarse measure such as the ratio of culvert opening to upstream watershed size to predict culvert failure. In August 2011, Hurricane Irene caused 3-7” of rain to fall in Massachusetts and Vermont, resulting in multiple culvert failures (Pealer 2012). These culvert failures provided the opportunity to test the relationship between culvert failure and the physical measurements of a culvert that comprise the aquatic score, that I surmised were likely to influence the probability of failure. Chapter 3 developed a risk of failure model for culverts, using culverts that had failed during Hurricane Irene as a response variable, and aquatic score and ratio of culvert opening to bankfull width as predictor variables.

Climate change predictions lend even more urgency to the task of updating road-stream crossings, from both an ecosystem processes and an infrastructure sustainability viewpoint. The ability of aquatic organisms to disperse in search of thermal refugia will be critical to their persistence, and interconnected habitats are crucial to metapopulation persistence in the highly fragmented aquatic systems such as the Connecticut River watershed and much of lower New England. Extreme flows will become more variable and more frequent (Moore et al. 1997), threatening our infrastructure, and summer temperatures are rising (IPCC 2007), threatening brook trout populations that inhabit an already highly fragmented network of streams. Increasing connectivity by removing barriers is one of the most effective ways to mitigate the effects of climate change (Nislow 2009), and improving road crossings would offer immediate and future ecological and infrastructure benefits.

4.2 Study objectives

On a regional level, conservation managers are looking to have resilient populations, diverse communities, and productive ecosystems, as well as safe, reliable, cost-effective infrastructure due to improved or replaced culverts. In this study I developed a prioritization scheme for the removal of aquatic barriers that considers fish habitat quantity, thermal habitat quality, aquatic organism passage, and infrastructure sustainability, that can contribute to the larger regional goal of conservation managers (Figure 1 in Chapter 1). Using brook trout as an indicator species because of their thermally dependent existence in highly fragmented habitats, I studied four HUC8-size watersheds in New England to examine these ideas in greater depth, and implemented this barrier prioritization scheme in one HUC8-scale watershed: the Westfield River watershed, in the Connecticut River drainage.

Chapter 2 addressed fish thermal habitat quality in depth, assigning a thermal resilience value to sample streams. Chapter 3 addressed infrastructure sustainability, and developed a culvert risk of failure model using the ratio of culvert opening to bankfull width, and aquatic score. I compared the prioritization ranking of road-stream crossings using the results from the thermal resilience study and the risk of failure model, and included potential habitat gained by removal of a barrier and aquatic passage at that crossing, as part of the overarching prioritization scheme.

4.3 Methods

4.3.1 Study area

This barrier prioritization scheme was implemented the Westfield River watershed, MA, a Hydrologic Unit Code (HUC) 8 scale watershed that drains to the Connecticut River, one of the largest rivers in New England. To assign a thermal habitat quality value, I directly measured paired air and water temperature in 12 streams. Culvert failure data was available for the entire Westfield River watershed, and for the town of Weston, VT, in the West River watershed, so the risk of failure model was developed using those two areas (Figure 13). Because the town of Weston only included two study sites where I measured paired temperatures, for this prioritization scheme I only prioritized culverts in the Westfield River watershed.

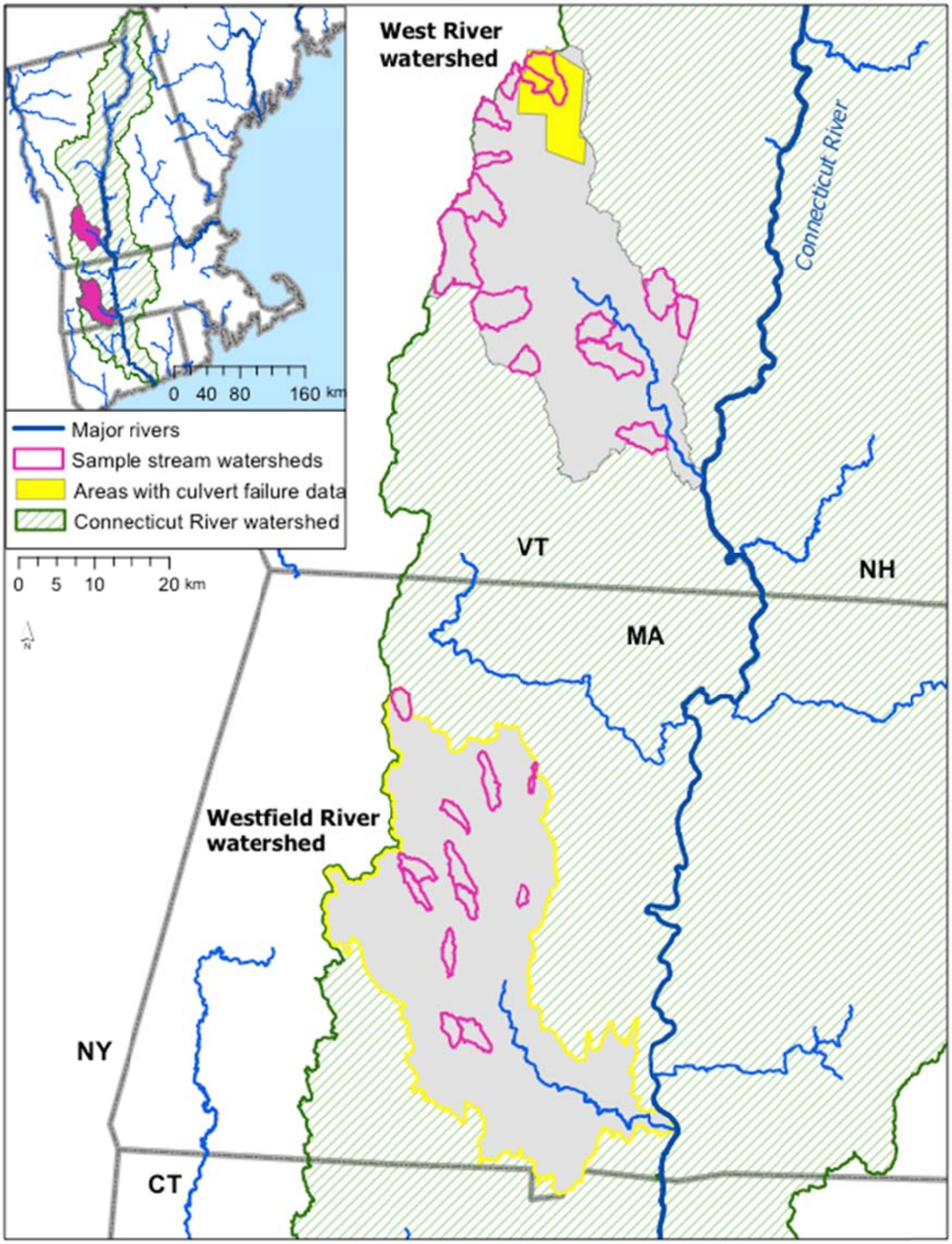


Figure 13: The model to predict risk of failure was based on culverts from the Westfield River watershed, MA, and from the town of Weston, VT, that had failed during Hurricane Irene (outlined in yellow). These watersheds are major drainages in the Connecticut River watershed, which drains most of New England, represented by green hatching in the map above. Pink outlines represent the sample streams where I measured thermal resilience, and limited the culvert failure model to those subwatersheds.

