THE IMPACT OF CLIMATE CHANGE ON BROOK TROUT (*SALVELINUS FONTINALIS*) THERMAL HABITAT IN THEIR NATIVE RANGE IN THE UNITED STATES

By

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ABSTRACT

THE IMPACT OF CLIMATE CHANGE ON BROOK TROUT (*SALVELINUS FONTINALIS*) THERMAL HABITAT IN THEIR NATIVE RANGE IN THE UNITED STATES

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Within their native range in the United States (U.S.), brook trout (*Salvelinus fontinalis*) are valued for the recreational opportunities they provide to anglers and for their utility as indicators of the environmental health of the habitats in which they are found. For brook trout, stream temperatures within their viable thermal range (0°-25°C) are vital to ensuring growth, reproduction, and survival. Changes in air temperatures related to climate change will influence stream temperatures, likely resulting in alterations in the distribution and quantity of thermal habitat available for brook trout, leading to changes in this fish's range and productivity.

I examined the effects of changing air temperature on brook trout thermal habitat availability for 51 streams across 30 subbasins spanning the latitudinal and longitudinal gradient of the brook trout's native range in the U.S. To determine the impact of air temperature changes driven by climate change for these streams, I converted air temperatures projections for the subbasin level from three coupled climate models into stream temperatures using two linear regression models and then rated the quality of stream habitat for brook trout growth and survival based on the results.

According to both linear regression models, all 30 subbasins were predicted to increase in temperature by between 0.94°C and 4.16°C from 2006 to 2056, resulting in reduced thermal habitat quality for brook trout in 20 subbasins according to the first model and 15 according to the second model.

To mitigate the effects of climate change related increases in water temperatures due to increased air temperature over the course of the next half-century, fisheries managers must focus their efforts on keeping streams as cool as possible by protecting and planting riparian zone shading and by guarding against additional sources of stream warming such as influxes of runoff during storm events and by maintaining other natural stream cooling mechanisms, like groundwater inputs.

To my family
For all your support, love, and good advice
And
To Lauri
For making my dreams come true.

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Introductory Summary

In the United States (U.S.), the brook trout, (Salvelinus fontinalis), is a highly valued sportfish, contributing to the recreational fishing industry and to the well being of participating anglers. In addition to the excitement they provide at the end of a fishing line, this species is also valued for its utility as an indicator of environmental health, due to their sensitivity to changes in water quality. Therefore, maintaining brook trout in their native waters is for the economic, social, and environmental benefit of the nation.

Maintaining this species in its native range will prove challenging for fisheries managers, however, in part because this species is reliant on a narrow range of cold water temperatures for growth, reproduction, and survival, making stream warming a threat to their persistence in U.S. streams. Air temperature, one of the drivers of stream temperature, is projected to change as greenhouse gas emissions continue to contribute to global climate change in the coming years (Melillo et al., 2014). As such, air temperature changes and concurrent changes in stream temperature, will affect the availability of thermal habitat for brook trout, making future strategies for the management of this species based on an understanding of the potential risk and magnitude of stream warming a necessity.

The goal of this thesis study was to improve this understanding by assessing the potential impacts of changing air temperatures, resulting from climate change, on stream temperature and therefore, on brook trout thermal habitat across their native U.S. range. Specifically, I evaluated changes in summer stream temperature between the years 2006, 2012, 2026, and 2056, based on projected changes in air temperatures for selected streams currently

supporting productive brook trout populations and fisheries. Then, I used these findings to project changes in the future thermal habitat suitability of these streams for this species. Lastly, this study provides a methodology for managers to predict current and future stream temperatures and resultant thermal habitat suitability from air temperatures to aid in developing future management plans for brook trout.

Introduction

Brook Trout Life History

The brook charr, Salvelinus fontinalis, or as it is colloquially known in the United States, the brook trout, is native to a large portion of North America. Its range extends from the Canadian province of Manitoba in the west, north to Newfoundland and Labrador, through the Great Lakes Basin, and south along the Appalachian Mountain Chain (MacCrimmon and Campbell, 1969, Waco, 2009). Within this range, brook trout exhibit three distinct life-history forms. Two of these forms exist entirely in freshwater and one is anadromous, indicating time spent in both fresh and salt water. The anadromous form, commonly called “the salter,” can be found along the east cost of North America and migrates to the ocean most likely for feeding opportunities (Karas, 1997). The salter becomes silver in color while living in marine waters, but returns to typical freshwater brook trout coloration upon its return to rivers and streams (Karas, 1997). The two entirely freshwater forms of brook trout are the stream variety and the larger potamodromous “coaster.” The stream brook trout is typically found in coldwater streams and is small and short lived, with a lifespan of approximately 3-5 years and a typical length of between 20 and 25cm (Waco, 2009). Relative to the stream variety, the coaster form is larger, later to mature, and longer lived. The coaster, which inhabits large lakes and rivers, as well as streams, may live to between eight and ten years old and attain a weight of between four and six kg (Power, 1980, Waco, 2009, Raleigh, 1982).

While brook trout do exhibit distinct differences in external appearance depending on location (MacCrimmon and Campbell, 1969), in freshwater brook trout typically have an olive green to black body with red spots, some of which are surrounded by blue halos on their sides (Page and Burr, 1991, MI DNR, 2012). The belly is typically white and wavy light green or cream-colored vermiculations run along the back and dorsal fin (MI DNR, 2012). The caudal fin is only very slightly forked to nearly straight-edged and the lower fins are edged in white (MI DNR, 2012, Page and Burr, 1991). A brook trout's mouth is large and extends past the eye (MI DNR, 2012). Breeding males have black bellies and bright red-orange sides (MI DNR, 2012, Page and Burr, 1991).

The Importance of Stream Temperature

The brook trout is a stenothermic cold-water obligate fish, therefore maintaining stream temperatures within its optimal thermal range (Table 5) is vital to ensuring the efficient functioning of life processes critical to survival and productivity. This is because the internal temperature of poikilothermic organisms, like brook trout, is directly controlled by the surrounding water temperature, which ultimately influences their metabolic processes, reproduction, behavior (Helfman et al., 2009), and distribution both in a broad geographic sense and within a single river system (Hynes, 1970).

Fish metabolism increases with increasing temperature, resulting in a rising demand for oxygen intake and consumed energy to fuel cellular processes (Helfman et al., 2009). As a component of anabolic metabolism, growth is also closely related to stream temperature (Hynes, 1970, Allan, 1995). Feeding activity and digestion rate increase as temperatures rise, allowing fish to grow faster provided that the demand for food and oxygen to fuel this process can still be met (Allan, 1995). Dissolved oxygen concentration in water decreases as temperature increases, however, and at some point fish can no longer meet the oxygen demands of a heightened metabolism at high temperatures. Even when dissolved oxygen concentration is not the limiting factor for supporting a heightened metabolism, limited food availability could be. Trout, for example, are not typically found in warm water streams in part because at approximately 20°C they reach a thermal threshold above which they are unable to meet their energetic demands (Allan, 1995). Additionally, at temperatures near a fish's upper thermal limit, more energy must be utilized for metabolic processes more crucial to survival than growth, which explains why growth is typically reduced as fish approach their upper thermal limits (Allan, 1995).

Gonadal growth and development is also influenced by water temperature in the same way that somatic growth is, therefore, water temperatures play a role in fish reproduction (Helfman et al., 2009, Strussmann et al., 1998). Additionally, fecundity is also influenced by the effect of water temperature on growth because body size is positively correlated with the number of eggs produced (Beldade et al., 2012, Hislop, 1988). Water temperatures also affect fish reproduction by acting as a behavioral cue for spawning events (Hynes, 1970). For example, peak spawning activity was coincident with drops in lake temperature to below 11°C for lake-dwelling brook trout in Scott Lake Ontario, Canada over a period of two years (Blanchfield and Ridgway, 1997). As such, in order to maximize growth, survival, and reproduction, fish tend to select environmental temperatures where they function most efficiently (Coutant, 1987, Helfman et al., 2009). Therefore, reduction in the availability of optimal thermal habitat has potentially significant impacts on fish survival and productivity.

The brook trout's upper and lower thermal limits are 25.3°C and 0°C, respectively (Fry et al., 1946). These fish are most productive and exhibit the highest rate of growth between 11°C and 16°C (Raleigh, 1982), where internal physiological processes for this species function most efficiently (Brett, 1956). Outside this thermal range, brook trout experience reduced growth and reproductive potential and are also more vulnerable to external factors, such as predation and disease, which often result in increased mortality (Brett, 1956). For this reason, high temperatures during the summer months in the brook trout's native U.S. range are limiting to trout biomass and abundance (Bowlby and Roff, 1986). During the height of summer, brook trout can be found in high densities in 15°C-19°C water (Wehrly et al., 2003), suggesting congregation around cool-water refugia like groundwater springs (Helfman et al., 2009). In extreme cases, fish reliance on small pockets of thermally suitable water can result in overcrowding, which may lead to an increase in the prevalence of disease, locally depleted food resources, and overfishing, impacting growth, survival, and reproductive capacity (Helfman et al., 2009). As such, ambient stream temperatures can be a limiting factor to brook trout productivity and distributional range (McCormick et al., 1972); constraining them to cooler locations (Helfman et al., 2009, Meisner, 1990a).

Maintaining thermal conditions suitable for brook trout within their native U.S. range is important because this species is valued for the socioeconomic benefits it provides local communities and for its utility as an indicator of environmental health (Eastern Brook Trout Joint Venture, 2008). In 2006, the United States' trout fishery, which includes the brook trout, provided recreational fishing opportunities for an estimated 6.8 million anglers who spent US$4.8 billion (Harris, 2010). In 2011, participation in trout angling increased to an estimated 7.2 million participants (U.S. Department of Interior et al., 2011). In addition to their value as a recreationally important fish, brook trout are also considered a gauge of environmental condition due to their sensitivity to changes in water quality (Karas, 1997). Therefore, maintaining stream temperature within the brook trout's thermal range is for the economic, social, and environmental benefit of the nation.

Effect of Air Temperature on Stream Temperature

When managing thermally sensitive fish species, like brook trout, into the future, it is critical to understand the drivers of stream temperature and the influence that changes in these drivers may have. Stream temperatures are determined by climate, elevation, streamside (riparian) vegetation, runoff, groundwater inputs, and urban and agricultural land use (Allan, 1995, Nelson and Palmer, 2007). For this study, I focused on air temperature, a component of climate, because projected changes in climate are likely to influence this stream temperature driver, resulting in future impacts to brook trout populations.

Climate Change

Since air temperature, which is ultimately controlled by climate, is a driver of water temperature, which in turn influences brook trout survival and productivity, to manage their populations into the future it is important to understand how changing climate is likely to influence air temperature and therefore, stream temperatures. Climate change is generally understood as long term changes in weather patterns, like precipitation and air temperature, resulting from increasing concentrations of greenhouse gasses (GHGs), most notably carbon dioxide (CO_2), water vapor, methane, nitrous oxide, and chlorofluorocarbons, in the atmosphere (Henson, 2011, Houghton, 2009). These gasses essentially blanket the Earth, absorbing the heat emitted by the planet, while only releasing a portion of that heat back into space (Henson, 2011). As the concentration of GHGs in the atmosphere rises, its heat capacity to sequester heat increases, influencing Earth's climate (Henson, 2011, Houghton, 2009). Much of the increase in atmospheric GHGs since the beginning of the Industrial Revolution around the year 1750 has been attributed to changes in human activities including, but not limited to reliance on fossil fuels for energy, agriculture, and land use change (Henson, 2011). GHG emissions have continued to rise over time with humans adding an estimated 31 gigatons of CO_2 into the atmosphere in 2009, as opposed to approximately 26 gigatons in 2002, and 15 gigatons in 1970 (Henson, 2011).

To predict future greenhouse gas emission, a driver of climate change, in 2001 The International Panel on Climate Change (IPCC) developed a Special Report on Emissions Scenarios (SRES), which included descriptions of 35 likely futures for GHG emissions (Houghton, 2009). The 35 scenarios were developed based on differing sets of assumptions about the future, including factors like economic growth, human population growth, technological innovations, and the evolution of thought regarding social and environmental sustainability (Houghton, 2009).

To illustrate how climate may change, climate-influencing variables, like the projected GHG emissions scenarios described above, are incorporated into global climate models (GCMs). GCMs are highly sophisticated computer models used to simulate the interactions between the atmosphere, ocean, land, ice, and biosphere, which ultimately govern Earth's climate (Houghton, 2009). Many GCMs, called coupled models, incorporate two or more sub-models describing interactions between these different climate drivers (Henson, 2011). Such models can project future conditions for climatic variables, like air temperature and precipitation patterns.

Since GCMs typically provide projections of climate at a very large scale, regional models (RCMs) or statistical downscaling methods can be used to apply climate change projections at more appropriate resolution for scientific endeavors involving the progression of climate change in a fixed area (Henson, 2011, Houghton, 2009).

Climate Change and its Impact on Stream Temperature

The brook trout's native range within the U.S. includes the Midwestern states of Minnesota, Iowa, Wisconsin, Michigan, and Ohio and extends along the Appalachian mountain chain from Maine in the north to northeastern Georgia in the south (Figure 1) (MacCrimmon and Campbell, 1969). Within this range, climate change is predicted to result in rising air temperatures and longer, more frequent, and more severe summer heat events (Karl et al., 2009). In the Midwest, regional average air temperatures are expected to rise by between 3.1°C and 4.7°C by the end of the century (2081-2100) ((Melillo et al., 2014). In the Northeast, air temperatures are expected to rise by between 1.7°C to 5.6°C by the 2080s (Kunkel et al. 2012; (Horton and coworkers, (Melillo et al., 2014). In the Southeast, air temperatures are expected to rise by 5.6°C by 2100 (Kunkel et al. 2012). These changes in air temperature are expected to directly influence stream temperatures (Karl et al., 2009) because, as mentioned above, water temperatures typically fluctuate in synch with air temperature (Pilgrim et al., 1998), resulting in changes in brook trout thermal habitat. Rising water temperatures are of concern because many fish species, including brook trout, are often currently found living near their upper thermal limit (Magnuson and Destasio, 1997, Helfman et al., 2009), which means that even minimal changes in stream temperature could result in fish extirpation from the stream.