4.3.2 Stream habitat quantity

Habitat quantity is a GIS measure of the amount of stream habitat gained by the removal of a barrier. I used ArcGIS 10 to calculate the distance of all stream reaches between barriers, using the 1:100k NHD+ stream network (USGS). Although the 1:24k scale streams would make more biological sense, the lack of centerlines through water bodies at the 1:24k scale prevented a clean river kilometers measurement. Habitat quantity can be calculated in two dimensions: absolute gain and relative gain. Absolute gain is the shorter of either the upstream or downstream distance from a given barrier to the next barrier in all branches of the network, and helps to assign the relative importance of that barrier at the watershed scale. Relative gain is the absolute gain divided by the total upstream and downstream distances to the next barrier (Figure 14), and assigns the relative importance of that barrier at the reach scale. Absolute and relative gain were used in a stream connectivity analysis by The Nature Conservancy in 2008. To simplify the prioritization model inputs, I used absolute gain, standardized from 0-1, where 1 represents the longest stream network in the watershed, and 0 is the shortest network.

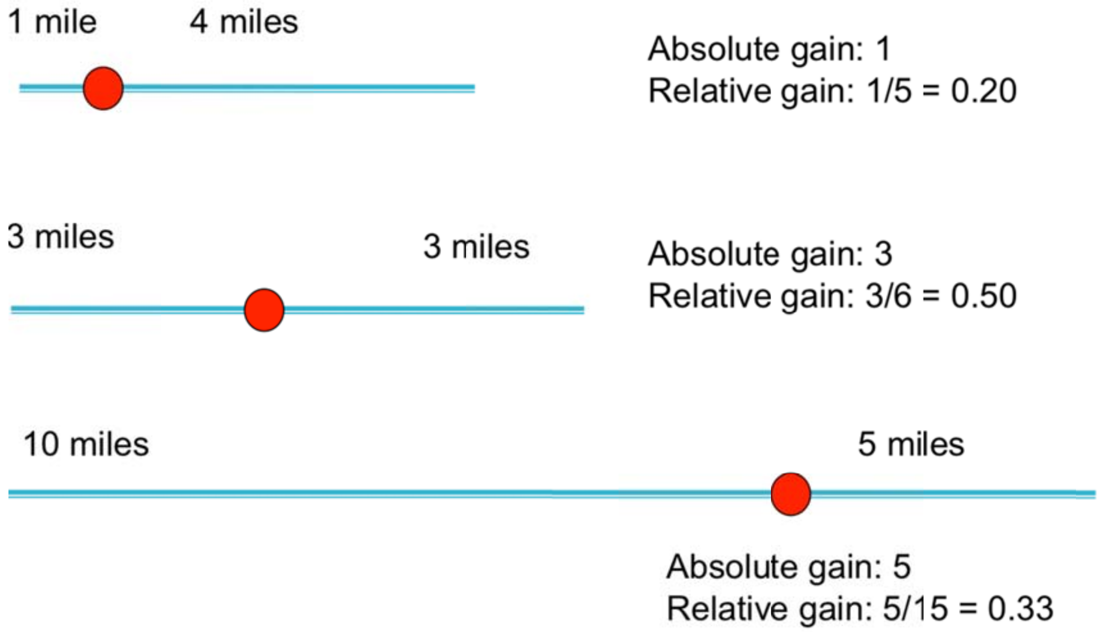


Figure 14. Relative vs. absolute gain in a river network.

4.3.3 Thermal habitat quality

I directly measured paired air and water temperature in sample streams, and calculated the sensitivity (stream thermal response) and exposure (stream temperature beyond a given threshold) for each sample stream as a measure of thermal resilience using daily maximum temperatures for those days that fell in the range from 21-30˚C. Full details of the sensitivity and exposure calculations can be found in Chapter 2. Sensitivity is the response of water temperature to a change in air temperature, and exposure is a combined measure of the frequency, duration, and magnitude of days where temperature exceeded a given threshold. Exposure was calculated for both 21˚C, considered to be the distributional limit for brook trout, and at 17˚C, the point where brook trout growth rates begin to be affected (Xu et al. 2010, Lund et al. 2002). In the ultimate prioritization, I used the data at 17˚C, giving me a larger sample size, because exposure at 21˚C and exposure at 17˚C were highly correlated (0.80) (see Chapter 2).

I used sensitivity and exposure to classify streams for prioritization, resulting in a thermal resilience value for each stream. I codified the classification process by assigning each stream a value that corresponded with the distance of that stream's sensitivity and exposure from the median sensitivity and exposure for each HUC8 watershed. Median sensitivity and exposure were represented by the line where sensitivity and exposure are at a balance, on a plot scattering exposure against sensitivity ($y = -1*x + 0.5$). Both exposure and sensitivity were standardized to range from 0-1.

Stream thermal habitat quality and habitat quantity can be combined for the sake of prioritization into a single habitat quality metric. It does not make sense to remove a culvert that is on a thermally resilient stream, only to gain a small amount of habitat, just as it is not logical to remove a culvert that opens a large amount of poor thermal quality habitat. Thus, habitat quantity and thermal habitat quality must be considered collectively.

4.3.4 Infrastructure sustainability

I developed a culvert risk of failure model using the ratio of culvert width to bankfull width, and aquatic score. Surveys about basic physical characteristics of each culvert were carried out by the River and Stream Continuity Project (2009), and those physical characteristics were used to calculate the aquatic score for each crossing (Appendix A, Figure 9). After Hurricane Irene (August 2011), culvert failure data were collected by Carrie Banks of Massachusetts Riverways in the Westfield River watershed, and by the Town of Weston, VT. I developed a logistic regression with culvert failure due to Hurricane Irene as a response variable, that significantly predicted culvert failure, using the Westfield and Weston data with state as a factor. I applied this logistic regression to each culvert in the watersheds of the sample streams to get a risk of failure value for use in the overarching prioritization scheme.

4.3.5 Prioritization ranking

I combined the four different variables to prioritize crossings in the HUC8 watersheds, and also a two-variable prioritization that considers habitat quantity and thermal habitat quality collectively, and aquatic score and risk of failure together. All variables in the prioritization scheme had been standardized to have a range from 0-1, where 0 is the lowest priority and 1 is the highest priority. In this study, I started by weighting all variables at 1, then added them together to get a prioritization score. I compared the ranks of crossings that had been prioritized with 1, 2, 3, or 4 variables (Table 14).

Table 14. All combinations of all variables used in a variety of different prioritization schemes in the Westfield River watershed.

# Variables	Combinations
1	Habitat quantity (gain)
1	Thermal resilience (quality)
1	Aquatic organism passage (passage)
1	Risk of failure (risk)
2	Gain + quality
2	Gain + passage
2	Gain + risk
2	Quality + passage
2	Quality + risk
2	Passage + risk
3	Gain + quality + passage
3	Gain + quality + risk
3	Gain + passage + risk
3	Quality + passage + risk
4	Gain + quality + passage + risk

The second type of prioritization ranking tested was a piecewise approach, where I first excluded culverts that were in the best two quarter percentiles of aquatic score by assigning a coefficient of zero, indicating that they are not significant barriers to fish passage, and then excluded all culverts in the worst two quarter percentiles of habitat gain by assigning a coefficient of zero, in an attempt to only prioritize culverts that open a decent amount of habitat. At that point I weighted all remaining culverts evenly, and added all prioritization values together.

In an effort to simplify and increase the practicality of the prioritization scheme, I also ran a piecewise approach that used only culverts in the best 75% of overall habitat quality (habitat quantity + thermal habitat quality) and culverts in the worst 75% of infrastructure risk (aquatic score + risk of failure), such that the only culverts being prioritized are those that open high quality habitat, are likely to fail, and do not pass fish. I then simplified the prioritization scheme even further, and extracted culverts that fit the 75% of best overall habitat criteria, and ranked those by infrastructure risk and aquatic score.

4.4 Results

The Westfield River watershed had 66 culverts that had been surveyed for aquatic score and were within a watershed where I had measured stream thermal vulnerability. Of these culverts, 37 fell into the top 75% of overall habitat quality and the top 75% of infrastructure replacement need. Habitat gain if a culvert were removed ranged from 0 to 3.23km (0.43 ± 0.071SE) of streams (Figure 15).