Rising air temperatures are particularly problematic during the summer months, as annual air and water temperatures reach their maximums during mid to late summer, making brook trout vulnerable to heat-related stress during this season (Meisner, 1990b). Longer, hotter summers predicted with climate change (Karl et al., 2009) are likely to result in an increase in the

FIGURE 1. The brook trout's native U.S. range divided into its Midwestern and Eastern portions. The subbasins (HUC8s) containing each study stream are numbered and their corresponding identification numbers and names are listed in Table 1.

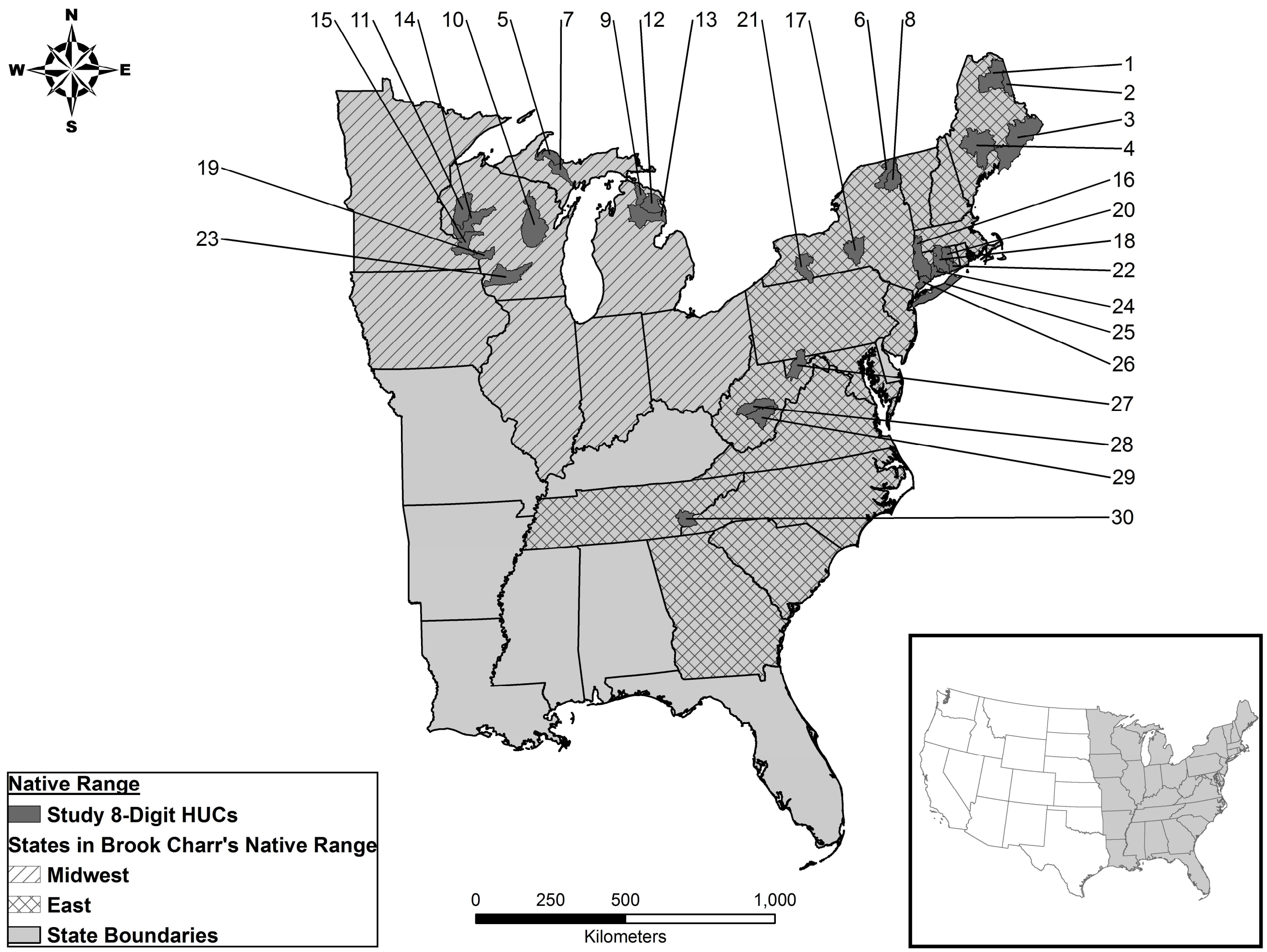


TABLE 1. List of high quality brook trout streams and number corresponding to each subbasin (HUC8) included in the national study site map (figure 1).

National Site Map Key		
State	**Watershed Name**	**Map ID**
CT	Housatonic	16
CT	Lower Connecticut	18
CT	Shetucket	20
CT	Thames	22
CT	Quinnipiac	24
CT	Saugatuck	26
ME	Aroostook	1
ME	Meduxnekeag	2
ME	Maine Coastal	3
ME	Lower Kennebec	4
MI	Dead-Kelsey	5
MI	Escanaba	7
MI	Black	9
MI	Thunder Bay	12
MI	Au Sable	13
MN	Buffalo-Whitewater	15
NC	Lower Little Tennessee	30
NY	Great Chazy-Saranac	6
NY	Ausable	8
NY	Chenango	17
NY	Upper Genesee	21
NY	Southern Long Island	25
WI	Wolf	10
WI	Red Cedar	11
WI	Lower Chippewa	14
WI	La Crosse-Pine	19
WI	Lower Wisconsin	23
WV	North Branch Potomac	27
WV	Elk	28
WV	Gauley	29

incidence and severity of heat related stress events on brook trout, impacting their distribution (Meisner, 1990a, Meisner, 1990b, Magnuson et al., 1990, Shuter and Post, 1990), and productivity (Hokanson, 1977, Drake and Taylor, 1996) making future strategies for the management of this species based on an understanding of the potential risk and magnitude of stream warming a necessity.

Goals and Objectives

The goal of this study was to assess the potential impacts of changing air temperatures, resulting from climate change, on brook trout thermal habitat across their native U.S. range. The specific objectives of this study were: 1) evaluate changes in summer stream temperature between the years 2006, 2012, 2026, and 2056, based on projected changes in air temperatures for selected streams currently supporting productive brook trout populations and fisheries; 2) to project changes in future thermal habitat suitability of these streams for brook trout in terms of growth and survival; and 3) to provide a methodology for managers to predict current and future stream temperatures and resultant thermal habitat suitability for brook trout from air temperatures.

Methods

Site Selection

I chose 52 high quality brook trout streams (Figures 1-9; Table 2) distributed across their native U.S. range to evaluate the potential effect of climate change related shifts in air temperature on thermal habitat suitability for this species. I selected streams from states spanning the latitudinal and longitudinal gradient this range, in an effort to capture current and predicted differences in climate along this expanse. States represented in this study include: Minnesota (MN), Wisconsin (WI), and Michigan (MI) in the midwestern region and Maine (ME), New York (NY), Connecticut (CT), and North Carolina (NC) in the Eastern region (Figures 1-9; Table 2).

FIGURE 2. Location of each subwatershed (HUC12) containing a high quality study stream in the state of Minnesota.

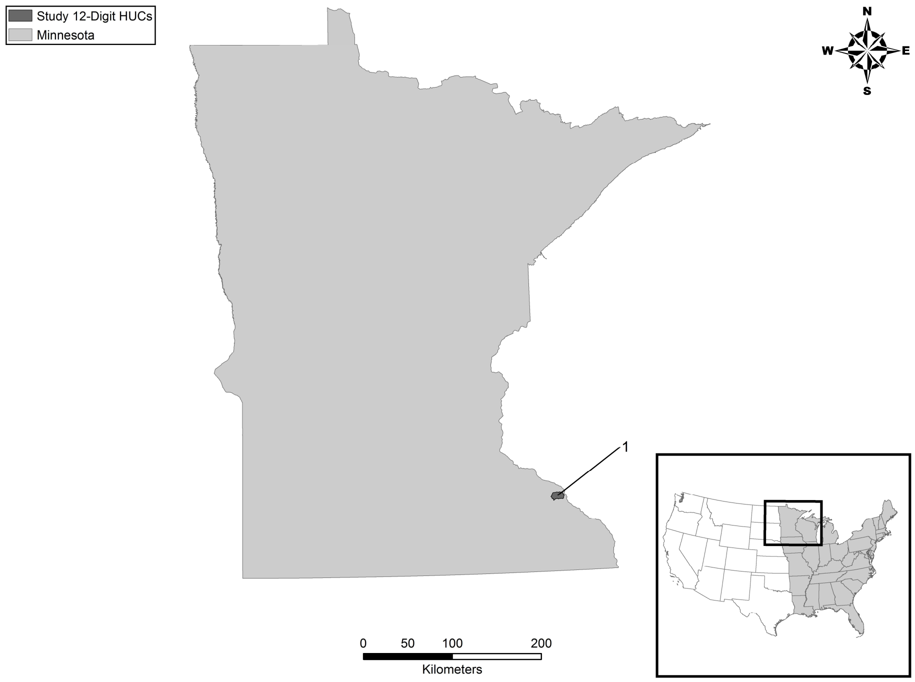


FIGURE 3. Location of each subwatershed (HUC12) containing a high quality study stream in the state of Wisconsin.

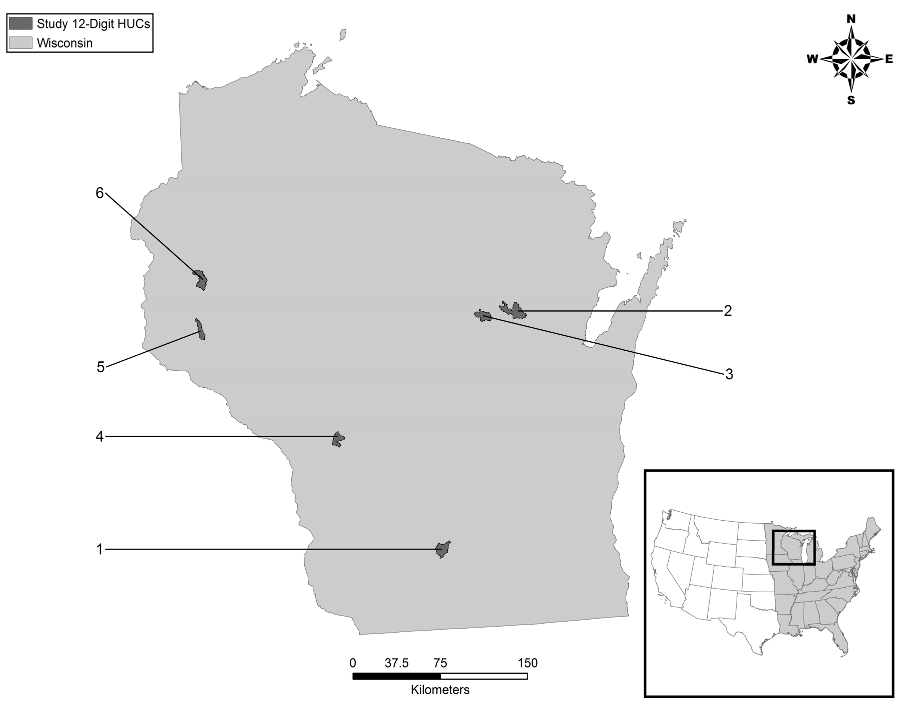


FIGURE 4. Location of each subwatershed (HUC12) containing a high quality study stream in the state of Michigan.

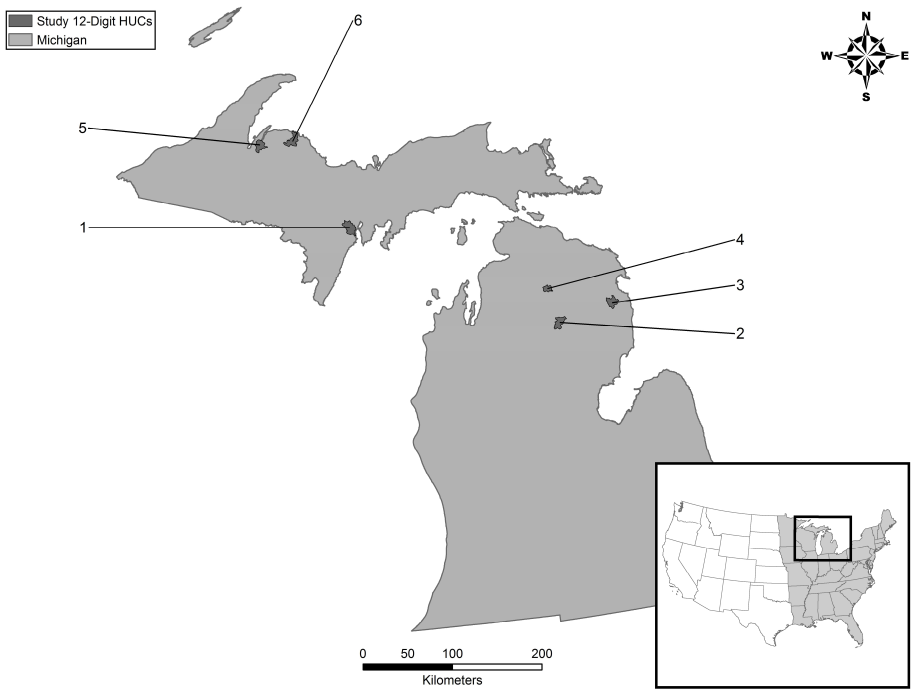


FIGURE 5. Location of each subwatershed (HUC12) containing a high quality study stream in the state of Maine.

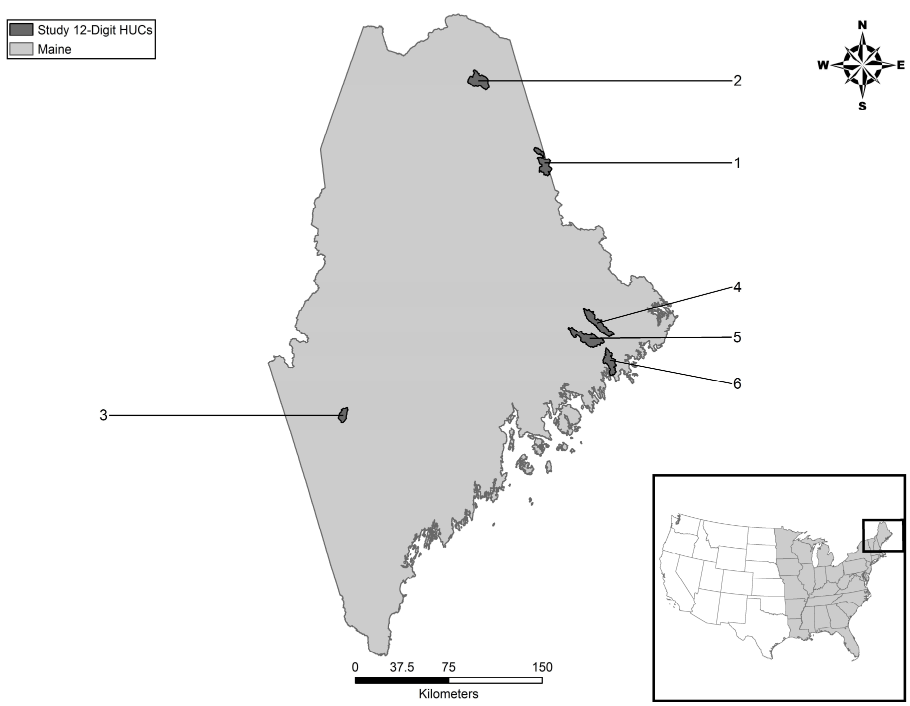


FIGURE 6. Location of each subwatershed (HUC12) containing a high quality study stream in the state of New York.

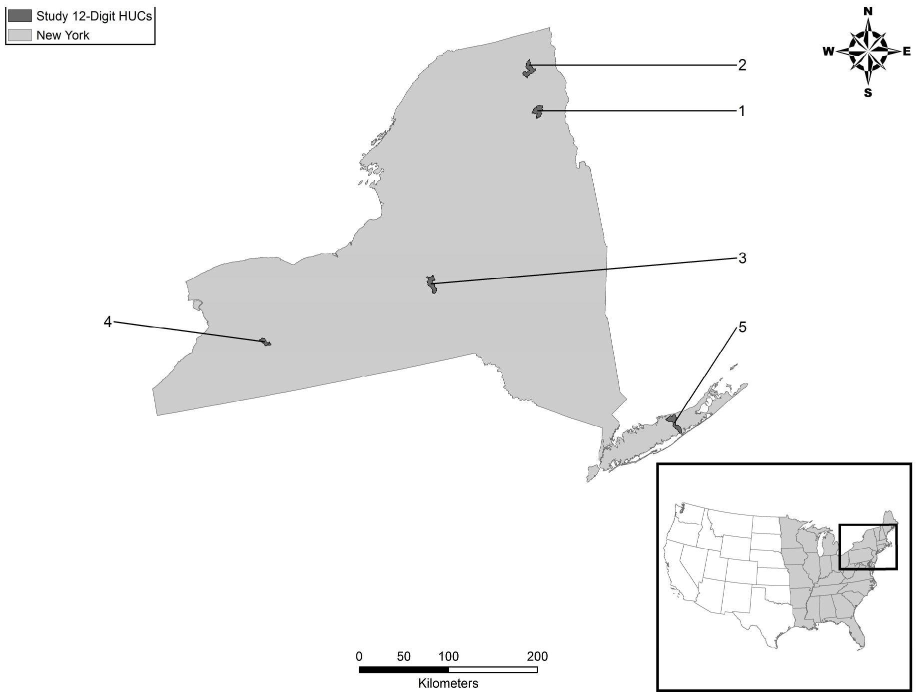


FIGURE 7. Location of each subwatershed (HUC12) containing a high quality study stream in the state of Connecticut.

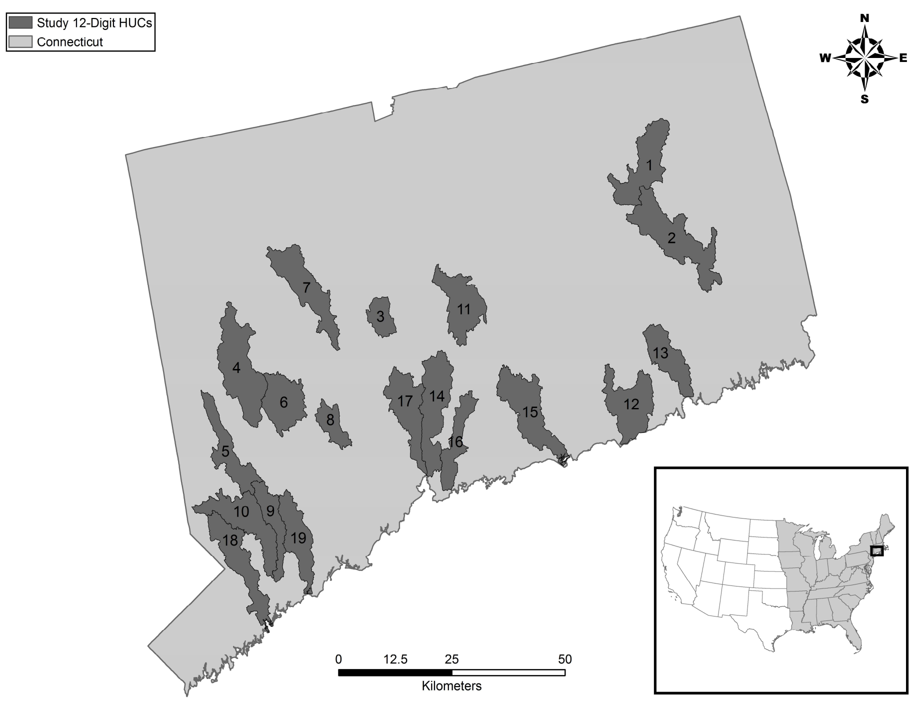


FIGURE 8. Location of each subwatershed (HUC12) containing a high quality study stream in the state of West Virginia.

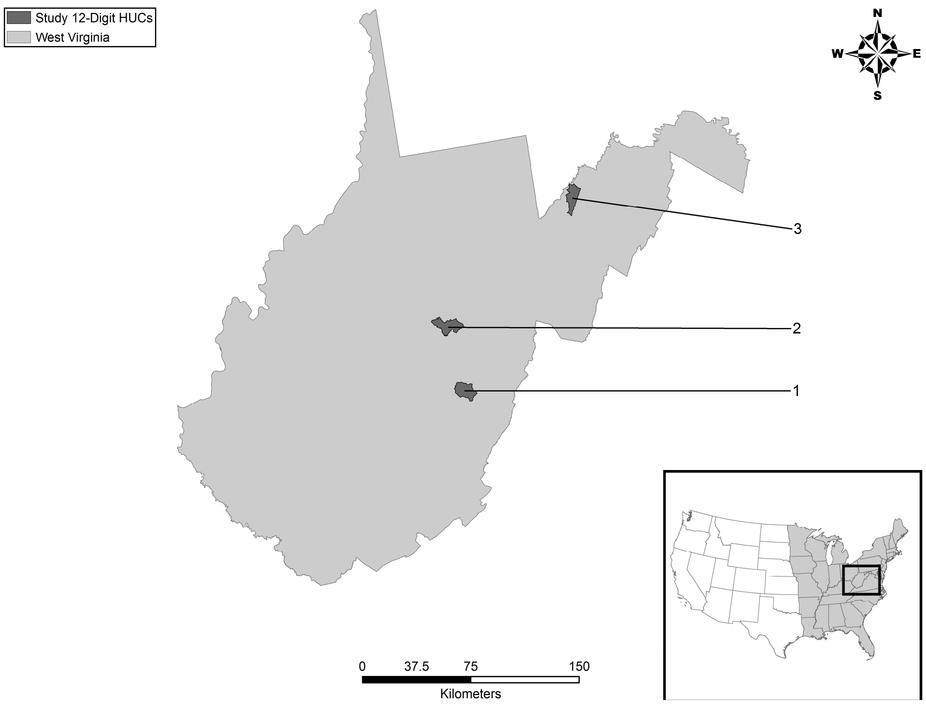


FIGURE 9. Location of each subwatershed 12 (HUC12) containing a high quality study stream in the sate of North Carolina (NC).

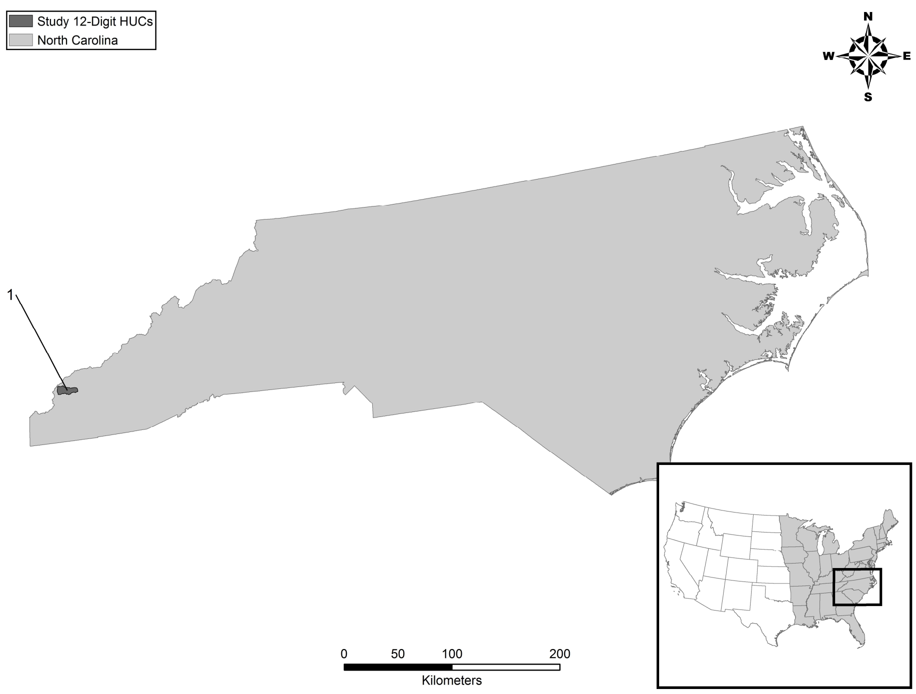


TABLE 2. List of high quality brook trout streams and number corresponding to each subwatershed (HUC12) included in the state study site maps (figures 2- 9).

State Site Map Key		
State	**Stream Name**	**Map ID**
CT	*Ames Brook*	1
CT	*Ballymahack Brook*	2
CT	*North Branch Hamlin Brook*	3
CT	*Mallory Brook*	4
CT	*West Brook*	5
CT	*Good Hill Brook*	6
CT	*Humaston Brook*	7
CT	*Jericho Brook*	7
CT	*Sutliffe Brook*	7
CT	*Riggs Street Brook*	8
CT	*North Branch West Branch Saugatuck River*	9
CT	*Cemetery Brook*	10
CT	*West Swamp Brook*	11
CT	*Broad Swamp Brook*	12
CT	*Lake Pond Brook*	13
CT	*Watermans Brook*	14
CT	*Bunker Hill Brook*	15
CT	*Gulf Brook*	16
CT	*Brooksvale Stream*	17
CT	*Bryant Brook*	18
CT	*Gilbert Bennett Brook*	18
CT	*Woods Pond Brook*	18
CT	*Morehouse Brook*	19
ME	*Meduxnekeag River*	1
ME	*Salmon Brook*	2
ME	*Sandy River*	3
ME	*Old Stream*	4
ME	*Little Mopang/Mopang Stream*	5

Table 2 (cont'd).

ME	*Pleasant River*	6
MI	*Escanaba River*	1
MI	*Au Sable River*	2
MI	*Comstock Creek*	3
MI	*Black River*	4
MI	*Silver River*	5
MI	*Salmon Trout River*	6
MN	*Snake Creek*	1
NC	*Deep Creek*	1
NY	*East Branch Ausable River*	1
NY	*True Brook*	2
NY	*Otselic River*	3
NY	*Bush Brook*	4
NY	*Carmans River*	5
WI	*Black Earth Creek*	1
WI	*Red River*	2
WI	*Embarrass River*	3
WI	*Silver Creek*	4
WI	*Cady Creek*	5
WI	*Connors Creek*	6
WV	*North Fork Cranberry River*	1
WV	*Laurel Fork*	2
WV	*Johnnycake Run*	3

I chose to investigate the impacts of changing air temperatures resulting from climate change on *high quality* brook trout streams specifically, because if the thermal habitat suitability of these streams is impacted, then changing air temperatures will also affect the habitat suitability of more thermally marginal streams within the same regions. Therefore, to select the study streams, I examined streams designated by state fisheries management agencies as high quality recreational brook trout fishing waters with naturally reproducing populations (Table 3). The lists of high quality streams were either obtained from publically available state agency websites, or via direct contact with the agencies. Naturally reproducing populations of brook trout and the presence of a recreational fishery generally indicate high fish productivity, which I assumed reflected the presence of preferred thermal habitat conditions. Therefore, I designated streams supporting a naturally reproducing population of brook trout, a recreational fishery, and therefore, optimal thermal habitat as "high quality" streams for the purposes of this study.

TABLE 3. The names of state agencies that designated each study stream as high quality for each state: Michigan Department of Natural Resources, Wisconsin Department of Natural Resources, Minnesota Department of Natural Resources, Maine Department of Inland Fisheries and Wildlife, Pennsylvania Fish and Boat Commission, North Carolina Wildlife Resources Commission. *Indicates states with publically-available lists.

Source of Designated High Quality Brook Trout Stream Lists	
State	**Source**
CT	Connecticut Department of Energy and Environmental Protection (CDEEP)
ME	Maine Department of Inland Fisheries and Wildlife (MDIFW)*
MI	Michigan Department of Natural Resources (MDNR)*
MN	Minnesota Department of Natural Resources (MNDNR)*
NC	North Carolina Wildlife Resources Commission (NCWRC)*
NY	New York Department of Environmental Conservation (NYDEC)
WI	Wisconsin Department of Natural Resources (WDNR)*
WV	West Virginia Department of Natural Resources (WVDNR)

I used the National Hydrography Dataset Plus Version 1 (NHDPlusV1) (U.S. Geological Survey and U.S. Environmental Protection Agency, 2005) Watershed Boundary Dataset to determine the eight and 12-digit hydrologic unit codes, HUC8 (Table 2; Figure 1) and HUC12 (Figures 2-9) respectively, containing each study stream selected using the method above. These hydrologic unit codes are used to catalog the hydrologic drainage system in the United States, with unit boundaries defined by hydrographic and topographic features (U.S. Department of Agriculture, Natural Resource Conservation Service). The system is nested hierarchically into six levels based on the size of the drainage unit; the levels from largest to smallest are: region, subregion, basin, subbasin, watershed, and subwatershed (U.S. Department of Agriculture, Natural Resource Conservation Service). The HUC8s and HUC12s used in this study correspond to the subbasin (HUC8) and subwatershed (HUC12) levels. The Subcommittee on Spatial Water Data, including members of several United States federal agencies, is responsible for the development of the Watershed Boundary Dataset, which contains the delineations for HUCs (U.S. Department of Agriculture, Natural Resource Conservation Service).