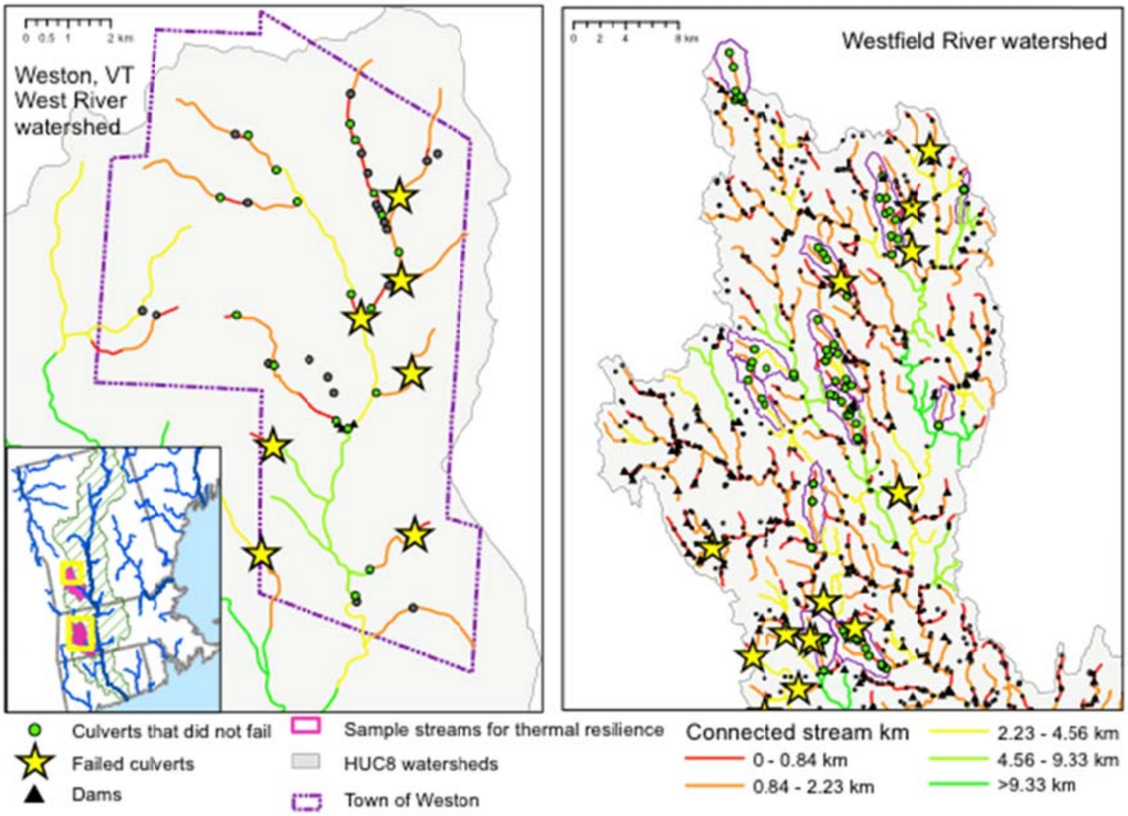


Figure 15. Maps showing distribution of the longest networks in the Westfield River watershed and the town of Weston VT. Although I did not prioritize the Weston crossings, failure data from those crossings were used as inputs in the risk of failure model (See Chapter 3 for details). River lengths range from red to green, with green stream reaches representing the longest stretches of connected habitat. Also shown are dams and culverts, with yellow stars marking the location of culverts that failed during Hurricane Irene.

4.4.1 Thermal Habitat Quality

Because exposure (stream temperature beyond a given temperature threshold) at 21˚C and at 17˚C were correlated (0.80), I chose to use exposure at 17˚C for prioritization, because of the larger sample size available. Median sensitivity (stream temperature response to air temperature) in the Westfield River watershed was 0.44, ranging from 0.12 to 1.09. When sample streams were plotted in a standardized sensitivity-exposure space, and the distance from median sensitivity and exposure were graphed, the stream residuals ranged from 0.06 to 1.00 (Figure 16). For use in the ultimate prioritization scheme, I flipped the values (1 – distance from the line) such that a higher number now represented higher quality thermal habitat, and a low number represented poor thermal habitat.

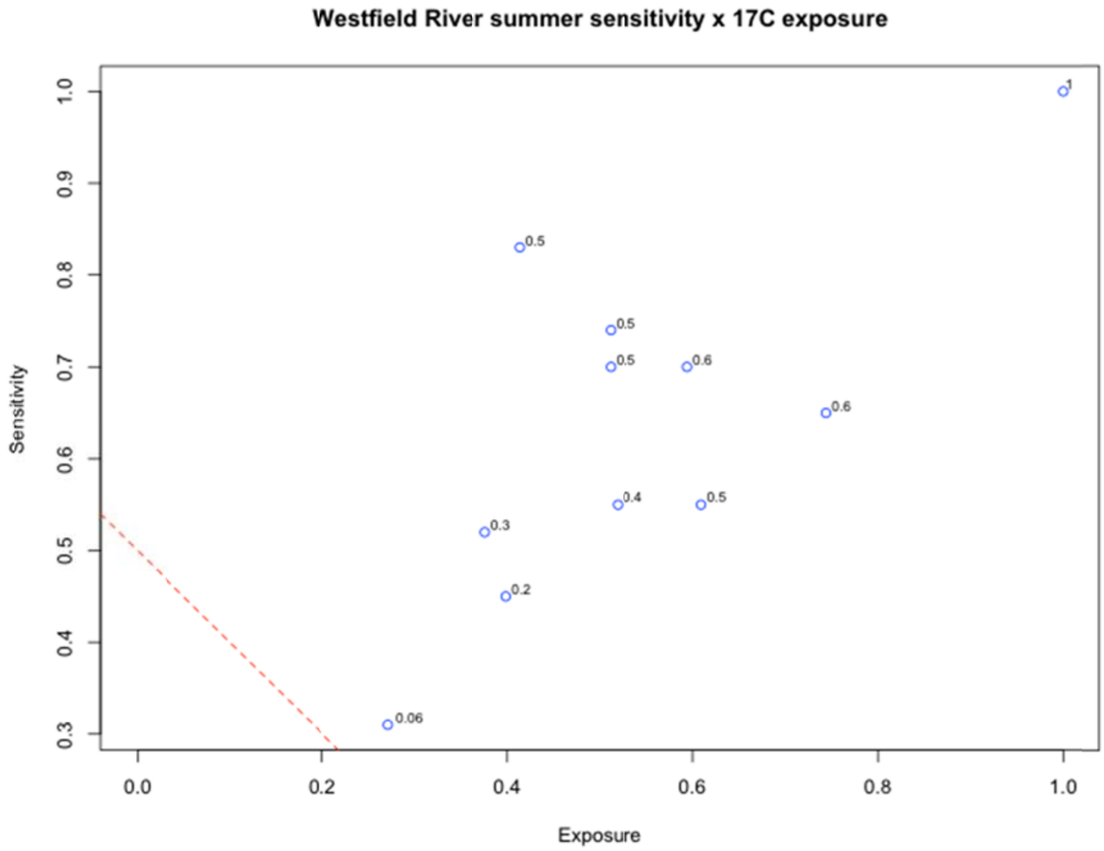


Figure 16. Sample streams for prioritization in the Westfield River watershed, classified at a 17˚C exposure threshold. The dotted line represents the median sensitivity and exposure for that HUC8 watershed. The number next to each sample stream's point represents the distance of that point from the line y=(-1)*x+0.5.

After calculating 25th percentiles for the stream classification results and the potential stream habitat gain, and selecting only those streams in the best 50% of thermal habitat and longest 50% of potential added miles, I was left with 66 streams to use in the prioritization. This combination of habitat quantity and thermal habitat quantity is being referred to as overall habitat quality (Table 15). Figure 17 shows the spatial distribution of stream crossings and their relative habitat quantity and thermal habitat quality ranking.