Then, I used NHDPlusV1 (U.S. Geological Survey and U.S. Environmental Protection Agency, 2005) to locate stream temperature-recording gages within the same subwatersheds (high quality HUC12s) as each of the high quality streams. High quality streams without any gages within their HUC12 were removed from the study. Once I had identified all the stream temperature-recording gages located within each high quality HUC12, I chose one gage to represent each remaining high quality stream. For the purposes of this study, the gages chosen had to be included in the network of gages contributing data to the Northeast Climate Center's (NECSC) database[2] and must have had stream temperature data available to produce monthly averages for at least one summer month, June, July, or August, in either the year 2006, 2012, or

[2] NECSC project title: "A Stream Temperature Inventory Network and Decision Support Metadata Mapper - Evaluating the Resources to Understanding Climate Change Effects on Streams in New England and the Great Lakes States"

both[3]. Gages that did not meet these criteria were removed from the study. In the event that multiple gages meeting these criteria were available in a high quality HUC12, a gage located directly on the high quality stream was preferentially chosen. If there were multiple gages located on the high quality stream, the most upstream gage was chosen. Similarly, if no gages were available directly on the high quality stream, than the most upstream gage on the most proximal gaged stream within the same subwatershed (HUC12) was used. The rationale behind choosing the most upstream gage was that stream temperatures are typically coolest at their most upstream reaches, warming as the water moves downstream, therefore the most optimal habitat for cold water obligate brook trout would likely be in the most upstream reaches. Gages located directly below dams were disqualified from the study, as the temperature of the water discharged from dams may be artificially altered (Lessard, 2000).

At the end of the selection process, I had collected an average monthly water temperature for at least one summer month (June, July, or August), in the year 2006, 2012, or both from 51 stream temperature-recording gages located within the same HUC12 as a state agency designated high quality brook trout stream. Table 4 summaries all metrics collected for all 51 study sites including: high quality stream name, state, subbasin (HUC8), subbasin name, subwatershed (HUC12), NorEast gage identification number for the gage representing each stream (NorEast ID), area weighted average of percent groundwater contribution to streams within each HUC12 (GW%), and Strahler stream order for each gaged stream (Stream Order).

[3] Downscaled air temperature projections were available for the years 2006, 2012, 2026, and 2056.

TABLE 4. Descriptive data for each high quality stream site including: stream name (HQ Stream Name)[4], state, subbasin (HUC8), subbasin name (HUC8 Name), subwatershed (HUC12), NorEast gage identification number for the gage representing each stream (NorEast ID), area weighted average of percent groundwater contribution to streams within each HUC12 (GW%), Strahler stream order for each gaged stream (Stream Order).

High Quality Stream Information							
Stream Name	**State**	**HUC8**	**HUC8 Name**	**HUC12**	**NorEast ID**	**GW %**	**Stream Order**
Good Hill Brook	CT	01100005	Housatonic	011000050903	CT_DEP_922	47.34	4
Humaston Brook	CT	01100005	Housatonic	011000051105	CT_DEP_194	47.30	3
Jericho Brook	CT	01100005	Housatonic	011000051105	CT_DEP_197	47.30	4
Mallory Brook	CT	01100005	Housatonic	011000050703	CT_DEP_1455	48.79	4
Riggs Street Brook	CT	01100005	Housatonic	011000051206	CT_DEP_5991	47.93	3
Sutliffe Brook	CT	01100005	Housatonic	011000051105	CT_DEP_725	47.30	4
West Brook	CT	01100005	Housatonic	011000050802	CT_DEP_333	49.44	4
Broad Swamp Brook	CT	01080205	Lower Connecticut	010802050905	USGS_01194750	48.01	6
W. Swamp Brook	CT	01080205	Lower Connecticut	010802050603	CT_DEP_453	49.57	2
Brooksvale Stream	CT	01100004	Quinnipiac	011000040301	CT_DEP_1807	48.99	2
Bunker Hill Brook	CT	01100004	Quinnipiac	011000040202	CT_DEP_1853	47.95	2
Gulf Brook	CT	01100004	Quinnipiac	011000040206	CT_DEP_68	48.14	2
N. Branch Hamlin Brook	CT	01100004	Quinnipiac	011000040101	CT_DEP_488	50.49	2
Watermans Brook	CT	01100004	Quinnipiac	011000040105	CT_DEP_289	49.24	4
Bryant Brook	CT	01100006	Saugatuck	011000060202	CT_DEP_245	47.58	4
Cemetery Brook	CT	01100006	Saugatuck	011000060102	CT_DEP_319	47.88	3
Gilbert Bennett Brook	CT	01100006	Saugatuck	011000060202	CT_DEP_235	47.58	3
Morehouse Brook	CT	01100006	Saugatuck	011000060302	CT_DEP_1810	47.71	2
N. Branch W. Branch Saugatuck River	CT	01100006	Saugatuck	011000060103	CT_DEP_1288	49.11	2
Woods Pond Brook	CT	01100006	Saugatuck	011000060202	CT_DEP_236	47.58	4
Ames Brook	CT	01100002	Shetucket	011000020206	CT_DEP_5955	49.25	1
Ballymahack Brook	CT	01100002	Shetucket	011000020303	CT_DEP_5968	50.86	1

[4] Stream names indicating directionality have been abbreviated. For example, N. Fork Cranberry River represents North Fork Cranberry River and etc.

Table 4 (cont'd).

Lake Pond Brook	CT	01100003	Thames	011000030304	USGS_011277905	51.18	2
Salmon Brook	ME	01010004	Aroostook	010100041001	ME_DMR_14_1SALMON6_40	53.75	2
Meduxnekeag River	ME	01010005	Meduxnekeag	010100050407	USGS_01018035	53.35	4
Sandy River	ME	01030003	Lower Kennebec	010300030902	ME_DMR_9SANDYR97_66	44.01	3
Mopang Stream	ME	01050002	Maine Costal	010500020901	ME_DMR_5MOPANG34_81	52.82	2
Old Stream	ME	01050002	Maine Costal	010500020803	ME_DMR_5OLDSTR27_86	56.23	3
Pleasant River	ME	01050002	Maine Costal	010500021202	ME_DMR_4MAINST11_00	53.50	4
Silver River	MI	04020105	Dead-Kelsey	040201050605	USGS_04043150	58.02	4
Salmon Trout River	MI	04020105	Dead-Kelsey	040201050401	USGS_04043238	61.59	2
Escanaba River	MI	04030110	Escanaba	040301100308	USGS_04059000	58.77	5
Black River	MI	04070005	Black Watershed	040700050201	MI_IFR_38	80.18	1
Comstock Creek □	MI	04070006	Thunder Bay	040700060502	MI_IFR_1189	69.14	3
Au Sable River	MI	04070007	Au Sable	040700070501	USGS_04136000	78.29	5
Snake Creek	MN	07040003	Buffalo-Whitewater	070400030602	MN_DNR_03LM002	69.76	2
Deep Creek	NC	06010204	Lower Little Tennessee	060102040107	USGS_0351706800	63.92	NA
E. Branch Ausable River	NY	02010004	Ausable	020100040103	NY_DEC_Ausable River, East Br._31	47.95	3
True Brook	NY	02010006	Great Chazy-Saranac	020100060501	NY_DEC_True Brook_107	57.97	2
Carmans River	NY	02030202	Southern Long Island	020302020302	NY_DEC_Carmans River_12	85.02	1
Otselic River	NY	02050102	Chenango	020501020301	NY_DEC_Otselic River_137	47.73	3
Bush Brook	NY	04130002	Upper Genesee	041300020705	NY_DEC_Wiscoy Creek_239	36.25	4
Embarrass River	WI	04030202	Wolf	040302021005	USGS_0407809265	70.69	3
Red River	WI	04030202	Wolf	040302020505	USGS_04077630	66.76	4
Silver Creek	WI	07040006	La Crosse-Pine	070400060203	USGS_05382284	59.67	3
Cady Creek	WI	07050005	Lower Chippewa	070500051003	WI_WDNR_ZZCady1	60.30	2
Connors Creek	WI	07050007	Red Cedar	070500070501	WI_WDNR_Zzsfxhay	60.30	4
Black Earth Creek	WI	07070005	Lower Wisconsin	070700050501	USGS_05406500	59.74	4
Johnnycake Run	WV	02070002	North Branch Potomac	020700020204	WV_DEP_PNB-00014-10.9	40.93	2
N. Fork Cranberry River	WV	05050005	Gauley	050500050201	WV_DEP_KG-00212-0.2	36.38	2
Laurel Fork	WV	05050007	Elk	050500070301	WV_DEP_KE-00203-0.5	30.27	2

Air Temperature Projections

I used three coupled climate models (CCMs) to project future summer air temperatures for the years 2026 and 2056 and to backcast air temperatures for 2006 and 2012: the Third Generation Coupled Global Climate Model (CGCM3, Canadian Centre for Climate Modelling and Analysis) the CM2 Global Coupled Climate Model (CM2, Geophysical Fluid Dynamics Laboratory at the National Oceanic and Atmospheric Administration), and the Hadley Centre Coupled Model version 3 (HadCM3, Met Office, United Kingdom's National Weather Service), to project future summer air temperatures for the years 2026 and 2056 and to backcast air temperatures for 2006 and 2012. All three models, based on the World Climate Research Programme's (WRCP) Coupled Model Intercomparison Project phase 3 (CMIP3), were spatially downscaled using the Bias-Correction Spatial Disaggregation (BCSD) approach (Maurer et al., 2007). This is a statistical downscaling method where the spatial resolution of the climate model (approximately 200km x 200km) is adjusted to a finer resolution (12km x 12km) more relevant to the scale of the study with differences between observed and modeled variables (i.e., air temperature and precipitation) used to adjust or correct future simulations for each time step and grid cell (Maurer et al., 2007).

I ran all three CCMs with the WCRP's CMIP3 and chose to assume the Special Report on Emission Scenarios (SRES) A1B climate forcing scenario. SRES A1B is considered the middle emissions path, predicting atmospheric CO_2 concentrations of 700ppm by 2100 (Meehl et al., 2007). I chose to use the A1B climate-forcing scenario because I considered it to be the most moderate of the three SRES scenarios, thereby avoiding extreme possible future climate conditions.

The United States Forest Service's (USFS) Eastern Forest Environmental Threat Assessment Center (EFETAC) in North Carolina calculated average monthly air temperatures for the subbasin level based on the predictions provided by the three coupled climate models (CGCM3, CM2, and HadCM3) using area-weighted means for the years 2006, 2012, 2026, and 2056. EFETAC provided us with the monthly summer (June, July, and August) air temperature averages for each HUC8 containing one of the selected high quality brook trout streams. I chose to predict stream temperature for these months because they are typically the warmest months in the studied region and therefore pose the highest risk of heat stress to brook trout.

Air Temperature to Stream Temperature Conversion

Air temperature is, in many cases, an accurate predictor of current and future stream temperatures, as several studies have cited a nearly 1:1 linear relationship between water an air temperature for weekly and monthly data (Stefan and Preud'homme, 1993, Pilgrim et al., 1998). For example, near 1:1 linear relationships between air and stream temperature have been described for 39 Minnesota streams (Pilgrim et al., 1998) and 11 Mississippi basin streams (Stefan and Preud'homme, 1993).Therefore, air temperatures can be used to approximate stream temperature using linear regression models (Crisp and Howson, 1982, Stefan and Preud'homme, 1993, Pilgrim et al., 1998, Mohseni and Stefan, 1999, Krider et al., 2013).

I chose to use two linear equations estimating weekly air-water temperature relationships to convert the HUC8 level air temperature projections I received from EFETAC into stream temperatures for the four study years. The two linear regression equations used were Stefan and Preud'homme's (1993) weekly stream temperature estimation model and Krider et al.'s (2013) composite model.

For Stefan and Preud’homme’s (1993) model, weekly stream temperature is estimated by:

T_w (t) = 2.9 + 0.86 T_a.

Where T_w is water temperature (°C) and T_a is air temperature (°C).

Stefan and Preud’homme (1993) developed both generalized daily and weekly temperature empirical models to convert air temperatures into water temperatures for 11 rivers and streams within the Mississippi River basin to investigate the practice of using air temperatures to predict water temperatures. Stream and air temperatures are more strongly correlated at weekly and monthly timescales than at the daily timescale (Stefan and Preud'homme, 1993, Pilgrim et al., 1998, Erickson and Stefan, 2000). This principle is reflected by the standard deviations produced for Stefan and Preud’homme’s (1993) daily and weekly models. The standard deviation for the generalized daily model is 2.70°C, whereas the weekly model produces more accurate predictions, with an average standard deviation of 2.16°C (Stefan and Preud'homme, 1993). Therefore, I chose to use the weekly temperature model for this study.

For Krider et al.’s (2013) model, weekly stream temperature is estimated by:

T_w (t) = 6.63 + 0.38 T_a.

Where T_w is water temperature (°C) and T_a is air temperature (°C).

This model was developed specifically to predict weekly stream temperatures from air temperatures for streams with substantial groundwater inputs (Krider et al., 2013). The 40 streams used to develop this composite linear model were from groundwater fed streams from southeastern Minnesota, a region dominated by karst topography (Krider et al., 2013). The standard deviation for this equation is 4.80°C.

I chose to pair these two equations because at summer air temperatures, Stefan and Preud'homme's (1993) equation produces stream temperatures close to air temperature, indicating an equation that should predict temperature well for surface water dominated streams, with temperatures primarily driven by air temperatures. On the other hand, because Krider et al.'s (2013) equation was developed for groundwater dominated streams that fluctuate in temperature less with changing air temperature, due to continuous inputs of groundwater which remain at a relatively stable temperature throughout the year, the equation produces stream temperatures which are much cooler than air temperature. Essentially, the two equations form a range of projected stream temperatures based on the prominence of either air temperature or groundwater input as drivers of stream temperature. The Stefan and Preud'homme (1993) equation predicts temperatures for surface water dominated streams, those that are likely most reactive to changes in air temperature, while the Krider et al. (2013) equation predicts temperatures for groundwater dominated streams, which are likely less reactive to changes in air temperatures. I hypothesize that future stream temperatures for the high quality brook trout streams will fall within the range of temperatures predicted by the Stefan and Preud'homme (1993) equation as a maximum and the Krider et al. (2013) equation as a minimum, based on the relative importance of groundwater inputs and air temperature as drivers of stream temperature.

Since there is nearly a 1:1 relationship between daily and monthly air and water temperatures (Ozaki et al., 2003), I assumed the weekly and monthly relationships to be comparable and substituted the projected monthly air temperature data from EFETAC in place of weekly averages called for by the Stefan and Preud'homme (1993) and Krider et al. (2013) equations when preforming the air-stream temperature conversion.

I considered the standard deviations of 2.16°C from Stefan and Preud'hommes's (1993) equation and 4.80°C weekly air to water conversion model when analyzing the results of the study. Changes in temperature between years were compared to the equation's standard deviation when analyzing the results produced by both Stefan and Preud'hommes's (1993) (SD 2.16°C) equation and Krider et al.'s (2013) (SD 4.80°C) equation.

Stream Temperature Projections

I used an ensemble approach to report the stream temperatures predicted by the three CCMs to best reflect the range of possible changes in air temperature and to account for the uncertainty inherent in all climate models. The projected stream temperatures reported for 2006, 2012, 2026, and 2056 were based on the average of the air temperatures predicted by the three CCMs. For the sake of clarity and to emphasize the maximum stream temperatures brook trout are likely to face in each of the study years, only the stream temperature from the month with the warmest projected water temperature is reported. Since stream temperatures were predicted based on air temperature projections for the subbasin level, the projected stream temperatures reported reflect the temperatures of all streams within the same subbasin.

Brook Trout Thermal Habitat Suitability

I assigned a rating (status 1-4) of thermal habitat suitability to each subbasin for all four study years based on the reported projected stream temperatures. Habitat suitability ratings were based on the brook trout's capacity for growth and survival at different temperatures (Table 5). Streams rated as " status 1" were predicted to be between 11°C and 16.5°C, the optimal thermal range for brook trout growth (Raleigh, 1982). Streams assigned a rating of " status 2" were predicted to be between 16.5°C and 20°C, where brook trout experience reduced rates of growth compared to the optimal growth range. Streams designated as "3" were predicted to be between

20.5°C and 25.3°C, within this temperature range brook trout are capable of survival, but the energetic demands of living above their optimal thermal range inhibit all growth (Baldwin, 1957). Streams designated as "4" were predicted to be 25.3°C or higher, indicating that brook trout were no longer capable of survival within the stream (Fry et al., 1946).

TABLE 5. Thermal habitat status designations (thermal habitat status), their corresponding temperature range (temperature range), and the brook trout growth rate they represent (growth status) (Raleigh, 1982, Power, 1980, Fry et al., 1946).

Brook Trout Thermal Habitat Status Designation Chart		
Thermal Habitat Status	**Temperature Range**	**Growth Status**
1	$11 \leq °C \leq 16.5$	Highest rate of growth
2	$16.5 < °C \leq 20.5$	Reduced rate of growth
3	$20.5 < °C \leq 25.3$	No growth
4	$°C \geq 25.3$	Extirpation

Current Stream Temperatures

To determine the accuracy of the model, I compared the reported projected[5] stream temperatures for the years 2006 and 2012 to field measured (actual) average monthly stream temperatures for the same month and year. The field measured stream temperature data were provided by the NECSC database. Each gage within this database was identified by a NorEast ID. The NECSC database does not include gage data for the state of North Carolina, however. Therefore, the gage data used for Deep Creek, NC was retrieved from the United States Geological Survey's (USGS) National Water Information System (http://waterdata.usgs.gov/nwis).

[5] When field measured data were not available for the month projected to produce the warmest stream temperatures (reported stream temperature), I used the next warmest summer month for which field measured data was available.

Baseflow & Stream Order

I hypothesized that since baseflow contribution and stream order can influence stream temperature, the results of the air temperature based SP model were likely to deviate from field measured stream temperatures. The field measured temperatures for streams with high levels of groundwater input would cooler than predicted by the model, and high order streams were likely to be more accurately predicted by the model. Therefore, I collected data on percent groundwater contribution within each high quality subwatershed (HUC12) and the Strahler stream order of each gaged stream.

Percent groundwater contribution for each subwatershed was calculated as an area weighted average. Stream segments with known percent groundwater contribution to baseflow were multiplied by the local catchment area and the sum of these values was divided by the total area of the subwatershed. Strahler stream order for each gaged stream was determined using the ArcMap tool in ArcMap 10.2.1 software.

Individual Models

To further determine the accuracy of the models, individualized linear regression models were created using field measured stream temperature and air temperature data for a small subset of the high quality stream sites. I created linear regression models only for those streams represented by USGS operated stream temperature gages and retrieved available average monthly stream temperatures (°C) for the month of August between the years 2000 and 2014 using the USGS's National Water Information System. I selected August because the three CCMs predict August to be the warmest month in most of the studied subbasins by 2056 and the outputs of the individualized linear models should reflect the most strenuous future thermal conditions for brook trout.

Average August air temperatures from 2000 to 2014 were retrieved from The National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (http://www.ncdc.gov). This website allows access to weather gage stations across the United States and allows the user a variety of different methods in searching for the desired information. I chose to search for weather stations by subbasin. Since each subbasin included several weather gages, I chose one gage from each with collected monthly average air temperature data from between 2000 and 2014. If more than one gage fit these criteria, I chose the first gage listed.

With field-measured air and stream temperatures, I created linear regression models to predict stream temperatures from air temperatures for each stream. Those with fewer than four data points were removed from this portion of the study. I input air temperatures projected by the three CCMs into each individualized linear regression model to predict stream temperatures for 2006 and 2056.

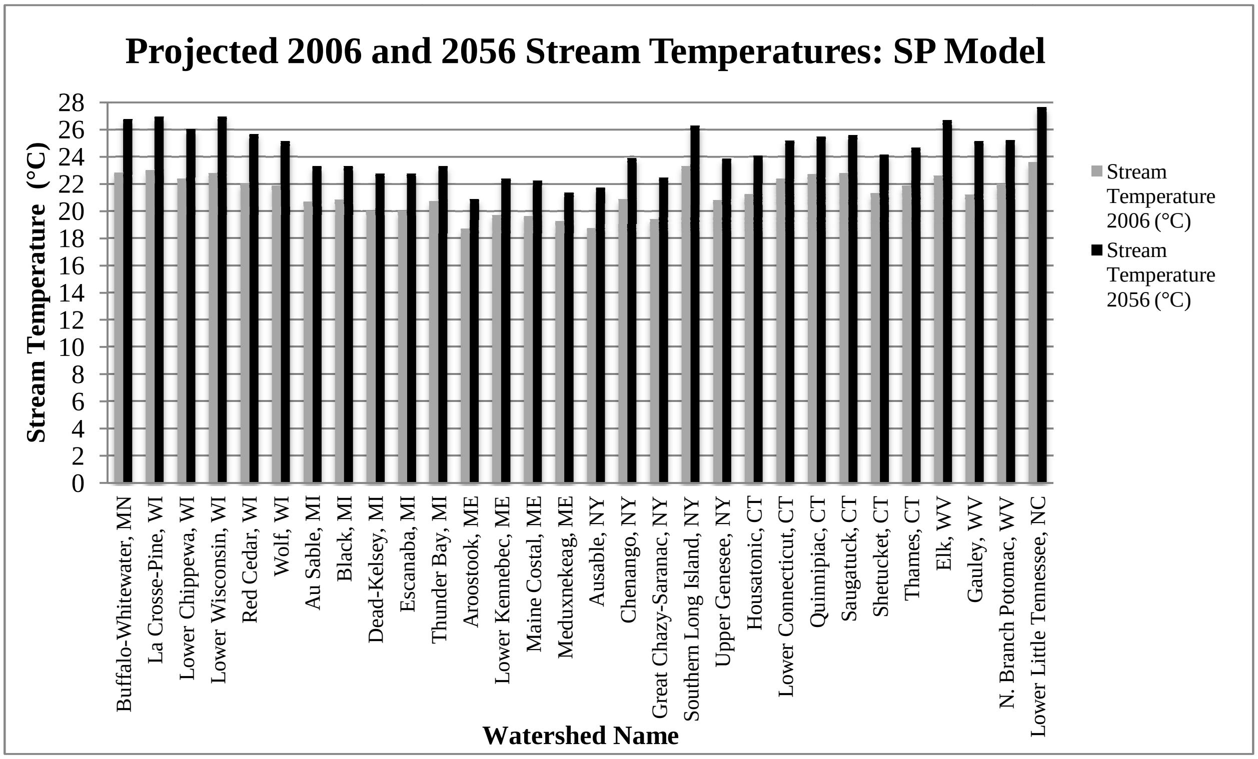
Results

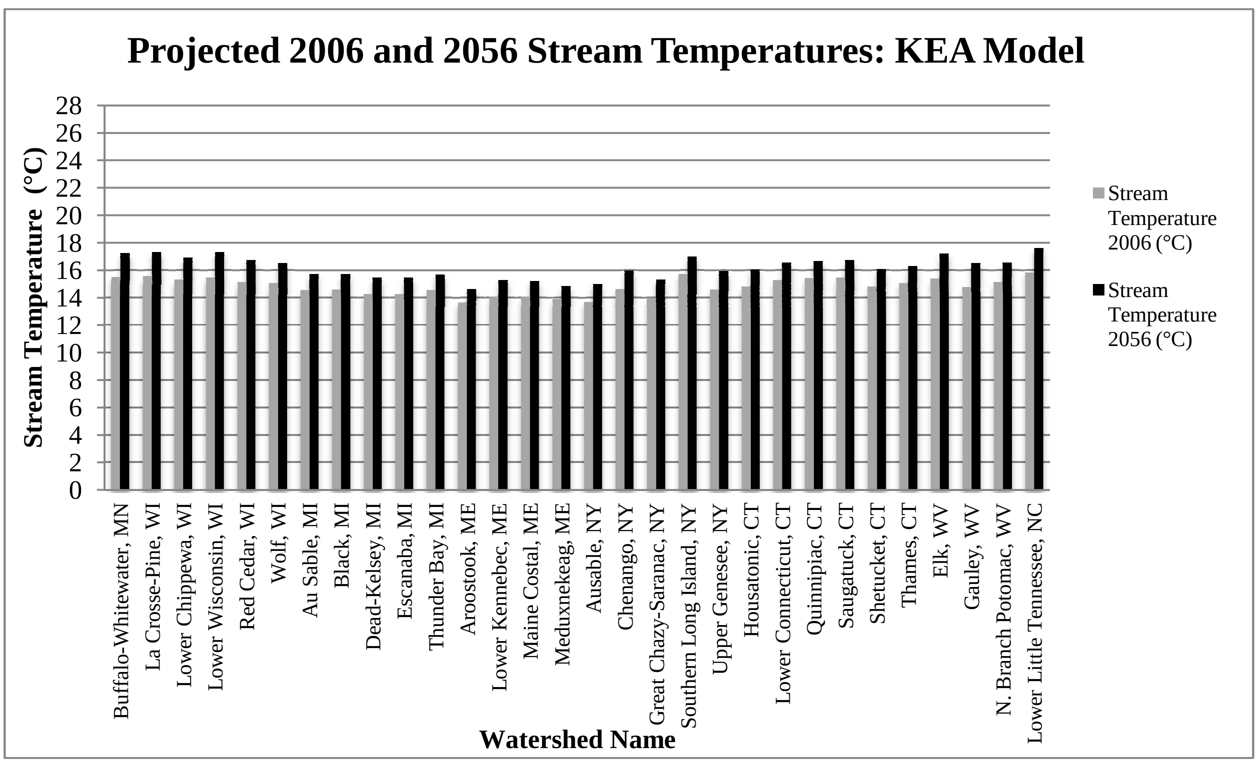
Changes in Stream Temperature and Thermal Habitat Suitability for Brook Trout

Stream temperatures predicted by the Stefan and Preud'homme[6] (1993) air-water temperature linear regression model (SP model) increased for all 30 subbasins between the beginning of the study period in 2006 and the end in 2056; 29 of 30 increased by more than 2.16°C. The range of cumulative stream temperature change between these years was from 2.11°C to 4.16°C, with an average change of 3.08°C (Figure 10). Meduxnekeag (ME) was the only subbasin not to experience a projected stream temperature change greater than 2.16°C over the course of the study, with a total change of 2.11°C.

[6] The SP model represents predominantly surface water streams, as stream temperature predictions using this model are much closer to air temperatures than those predicted by models developed for groundwater dominated streams, like the KEA model.

FIGURE 10. Stream temperatures projected for the years 2006 and 2056 for the 51 study streams using both the Stefan and Preud'homme (1993) (SP model) and Krider et al. (2013) (KEA model) air-stream temperature linear regression equations.





Between 2006 and 2012, 26 subbasins increased in temperature and four decreased, however, none of these changes were greater than 2.16°C. The range of stream temperature change during this first study period was -0.87°C to 1.36°C, with an average change of 0.67°C.