Table 15. Overall habitat quality, shown as the average of all sites in a HUC14 watershed for simplicity. Also shown are the overall habitat quality when you weight habitat gain more heavily than thermal resilience, because of the lower uncertainty associated with habitat gain. The final column is overall infrastructure replacement need, which is a combination of failure risk and aquatic score.

Watershed	Overall habitat quality (gain + temp)	Overall habitat quality weighting gain x 2	Overall infrastructure replacement need (Fail + aquatic)
Abbott	0.78	0.53	0.77
Bedlam	0.99	0.59	0.04
Chauncy	1.29	0.89	0.02
Gibbs	0.58	0.33	0.46
Glendale	0.60	0.35	0.53
Kinne	1.10	0.62	0.35
Powell	0.91	0.61	0.47
Taylor	0.57	0.32	0.49
Tuttle	1.13	0.83	0.43
Watts	0.96	0.49	0.45

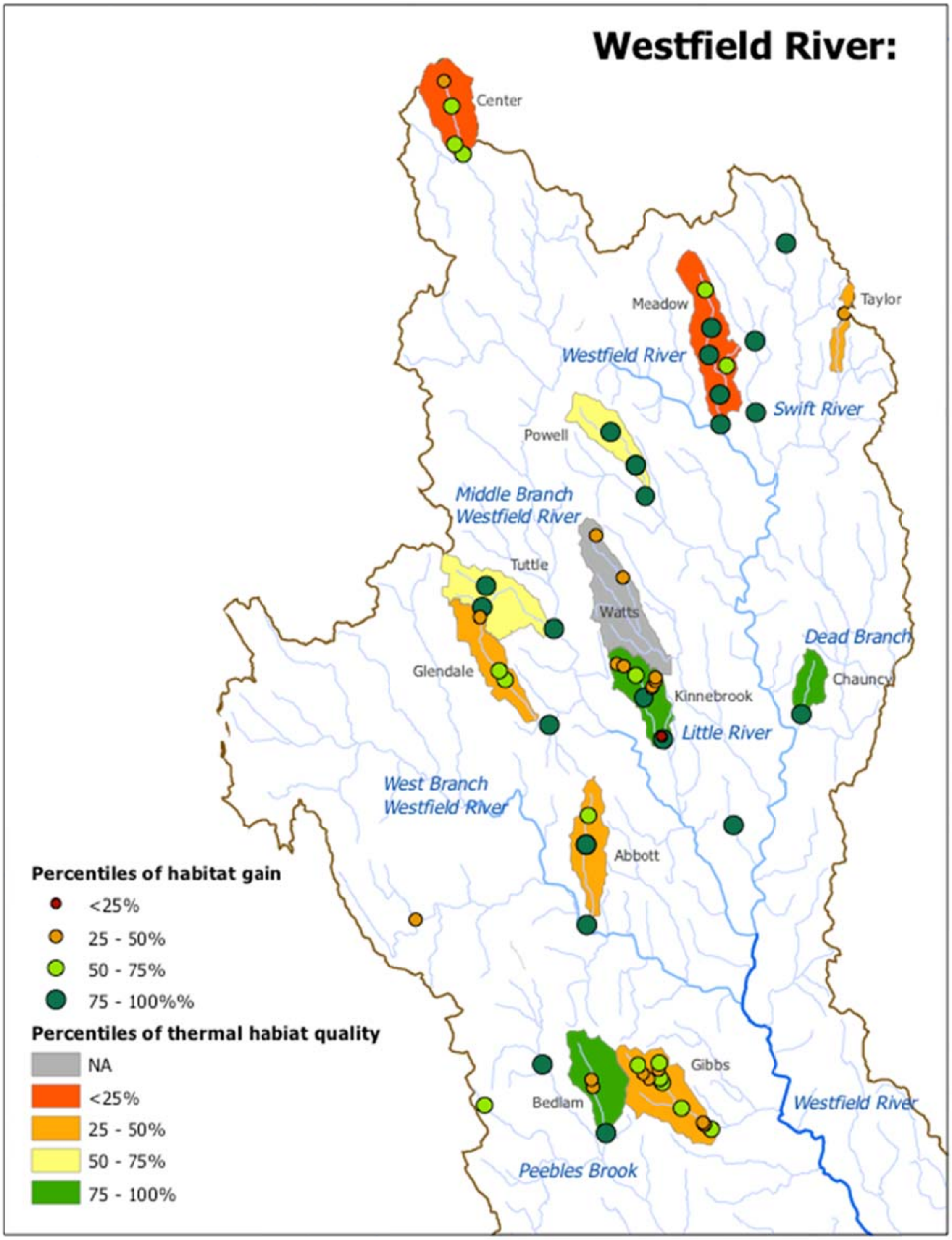


Figure 17. Overall habitat quality consisted of a combination of habitat quantity and thermal habitat quality, represented by the size and color of points on the map. 25th percentiles of each variable are shown, where green represents the highest quality.

4.4.2 Infrastructure sustainability

I developed a risk of failure model using 145 culverts in the Westfield River watershed and 20 culverts in the town of Weston, using failure as the response variable and aquatic score and the ratio of culvert width to bankfull width as predictor variables in a logistic regression (Likelihood ratio test, X2=59.1, df=3, p-value=9.2e-13). The risk of failure model addressed a culvert's risk of failure in an extreme flow event, but the raw aquatic score addressed the degree to which that culvert was actually a barrier to fish passage, and so these two factors taken together comprise the infrastructure overall ranking (Table 15).

4.4.3 Prioritization ranking

The prioritization ranks of various culverts differed depending on the number, type, and combination of rankings. Using all four variables to prioritize crossings in the Westfield River watershed resulted in a more stable ranking system than using fewer variables, where an outlier could pull a crossing up or down in the rankings (Table 16).

Table 16. Prioritization ranking using 2, 3, or 4 variables for the Westfield River watershed. The first number shown is the raw data of the combined variables, and the number shown in parentheses is the rank of that watershed given that variable. Lower ranks mean higher priority for restoration.

Watershed	Gain + Fail + Temp + Aquatic	Gain + Fail + Temp	Gain + Temp + Aquatic	Fail + Temp + Aquatic	Gain + Fail + Aquatic	Gain + Temp	Fail + Temp	Gain + Fail	Gain + Aquatic	Fail + Aquatic
Abbott	1.54 (1)	0.99 (5)	1.32 (2)	1.27 (3)	1.04 (1)	0.77 (6)	0.72 (8)	0.49 (2)	0.82 (1)	0.77 (1)
Bedlam	1.18 (7)	0.93 (6)	1.10 (7)	1.12 (4)	0.38 (12)	0.85 (5)	0.88 (3)	0.13 (11)	0.30 (12)	0.32 (11)
center	1.03 (11)	0.67 (10)	0.86 (10)	0.92 (10)	0.63 (5)	0.50 (11)	0.57 (11)	0.27 (7)	0.46 (6)	0.52 (3)
Chauncy	1.30 (5)	1.29 (1)	1.30 (3)	0.81 (11)	0.50 (9)	1.29 (1)	0.80 (5)	0.49 (3)	0.50 (4)	0.01 (12)
Gibbs	1.04 (10)	0.75 (9)	0.85 (11)	0.97 (9)	0.54 (8)	0.56 (10)	0.68 (9)	0.25 (9)	0.35 (10)	0.47 (7)
Glendale	1.13 (8)	0.80 (8)	0.89 (9)	1.07 (7)	0.63 (4)	0.56 (9)	0.73 (7)	0.30 (5)	0.39 (8)	0.57 (2)
Kinne	1.45 (3)	1.22 (2)	1.29 (4)	1.33 (2)	0.50 (10)	1.06 (2)	1.10 (1)	0.27 (8)	0.34 (11)	0.38 (10)
Meadow	0.61 (12)	0.28 (12)	0.46 (12)	0.46 (12)	0.61 (6)	0.14 (12)	0.14 (12)	0.28 (6)	0.46 (5)	0.46 (8)
Powell	1.29 (6)	0.93 (7)	1.13 (6)	1.11 (5)	0.69 (3)	0.77 (7)	0.75 (6)	0.33 (4)	0.53 (3)	0.51 (4)
Taylor	1.05 (9)	0.66 (11)	0.95 (8)	0.98 (8)	0.55 (7)	0.56 (8)	0.59 (10)	0.16 (10)	0.45 (7)	0.48 (6)

Figure 18 shows a graphical comparison of 1, 2, 3, or 4 variables for stream rankings. For display purposes, all crossings within the same HUC-14 scale watershed were averaged, as thermal habitat quality was measured at the HUC-14 scale. The variability of each watershed's line can be compared to other lines, to determine the best watershed for restoration work given different variables. Table 17 shows the correlation coefficients between the ranks using different numbers of variables.

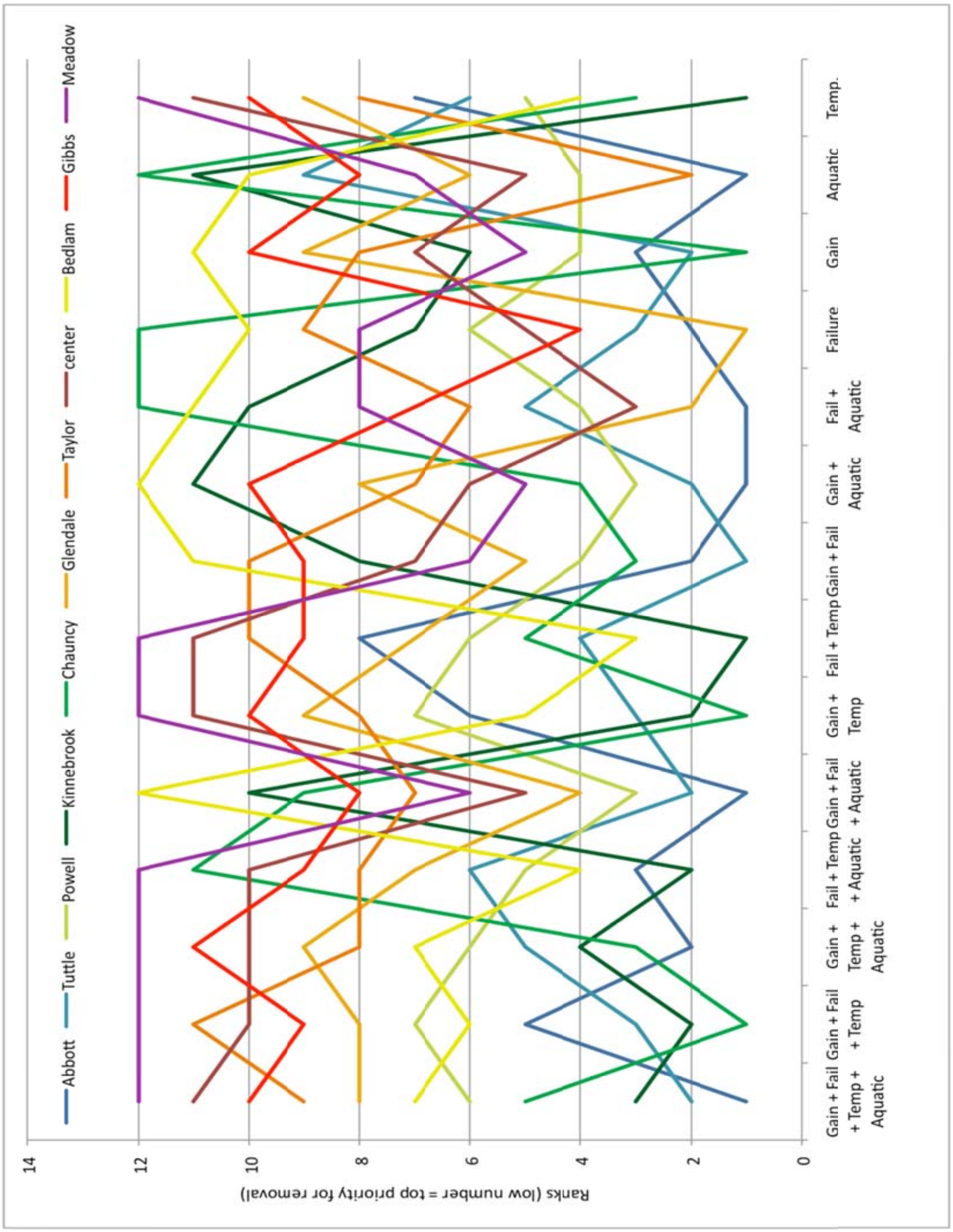


Figure 18. Ranking comparisons of the HUC14 watersheds in the Westfield River, where a low number indicates a top ranking for restoration. This figure shows all data for combinations of 1, 2, 3, and 4 variables in the prioritization scheme, and it is clear where one variable has a disproportionate effect on the other combinations of rankings.

Table 17. Correlation coefficients between the different combinations of variables, calculated for a piecewise hierarchical prioritization scheme. Coefficients greater than 0.80 are in bold.

	Gain + Fail + Temp	Gain + Temp + Aquatic	Fail + Temp + Aquatic	Gain + Fail + Aquatic	Gain + Temp	Fail + Temp	Gain + Fail	Gain + Aquatic	Fail + Aquatic	Fail	Gain	Temp
Gain + Fail + Temp	1.00											
Gain + Temp + Aquatic	0.90	1.00										
Fail + Temp + Aquatic	0.82	0.85	1.00									
Gain + Fail + Aquatic	0.56	0.75	0.59	1.00								
Gain + Temp	0.96	0.89	0.73	0.43	1.00							
Fail + Temp	0.79	0.56	0.78	0.06	0.74	1.00						
Gain + Fail	0.68	0.72	0.50	0.92	0.55	0.15	1.00					
Gain + Aquatic	0.55	0.80	0.54	0.97	0.49	0.00	0.87	1.00				
Fail + Aquatic	0.31	0.53	0.61	0.88	0.12	0.04	0.67	0.78	1.00			
Fail	0.24	0.11	0.40	0.48	-0.05	0.23	0.50	0.25	0.67	1.00		
Gain	0.67	0.77	0.38	0.83	0.65	0.07	0.91	0.89	0.46	0.11	1.00	
Temp	0.71	0.53	0.64	-0.13	0.77	0.93	-0.04	-0.10	-0.22	-0.16	0.02	1.00
Aquatic	0.27	0.61	0.57	0.87	0.18	-0.07	0.59	0.86	0.93	0.33	0.53	-0.20

Using a hierarchical piecewise approach to barrier prioritization not only makes more biological sense, it produces more consistent ranking scores. A hierarchical approach also increases confidence in the ultimate prioritization, as it applies a layer of common sense to an otherwise purely mathematical prioritization, by prioritizing only crossings that are actually barriers and that are actually opening up high quality habitat. Figure 19 shows the differences in ranking scores when using a hierarchical piecewise approach to ranking.