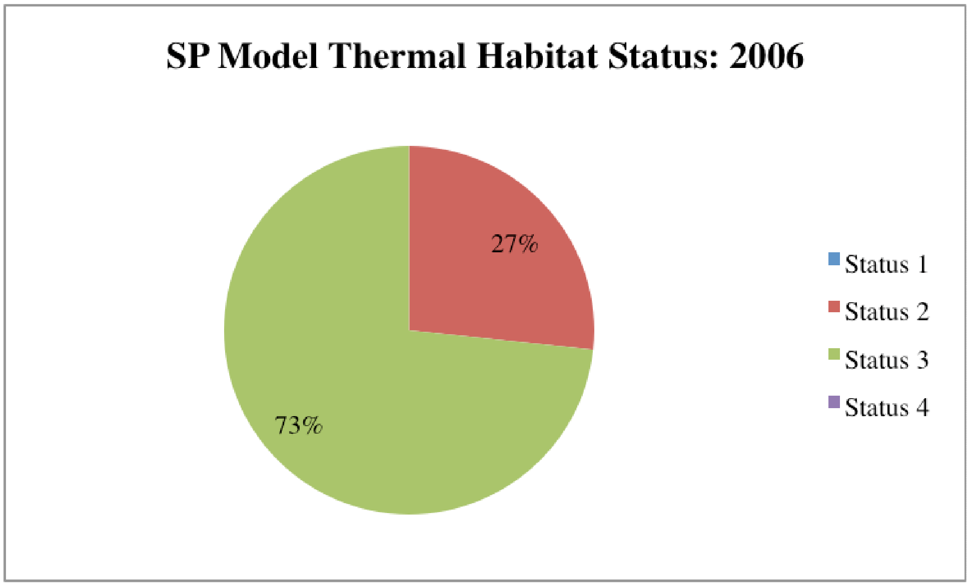
The first change in stream temperature greater than 2.16°C was recorded between the years 2012 and 2026, when the Lower Little Tennessee (NC) subbasin increased in temperature by 2.61°C. This second study period seemed to be characterized by a high number of stream cooling events, with 21subbasins cooling and only nine warming. The range of temperature change between 2012 and 2056 was -1.44°C to 1.36°C, with an average change of -0.05°C.

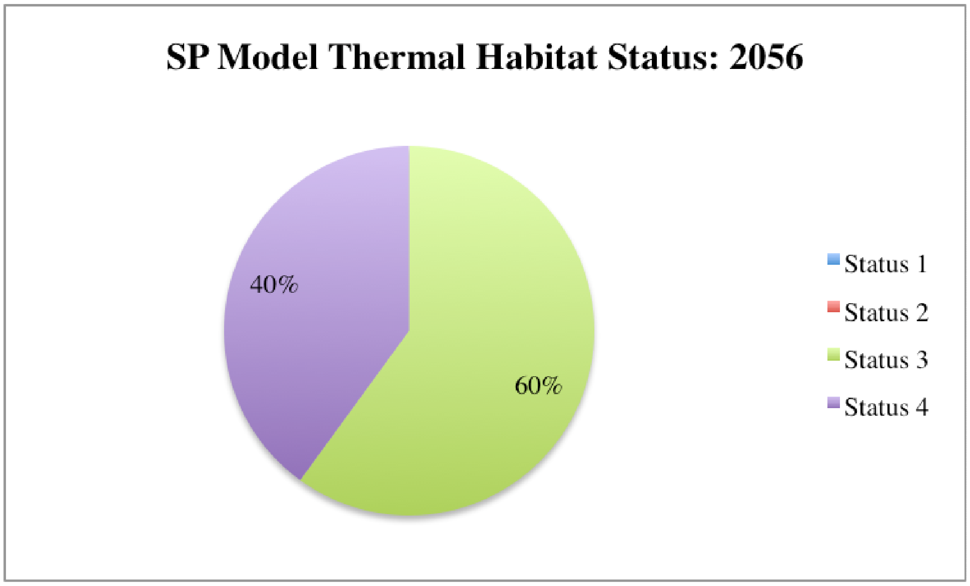
Between 2026 and 2056 the subbasins experienced the greatest increase in stream temperature between study years. During this time, all 30 subbasins increased in temperature, with 21 of these changes being greater than 2.16°C. The range of temperature change was between 1.86°C and 3.32°C, with an average temperature change of 2.47°C.

As a result of these changes in stream temperature, according to the SP model, 20 out of 30 subbasins containing streams currently listed as high quality brook trout habitat were given poorer habitat status designations at the end of the study in 2056 than at the beginning in 2006 (Figure 11). In essence, 20 out of 30 subbasins became warmer by more than 2.16°C and less conducive to brook trout growth and survival.

Chronologically, changes in habitat status designation were rare at the beginning of the study and most prominently observed between the last years of the study (2026-2056), as a result of the high number of changes in stream temperature greater than 2.16°C during this period. As such, there were four changes in status designation during the 2006-2012 study period, one status change during the 2012-2006 study period, and 19 status changes during the 2026-2056 study period.

Figure 11. Change in thermal habitat status for brook trout between the years 2006 and 2056 predicted by the SP model. Thermal habitat status designations are described in Table 5.





Of the 20 subbasins that became less suitable for brook trout growth and survival between 2006 and 2056, eight subbasins initially supporting brook trout growth (status 2) in 2006 could no longer sustain brook trout growth by 2056 (status 3) and 12 subbasins with thermal conditions allowing for species survival in 2006 (status 3) increased in temperature beyond the brook trout's upper thermal limit (status 4). Ten subbasins did not change status during this time period, although each increased in temperature. All ten remained at temperatures allowing for fish survival, but not growth (status 3) between the beginning and end of the study. The projected changes in stream temperature and thermal habitat status made by the SP model are listed in Table 6.

On the other hand, as would be expected of a model developed to predict temperatures for groundwater dominated streams, stream temperatures projected using the Krider et al. (2013) linear regression model (KEA model) were cooler than those predicted by the SP model. Stream temperatures predicted for all 30 high quality subbasins increased, though not by more than the equation's standard deviation between 2006 and 2056[7]. The range of change between the beginning and end of the study was 0.94°C to 1.85°C, with an average change of 1.37°C (Figure 10).

Since the same CCM projected air temperatures were used in calculating stream temperatures for both linear models (SP model and the KEA model), the same stream temperature fluctuations apparent in the SP model results were also present in the KEA results. Therefore, it is only pertinent to report the range and average temperature change and changes in thermal habitat status between study years for the KEA model. During the first study period, between 2006 and 2012, the changes in stream temperatures ranged from -0.39°C to 0.61°C,

[7] When employing the KEA model predict stream temperatures, the model's standard deviation used was 4.80°C.

Table 6. Average stream temperature (Average °C) for the warmest month (Month) projected by the three coupled climate models (CCMs) and the resulting thermal habitat status designation (Status) during the years 2006, 2012, 2026, and 2056 for each high quality HUC8. The air-water temperature conversion was conducted using Stefan and Preud'homme's (1993) equation (SP).

	Projected Stream Temperatures (°C) and Thermal Habitat Status Designation (SP)											
	2006			**2012**			**2026**			**2056**		
Watershed Name	**Month**	**SP Model**	**Status**	**Month**	**SP Model**	**Status**	**Month**	**SP Model**	**Status**	**Month**	**SP Model**	**Status**
Housatonic, CT	7	21.25	3	7	22.28	3	7	21.99	3	8	24.10	3
Lower Connecticut, CT	7	22.37	3	7	23.50	3	7	23.09	3	7	25.19	3
Quinnipiac, CT	7	22.69	3	7	23.73	3	7	23.55	3	7	25.48	4
Saugatuck, CT	7	22.79	3	7	23.77	3	7	23.70	3	8	25.60	4
Shetucket, CT	7	21.33	3	7	22.50	3	7	21.97	3	7	24.16	3
Thames, CT	7	21.86	3	7	23.00	3	7	22.56	3	7	24.66	3
Aroostook, ME	7	18.70	2	7	20.07	2	8	18.62	2	8	20.88	3
Meduxnekeag, ME	7	19.26	2	7	20.52	3	8	19.18	2	8	21.37	3
Lower Kennebec, ME	7	19.68	2	7	21.02	3	8	20.03	2	7	22.37	3
Maine Costal, ME	7	19.62	2	7	20.72	3	8	20.16	2	8	22.22	3
Dead-Kelsey, MI	7	20.04	2	7	20.25	2	7	19.78	2	8	22.74	3
Escanaba, MI	7	20.04	2	7	20.13	2	7	19.85	2	8	22.75	3
Black, MI	7	20.85	3	7	21.06	3	7	21.03	3	8	23.31	3
Thunder Bay, MI	7	20.75	3	7	21.06	3	7	21.18	3	8	23.28	3
Au Sable, MI	7	20.69	3	7	20.92	3	7	21.05	3	8	23.28	3
Buffalo-Whitewater, MN	7	22.81	3	7	23.54	3	7	23.50	3	8	26.76	4
Lower Little Tennessee, NC	8	23.60	3	7	22.73	3	7	25.34	4	7	27.63	4
Ausable, NY	7	18.75	2	7	19.96	2	7	19.20	2	8	21.74	3
Great Chazy-Saranac, NY	7	19.41	2	7	20.62	3	7	19.89	2	8	22.45	3
Southern Long Island, NY	7	23.30	3	7	24.28	3	7	24.23	3	8	26.27	4
Chenango, NY	7	20.90	3	7	21.53	3	7	21.34	3	8	23.91	3
Upper Genesee, NY	7	20.78	3	7	20.85	3	7	21.26	3	8	23.85	3
Wolf, WI	7	21.88	3	7	22.47	3	7	22.20	3	8	25.13	3
La Crosse-Pine, WI	7	23.00	3	7	23.73	3	7	23.87	3	8	26.94	4
Lower Chippewa, WI	7	22.39	3	7	23.21	3	7	22.81	3	8	26.03	4
Red Cedar, WI	7	22.05	3	7	22.86	3	7	22.35	3	8	25.66	4
Lower Wisconsin, WI	7	22.78	3	7	23.47	3	7	23.87	3	8	26.94	4
North Branch Potomac, WV	7	22.00	3	7	21.92	3	7	23.35	3	8	25.21	4
Gauley, WV	8	21.20	3	7	21.06	3	7	22.64	3	8	25.15	4
Elk, WV	7	22.61	3	7	22.56	3	7	24.12	3	8	26.68	4

with an average change of 0.30°C. Stream temperature change decreased during the second study period (2012-2026), cooling streams by -0.02°C on average. The range of change during this period was -0.64°C to 1.16°C. During the last study period (2026-2056) the greatest increases in stream temperature were observed, with temperature changes ranging from 0.83°C to 1.47°C and 1.10°C on average. It is important to note, however, than none of the changes in stream temperature were outside the equation's standard deviation.

When using the KEA model to predict stream temperatures, changes in stream temperature resulted in 15 changes in thermal habitat status between the beginning and the end of the study (2006-2056) (Figure 12). The first change in thermal habitat status, was again for the Lower Little Tennessee subbasin (NC) between 2012 and 2026, when it changed from optimal brook trout habitat (status 1) to habitat allowing for reduced growth rate (status 2). The remaining changes in habitat status occurred during the third study period between 2026 and 2056. All 15 reductions in thermal habitat status were a degradation from optimal habitat (status 1) to reduced growth conditions (status 2). The projected changes in stream temperature and thermal habitat status made by the KEA model are listed in Table 7.

As a result of projected rising air temperatures, both the SP and KEA models predict reductions in thermal habitat quality for brook trout between 2006 and 2056. The SP model predicts that by 2056 40% of the high quality subbasins studied will be too warm to support brook trout populations during the warmest summer month, while brook trout inhabiting the remaining 60% of study subbasins will not be capable of growth during this period. The KEA model predicts that while 50% of studied subbasins will remain optimal thermal habitat for brook trout; thermal habitat quality for the other 50% of streams will be reduced. As such, I conclude that whether the high quality streams are predominantly surface water or groundwater dominated, rising air temperatures related to climate change, overtime, will lead to substantial reductions in the quality of thermal habitat available to brook trout; ultimately resulting in extensive changes in their current distribution and productivity in the United States.

Figure 12. Change in thermal habitat status for brook trout between the years 2006 and 2056 predicted by the KEA model. Thermal habitat status designations are described in Table 5.

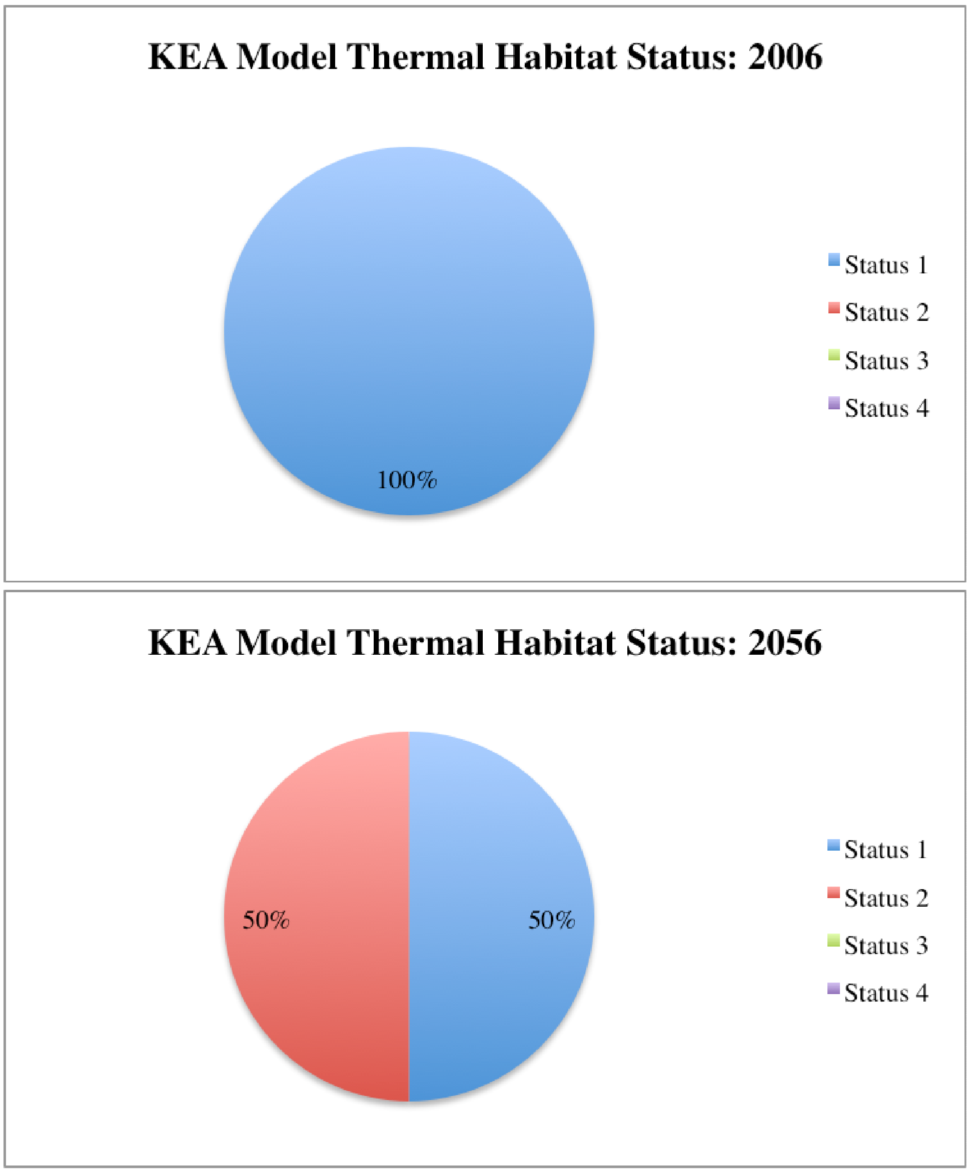


Table 7. Average stream temperature (Average °C) for the warmest month (Month) projected by the three coupled climate models (CCMs) and the resulting thermal habitat status designation (Status) during the years 2006, 2012, 2026, and 2056 for each high quality HUC8. The air-water temperature conversion was conducted using Krider et al.'s (2013) equation (KEA).