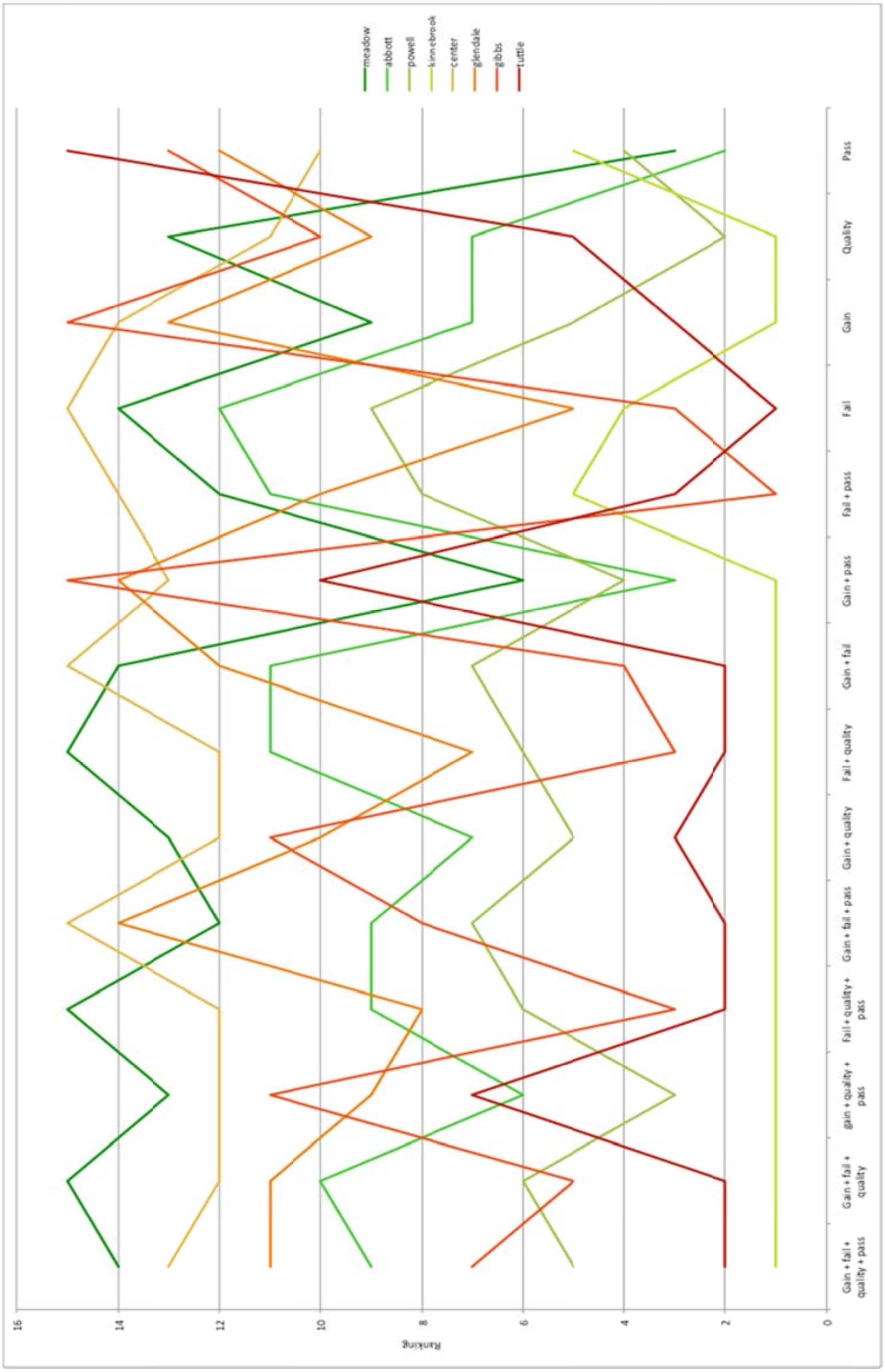


Figure 19. Hierarchical piecewise ranking scores in the Westfield River. The ranking scores are more consistent when using a piecewise approach than in a non-piecewise prioritization scheme, but individual variables can still pull the rankings dramatically in a direction. For example, Tuttle watershed (dark red) and Gibbs watershed (bright red) both have relatively high ranks when considered with all four variables, but it is clear from the single variable ranks that they already have good fish passage, and that they don't open up a lot of habitat.

To simplify the piecewise approach to ranking, one could consider that there are actually only two parameters: habitat quality (best 75% of crossings relative to their habitat gain and thermal habitat quality) and infrastructure replacement need (top 75% of crossings relative to their risk of failure and aquatic score). It does not accomplish much on the ground if a crossing is replaced and only opens up a tiny amount of habitat, or opens up poor quality habitat, thus the habitat variables ought to be considered collectively. The ranking scores look relatively similar for this two-criteria approach as they do with the four-criteria approach, as seen in Figure 20.

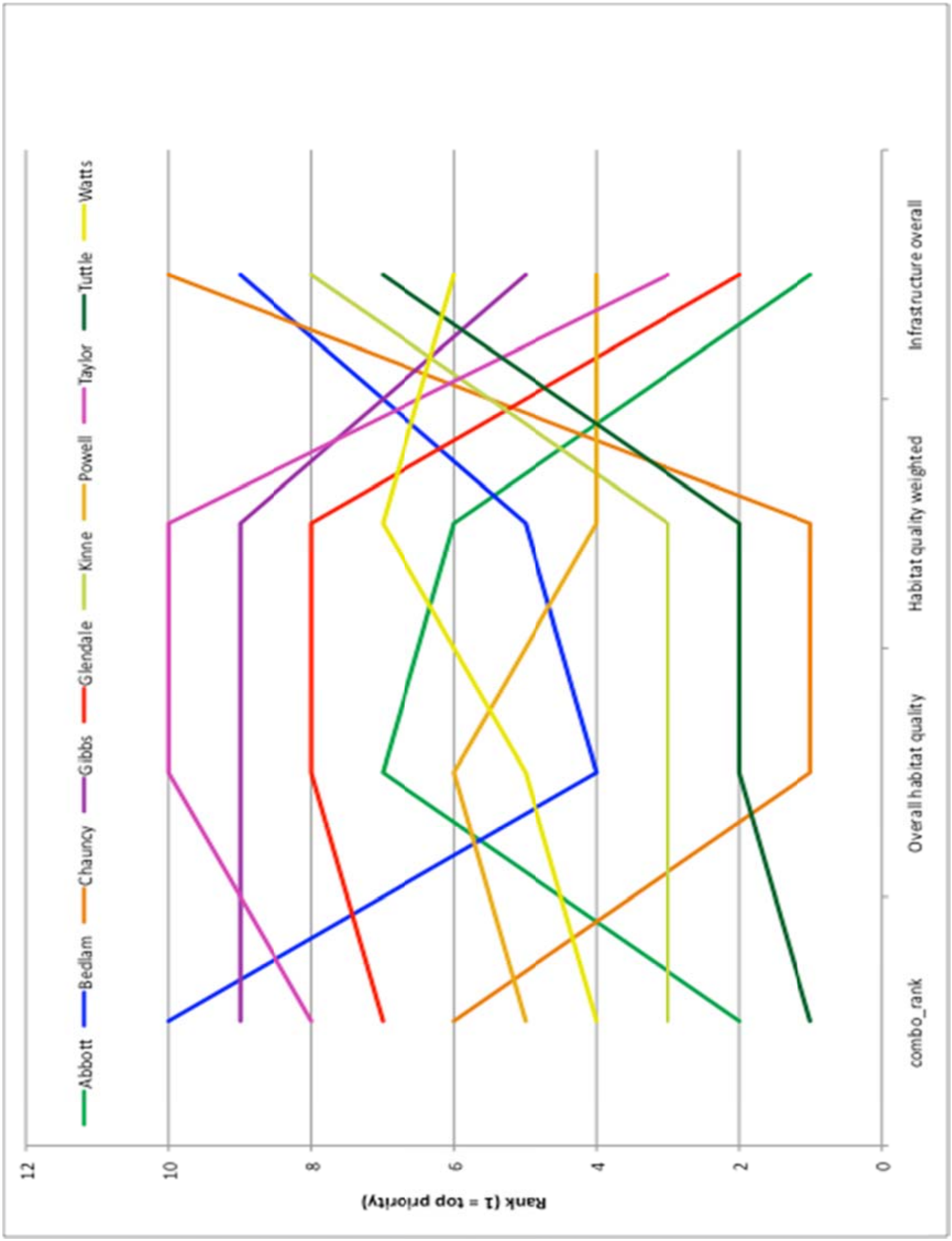


Figure 20. Comparison of watershed ranks when considering overall habitat quality as a single variable, including habitat quantity and thermal habitat quality. The overall habitat quality rank is not much different from the ranks when habitat quantity is weighted twice that of thermal habitat quality, due to the greater uncertainty associated with thermal habitat quality. The overall infrastructure replacement need clearly changes the ranks when included in the prioritization scheme, and can be a useful decider to an overall prioritization scheme.