	Projected Stream Temperatures (°C) and Thermal Habitat Status Designation (KEA)											
	2006			**2012**			**2026**			**2056**		
Watershed Name	**Month**	**KEA Model**	**Status**	**Month**	**KEA Model**	**Status**	**Month**	**KEA Model**	**status**	**Month**	**KEA Model**	**Status**
Housatonic, CT	7	14.78	1	7	15.23	1	7	15.11	1	8	16.04	1
Lower Connecticut, CT	7	15.27	1	7	15.77	1	7	15.59	1	7	16.53	2
Quinnipiac, CT	7	15.42	1	7	15.88	1	7	15.80	1	7	16.65	2
Saugatuck, CT	7	15.46	1	7	15.90	1	7	15.87	1	8	16.71	2
Shetucket, CT	7	14.81	1	7	15.33	1	7	15.10	1	7	16.07	2
Thames, CT	7	15.05	1	7	15.56	1	7	15.36	1	7	16.29	2
Aroostook, ME	7	13.64	1	7	14.25	1	8	13.61	1	8	14.61	1
Meduxnekeag, ME	7	13.89	1	7	14.45	1	8	13.86	1	8	14.83	1
Lower Kennebec, ME	7	14.08	1	7	14.67	1	8	14.23	1	7	15.27	1
Maine Costal, ME	7	14.05	1	7	14.54	1	8	14.29	1	8	15.21	1
Dead-Kelsey, MI	7	14.24	1	7	14.33	1	7	14.13	1	8	15.44	1
Escanaba, MI	7	14.24	1	7	14.28	1	7	14.15	1	8	15.44	1
Black, MI	7	14.60	1	7	14.69	1	7	14.68	1	8	15.69	1
Thunder Bay, MI	7	14.55	1	7	14.69	1	7	14.74	1	8	15.68	1
Au Sable, MI	7	14.53	1	7	14.63	1	7	14.69	1	8	15.68	1
Buffalo-Whitewater, MN	7	15.47	1	7	15.80	1	7	15.78	1	8	17.22	2
Lower Little Tennessee, NC	8	15.82	1	7	15.43	1	7	16.59	2	7	17.61	2
Ausable, NY	7	13.67	1	7	14.20	1	7	13.87	1	8	14.99	1
Great Chazy-Saranac, NY	7	13.96	1	7	14.50	1	7	14.17	1	8	15.31	1
Southern Long Island, NY	7	15.69	1	7	16.12	1	7	16.10	1	8	17.01	2
Chenango, NY	7	14.62	1	7	14.90	1	7	14.82	1	8	15.96	1
Upper Genesee, NY	7	14.57	1	7	14.60	1	7	14.78	1	8	15.93	1
Wolf, WI	7	15.05	1	7	15.32	1	7	15.20	1	8	16.50	1
La Crosse-Pine, WI	7	15.55	1	7	15.88	1	7	15.94	1	8	17.31	2
Lower Chippewa, WI	7	15.28	1	7	15.65	1	7	15.47	1	8	16.90	2
Red Cedar, WI	7	15.13	1	7	15.49	1	7	15.27	1	8	16.74	2
Lower Wisconsin, WI	7	15.46	1	7	15.76	1	7	15.94	1	8	17.30	2
North Branch Potomac, WV	7	15.11	1	7	15.07	1	7	15.71	1	8	16.54	2
Gauley, WV	8	14.75	1	7	14.69	1	7	15.39	1	8	16.51	2
Elk, WV	7	15.38	1	7	15.36	1	7	16.05	1	8	17.19	2

Stream Temperature Model Validation

When I used the SP model to predict stream temperatures, of the 37 streams with field measured stream temperature available for the year 2006, the field measured temperatures of 16 streams (43%) were warmer than predicted (under-predicted) and 21 (57%) were cooler than predicted (over-predicted). The actual temperatures of the16 under-predicted streams ranged from 0.02°C to 5.30°C higher than projected, with an average under-prediction of 1.76°C. Of the 21 over-predicted streams, actual stream temperatures ranged from 0.04°C to 6.72°C cooler than predicted, with an average over-prediction of 2.39°C.

Only 12 of the 37 streams (32%) were under *or* over-predicted, however, in accordance with the model's standard deviation. The standard deviation of the SP model was 2.16°C. Therefore, I considered any actual stream temperature beyond +/- 2.16°C of the projection value to be under or over-predicted by this measure. Of these 12 streams, the field measured temperatures of four were warmer than the upper bound of the SP standard deviation by between 0.34°C and 3.14°C (average 1.29°C). The field measured temperatures of eight streams were cooler than predicted by between 0.92°C and 4.56°C (average 2.5°C) below the lower bound of the standard deviation (Figures 11 and 12).

In 2012, like 2006, more streams were over predicted by model than were under-predicted. During this year, nine out of 22 streams were under-predicted by between 1.26°C and 4.26°C, with an average under-prediction of 2.59°C. The other thirteen streams were over predicted by between 0.55°C and 7.51°C, with an average over prediction of 3.01°C.

Twelve of the 22 streams were over *or* under-predicted beyond the upper and lower bounds of the equation's standard deviation in 2012. The four under-predicted streams were beyond the standard deviation by between 1.11°C and 2.10°C, with an average of 1.69°C beyond the standard deviation. The eight over-predicted streams were between 0.15°C and 5.35°C beyond the standard deviation, with an average of 1.75°C beyond the lower limit of the standard deviation. Figures 13-16 depict validation charts for the SP model.

The KEA model predicted much lower stream temperatures than the SP model. In 2006 all 37 streams were under predicted by the model by between 0.38°C and 10.87°C, with an average under-prediction of 5.88°C. Only 25 of these streams were cooler than the lower bound of the equation's standard deviation (4.80°C), however. The 25 under-predicted streams were between 0.18°C and 6.07°C warmer than the upper limit of the standard deviation, with an average under-prediction of 5.88°C.

Again, in 2012, all study streams with available data were under-predicted. The 22 streams with available field measured data in 2012 were between 0.60°C and 11.22°C warmer than predicted by the model. Of these 22 streams, 13 were under-predicted by between 0.61°C and 11.22°C beyond the standard deviation, with an average under-prediction of 5.87°C. Figures 17-20 depict validation charts for the KEA model. The field measured and projected stream temperatures (SP model and KEA model) for all sites in 2006 are summarized in Table 8 and those for 2012 are listed in Table 9.

Individualized Air-Stream Temperature Linear Regression Models

I created individualized air-stream temperature linear regression models (I-models) for eight streams, a subset of the 51 high quality brook trout streams selected for the study as a whole. Customized linear regression models best explain the relationship between air and stream temperatures for each individual stream, therefore they should more accurately predict stream temperatures than more generally applied models would. Thus, I created these I-models to compare with the SP model, to determine how consistent the results between the two models

FIGURE 13. Comparison between field measured (actual) stream temperature (°C) data and stream temperature projections made using the Stefan and Preud'homme (1993) (SP) model for the year 2006. Data is sorted by percent groundwater contribution to baseflow for each stream from least to greatest.

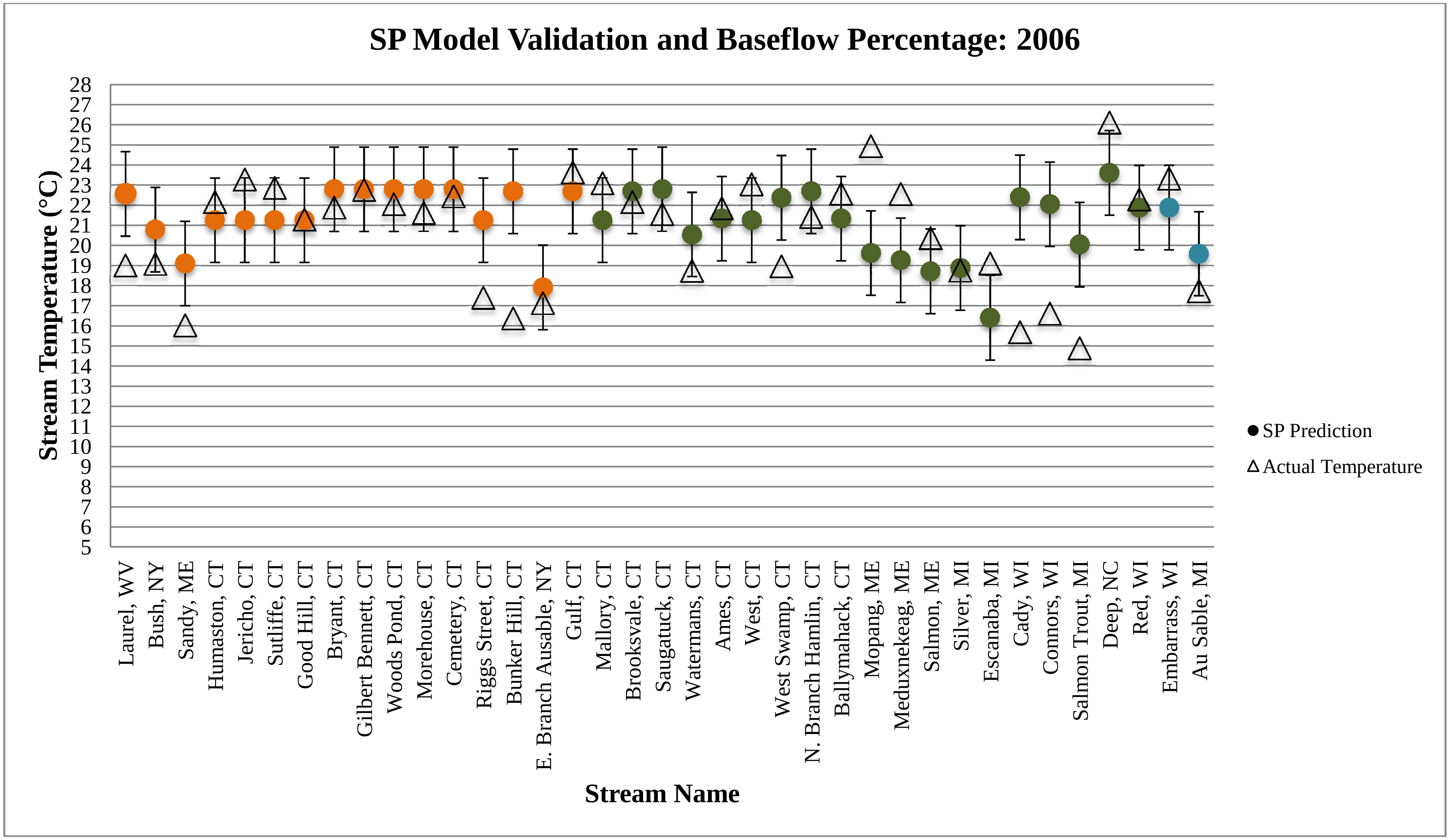


FIGURE 14. Comparison between field measured (actual) stream temperature (°C) data and stream temperature projections made using the Stefan and Preud'homme (1993) (SP) model for the year 2006. Data is sorted by the Strahler stream order for each gaged stream, from highest to lowest order.