If one simply uses overall habitat quality to select out crossings for ranking, orders the watersheds by aquatic score or risk of failure (Table 18), it becomes clear that the HUC-14 of Abbott stream would yield the most bang for your ecological buck, followed by Glendale stream and then Taylor stream. However, if aquatic score is taken out of the overall infrastructure replacement rankings, such that one is only ordering the streams using risk of failure, the prioritization of streams changes slightly, with Abbott still top priority followed by Glendale, but then Tuttle stream takes the next spot.

Table 18. Crossing rankings when considering a two-criteria piecewise approach and a simple ordering based on infrastructure replacement need after extracting only those crossings that open overall high quality habitat. The first number in each field is the raw variable, and the number in parentheses is the original ranking when only using that variable.

Watershed	Habitat quality	Ordered by infrastructure replacement need	Ordered by risk of failure
Abbott	0.77 (7)	1	1
Glendale	0.59 (8)	2	2
Tuttle	1.12 (2)	7	3
Gibbs	0.57 (9)	5	4
Kinne	1.09 (3)	8	5
Powell	0.91 (6)	4	6
Taylor	0.56 (10)	3	7
Watts	0.96 (5)	6	8
Bedlam	0.98 (4)	9	9
Chauncy	1.29 (1)	10	10

4.5 Discussion

The goal of this study was to develop and implement a prioritization scheme for aquatic barriers that includes habitat quantity, habitat quality, aquatic organism passage, and infrastructure sustainability in the Connecticut River watershed. A prioritization scheme using these criteria is simple to understand and easy to implement, making it ideal for managers seeking to maximize their conservation impact.

In the HUC14-scale watersheds that I used as my unit of analysis in the Westfield River watershed, the habitat gain was relatively low for all crossings, primarily because I ran the habitat gain analysis on the 1:100k scale NHD streams, rather than the 1:24k streams. The 1:24k streams would have been more applicable to brook trout conservation, as these streams show the headwater streams brook trout use as habitat, but the 1:24k stream dataset had problems revolving around the lack of a single center line through larger waterbodies, and the habitat gain calculations require a single centerline for streams.

Using multiple criteria in a barrier prioritization scheme changed the order of road-stream crossing prioritization ranks, sometimes drastically. How one combines and weights the different variables will affect the outcome, and even a prioritization based on one set of criteria can be informed by other criteria. Using equally weighted variables, there were very few crossings that had consistent ranks across all the combinations of prioritization variables, as there was often one variable skewing the ranking in some direction.

Although this study is nominally a four-way prioritization scheme, it is possible to combine the variables into a two-way prioritization scheme, looking at the larger picture of overall habitat quality, and overall infrastructure replacement need. In terms of habitat, a crossing ought to be considered only if it opens an acceptable amount of stream habitat, that is thermally acceptable to the species of interest. Thus, there is little point to considering either habitat gain or thermal habitat quality on its own. For infrastructure replacement need, the logistic regression that predicted culvert risk of failure incorporated both culvert ratio and aquatic score, which already has a constriction component to its dimensions. Aquatic score directly measures whether or not a road-stream crossing is passable by various aquatic animals, but it also contains information about culvert dimensions that affect a culvert’s risk of failure in extreme flow events. Thus, aquatic score actually addresses both culvert risk of failure and culvert passability.

Using a piecewise approach to prioritizing barriers for restoration or removal, where habitat quality and infrastructure replacement need define the ranges of the pieces, is a logical way to make sense of the ubiquitous road-stream crossings in both the Westfield River watershed and in the larger northeastern United States. When considering a host of culverts to prioritize for repair or removal, it makes sense to apply a habitat threshold, so that culverts that are important to fish populations are considered first. If one resolves the habitat issues first, the culverts can then be ranked using infrastructure replacement need, or aquatic score. Because the culvert rankings when using overall infrastructure replacement need and aquatic score were not terribly different, and risk of failure and aquatic score were correlated, one could surmise that aquatic score will provide an adequate justification for culvert prioritization, if there is not time to run a full risk of failure model. The piecewise approach allows managers to set some base criteria before comparing site ranks, eliminating the least desirable sites first. The high correlation between culvert risk of failure and aquatic score is another justification for limiting efforts to simply calculating the aquatic score, indicating that culverts that are likely to fail in extreme flow events are also barriers to fish passage. When using aquatic score in a prioritization scheme, the culverts that get prioritized are not only opening up habitat for fish, but likely have corollary benefits for infrastructure sustainability.

Even further justification for the use of aquatic score lies in the uncertainty associated with each variable. Thermal habitat quality has some uncertainty associated with it because there are other factors than thermal regime that affect stream quality that were not being measured in this study. The culvert risk of failure model has the most uncertainty associated with it, as there are many other factors that cause a culvert to fail than just its opening relative to bankfull width or its aquatic score, and though the model did significantly predict culvert failures in the study watershed, no model is perfect. Aquatic score and habitat gain had the least amount of associated uncertainty, and thus should probably be weighted most heavily in a prioritization scheme.

Ultimately, a barrier prioritization scheme is considering habitat quantity, quality, and accessibility. Regardless of the prioritization scheme chosen, it is important to consider these factors collectively. There are countless ways to combine and weight these variables into a prioritization scheme, that will depend in large part on the goal of the organization applying the prioritization scheme.

Climate change predictions lend even more urgency to the task of updating road-stream crossings, from both an ecosystem processes and an infrastructure sustainability viewpoint. Increasing connectivity by removing barriers is one of the most effective ways to mitigate the effects of climate change (Nislow 2009), and improving road crossings would offer immediate and future ecological and infrastructure benefits. This prioritization scheme can help conservation managers spend their dollars on the culvert restorations and removals that will provide the most ecological bang for their buck.

APPENDIX A

AQUATIC PASSAGE SCORING

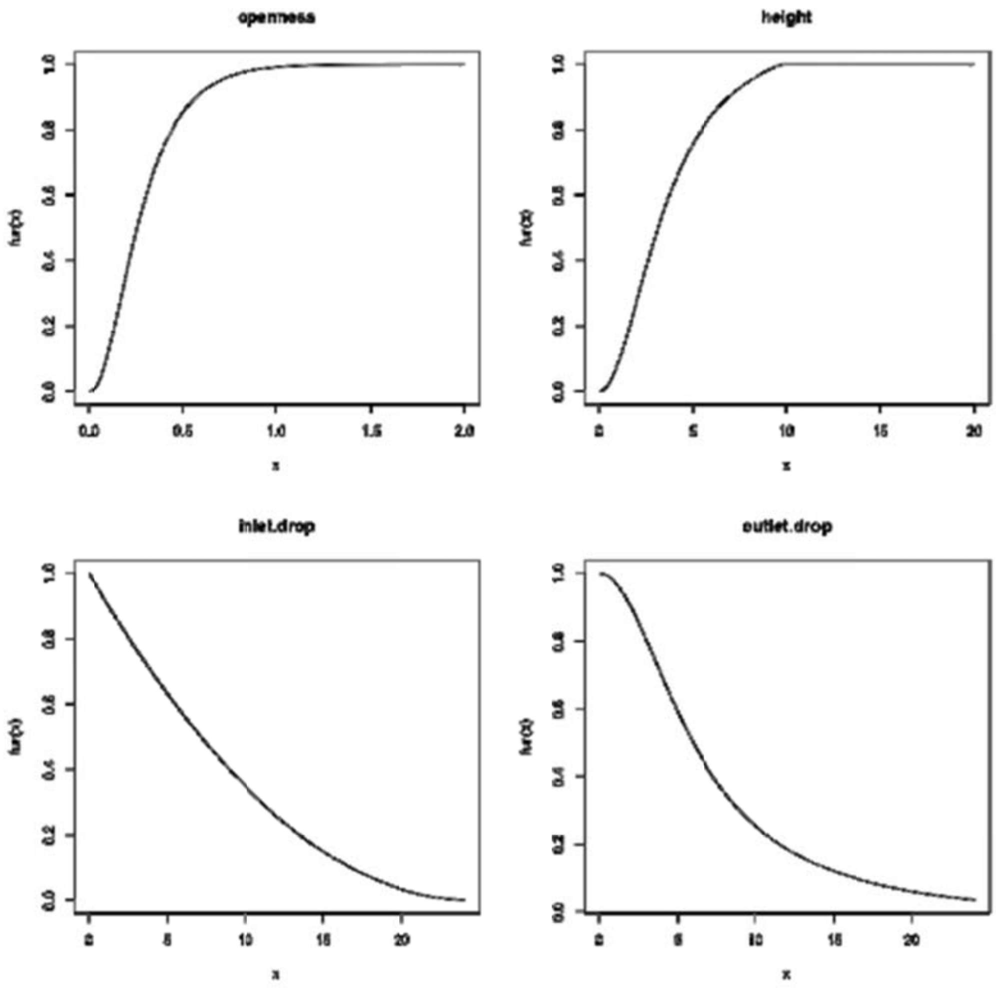
Parameter	Score	Weight	Weighted Score
Outlet drop		X 0.149	
Physical barriers		X 0.107	
Water velocity		X 0.104	
Water depth		X 0.098	
Inlet drop		X 0.093	
Crossing span		X 0.089	
Crossing substrate		X 0.084	
Crossing embedment		X 0.083	
Openness		X 0.061	
Scour pool		X 0.058	
Tailwater armoring		X 0.041	
Height		X 0.033	

Discrete variables:

Parameter	Level	Score
Crossing embedment	Not embedded	0
	Partially embedded	0.5
	Fully embedded	0.9
	No bottom	1.0
Crossing span	Severe	0
	Mild	0.5
	Spans bank to bank	0.9
	Spans channel and banks	1.0
Crossing substrate	None and smooth bottom	0
	Inappropriate, roughened, or corrugated	0.25
	Contrasting	0.75
	Comparable	1.0
Physical barriers	Severe	0
	Moderate	0.8
	Minor	0.9
	None	1.0
Scour pool	Large	0
	Small	1
	None	1
Tailwater armoring	Extensive	0
	Not extensive	0.5
	None	1.0
Water depth	No (significantly shallower)	0
	No (significantly deeper)	0.5
	Yes (comparable)	1.0
	Dry	0.75
Water velocity	No (significantly faster)	0
	No (significantly slower)	0.5
	Yes (comparable)	1.0
	Dry	0.75

Continuous variables:

The x-axis for each of these graphs is the value for the listed variable (e.g. “openness”, “outlet drop”) in the units specified on the data sheet. Use the graphed line to read off the score for each variable on the corresponding y-axis.


openness
height
inlet.drop
outlet.drop
fun(x)
x
0.0
0.2
0.4
0.6
0.8
1.0
0.5
1.5
2.0
0
5
10
15
20

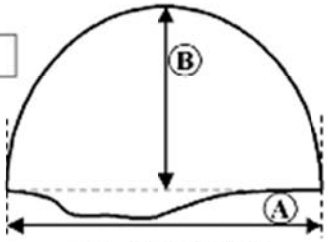
APPENDIX B

FORMULAS FOR CALCULATING OPENNESS

1. Open bottom arch openness = (0.785 * A * B)/L
2. Bridge with abutments openness = (A * B)/L
3. Bridge with side slopes openness = [(A*B)+(B*C)]/(2*L)
4. Bridge with side slopes and abutments openness = (A*B = B*C + A*D – C*D)/(2*L)
5. Round culvert openness = (0.785 * A*A)/L
6. Elliptical culvert openness = (0.785*A*B)/L
7. Box culvert openness = (A*B)/L
8. Embedded round culvert openness = [3.14*A*A – A*Asin^{-1}(C/A) + 2*B*C – A*C]/(4*L) (Trigonometric functions in radians rather than degrees)
9. Embedded elliptical culvert openness = (3.14*D*A*arcsin(C/A) + 2*B*C – C*D)/(4*L)

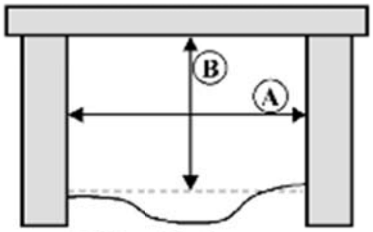
CROSSING DIMENSIONS

1.

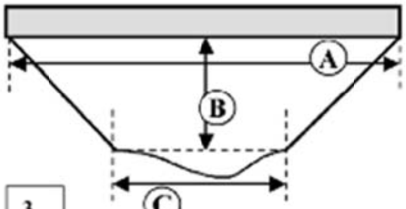


Open Bottom Arch

2.

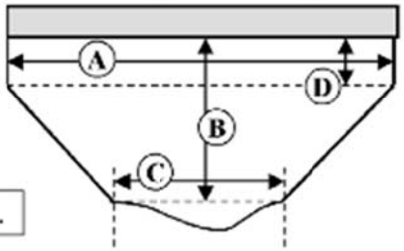


Bridge with Abutments



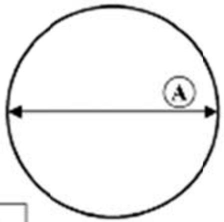
3.

Bridge with Side Slopes



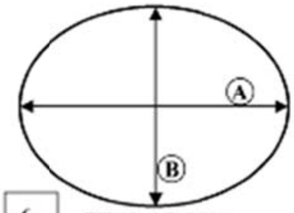
4.

Bridge w/ Side Slopes & Abutments



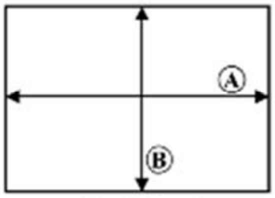
5.

Round Culvert



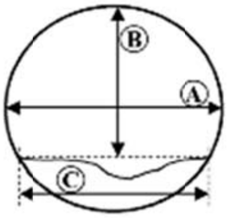
6.

Elliptical Culvert



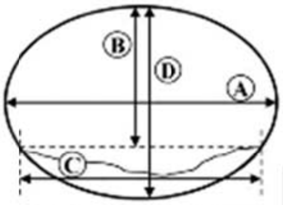
Box Culvert

7.



8.

Embedded Round Culvert



9.

Embedded Elliptical Culvert

Crossing Type (from above): ☐ 1. ☐ 2. ☐ 3. ☐ 4. ☐ 5. ☐ 6. ☐ 7. ☐ 8. ☐ 9. ☐ Ford

Upstream Dimensions (ft.): A) ____________ B)____________ C)____________ D) ____________

Downstream Dimensions (ft.): A) ____________ B)____________ C)____________ D) ____________

Length of stream through crossing (ft.): ____________________

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