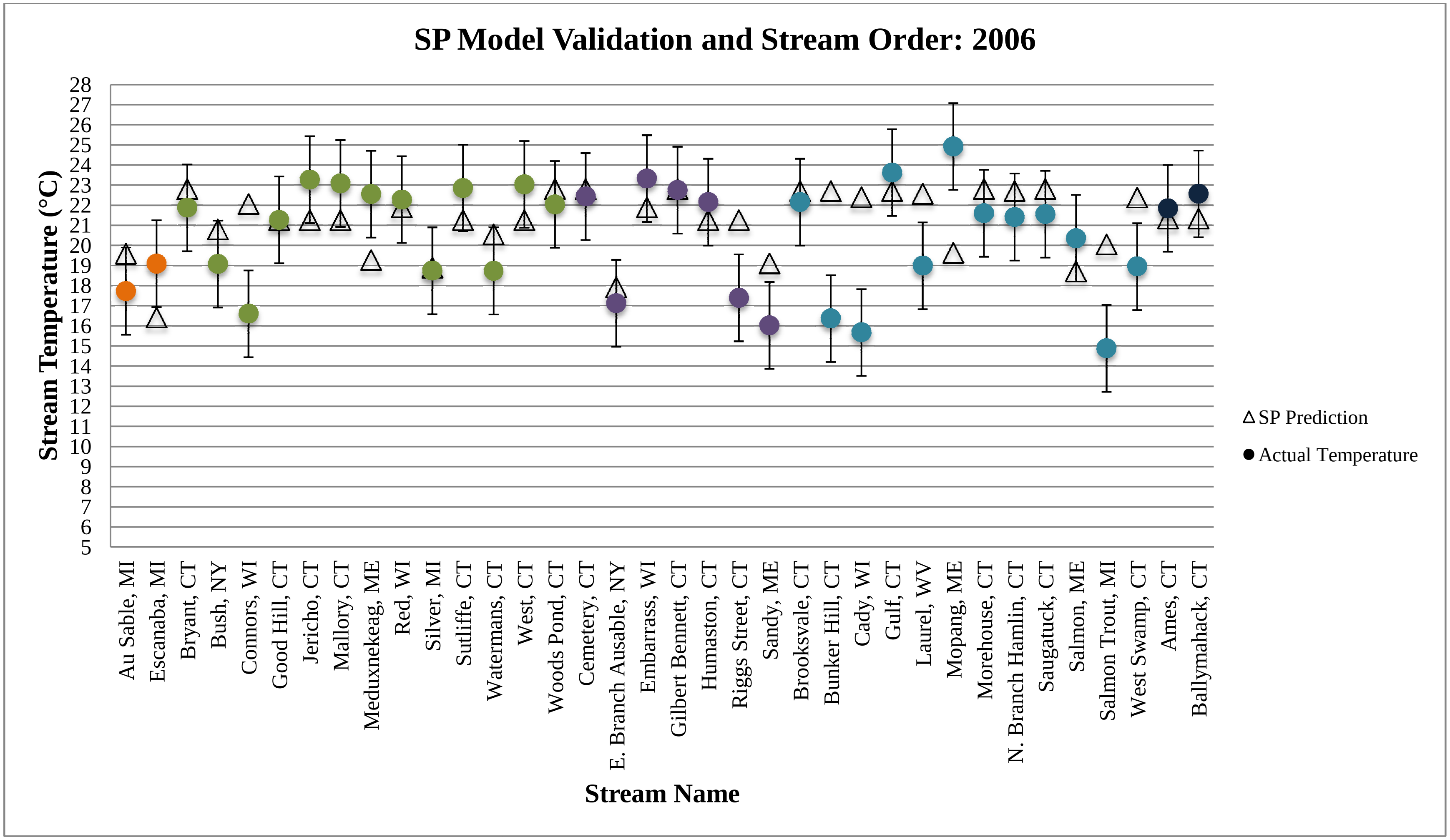


FIGURE 15. Comparison between field measured (actual) stream temperature (°C) data and stream temperature projections made using the Stefan and Preud'homme (1993) (SP) model for the year 2012. Data is sorted by percent groundwater contribution to baseflow for each stream from least to greatest.

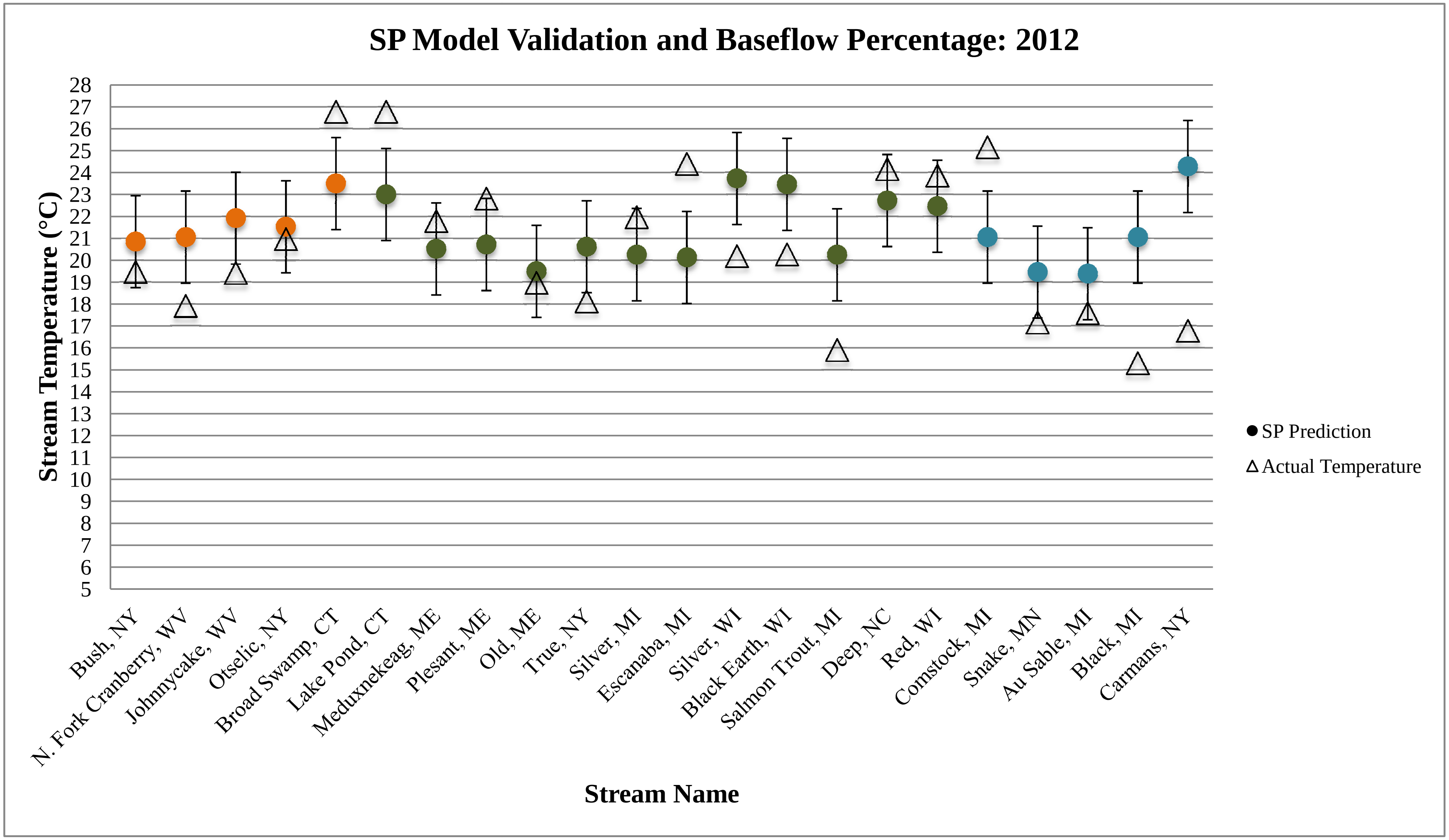


FIGURE 16. Comparison between field measured (actual) stream temperature (°C) data and stream temperature projections made using the Stefan and Preud'homme (1993) (SP) model for the year 2012. Data is sorted by the Strahler stream order for each gaged stream, from highest to lowest order.

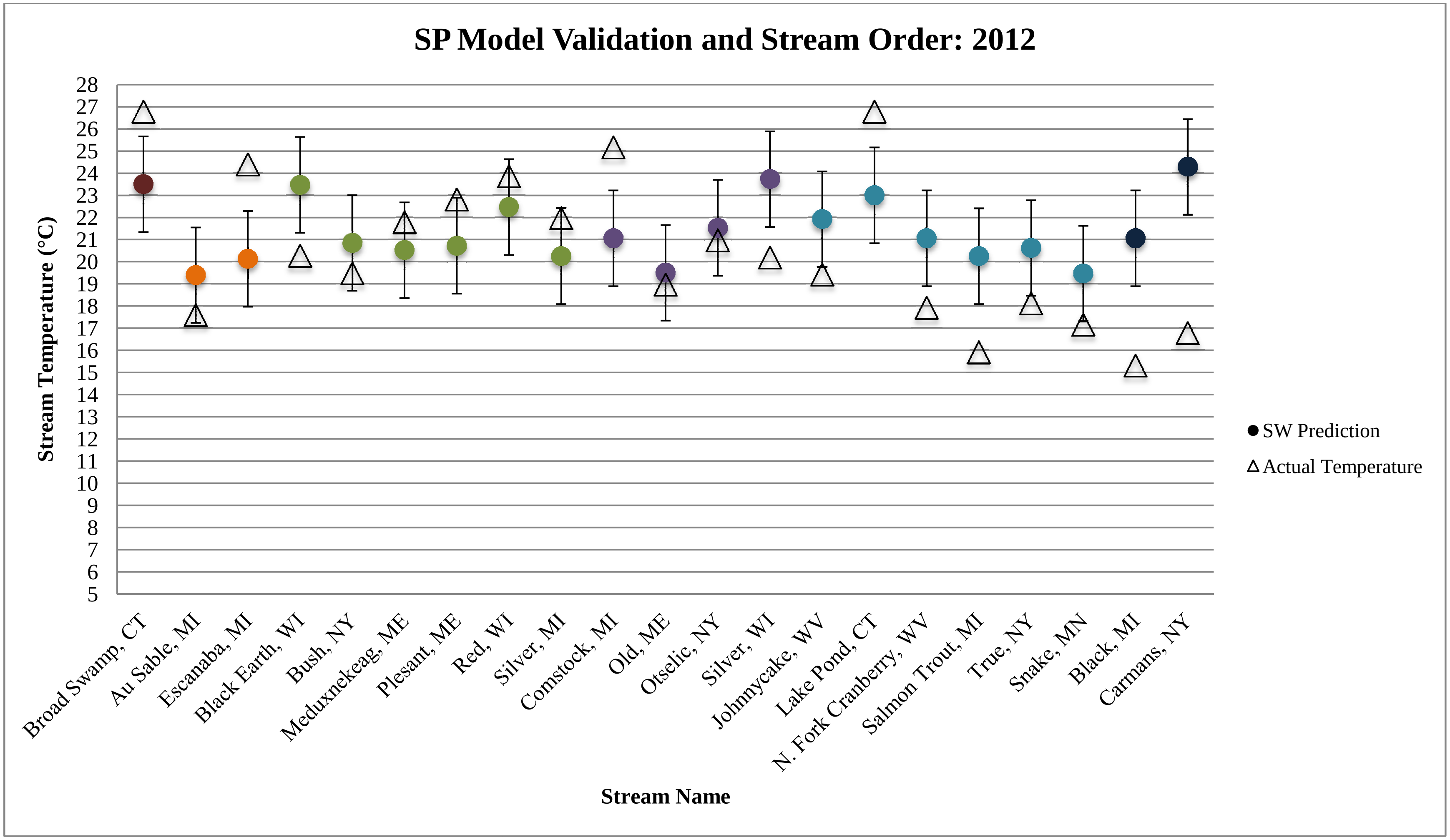


FIGURE 17. Comparison between field measured (actual) stream temperature (°C) data and stream temperature projections made using the Krider et al. (2013) (KEA) model for the year 2006. Data is sorted by percent groundwater contribution to baseflow for each stream from least to greatest.

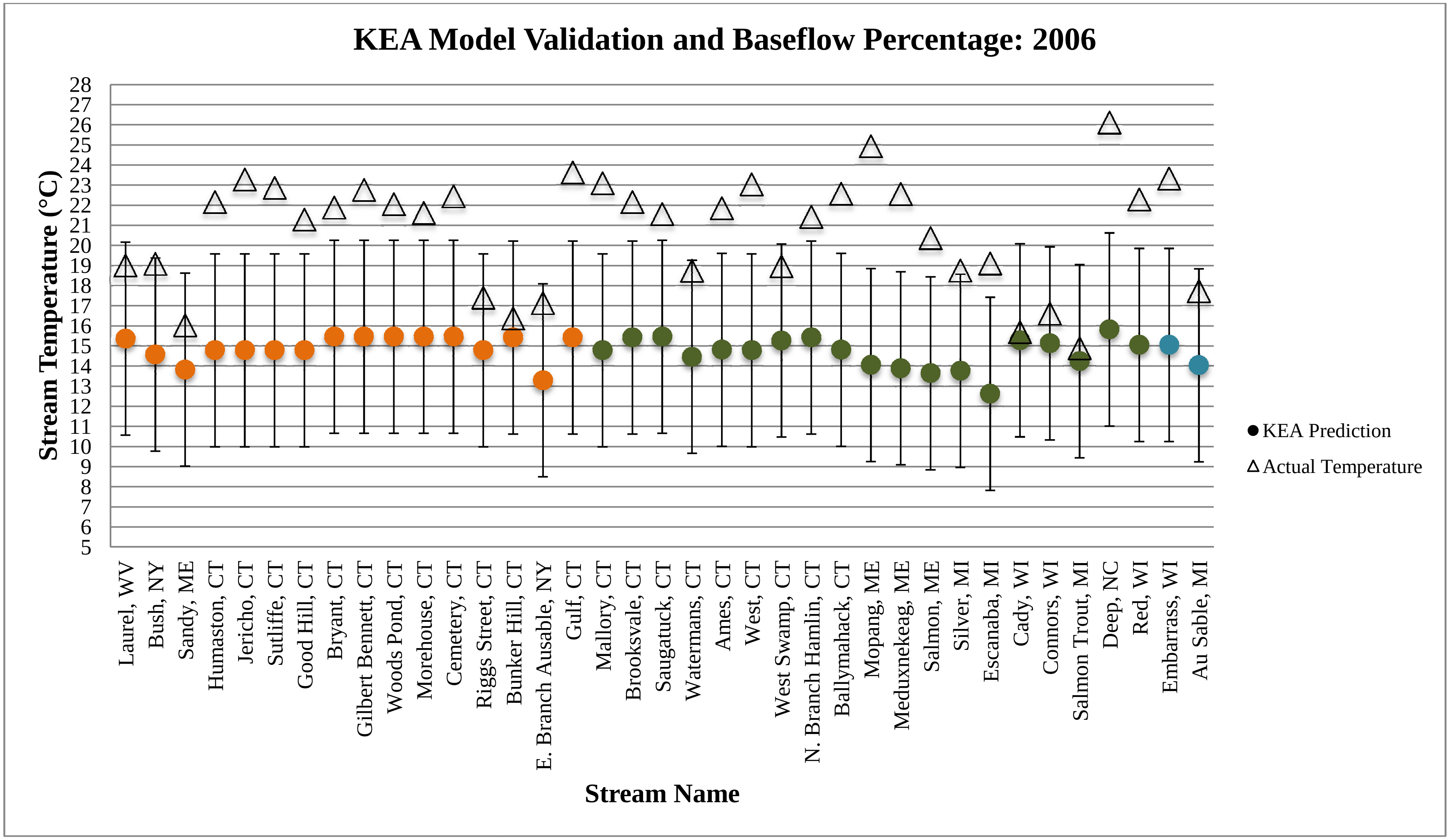


FIGURE 18. Comparison between field measured (actual) stream temperature (°C) data and stream temperature projections made using the Krider et al. (2013) (KEA) model for the year 2006. Data is sorted by the Strahler stream order for each gaged stream, from highest to lowest order.

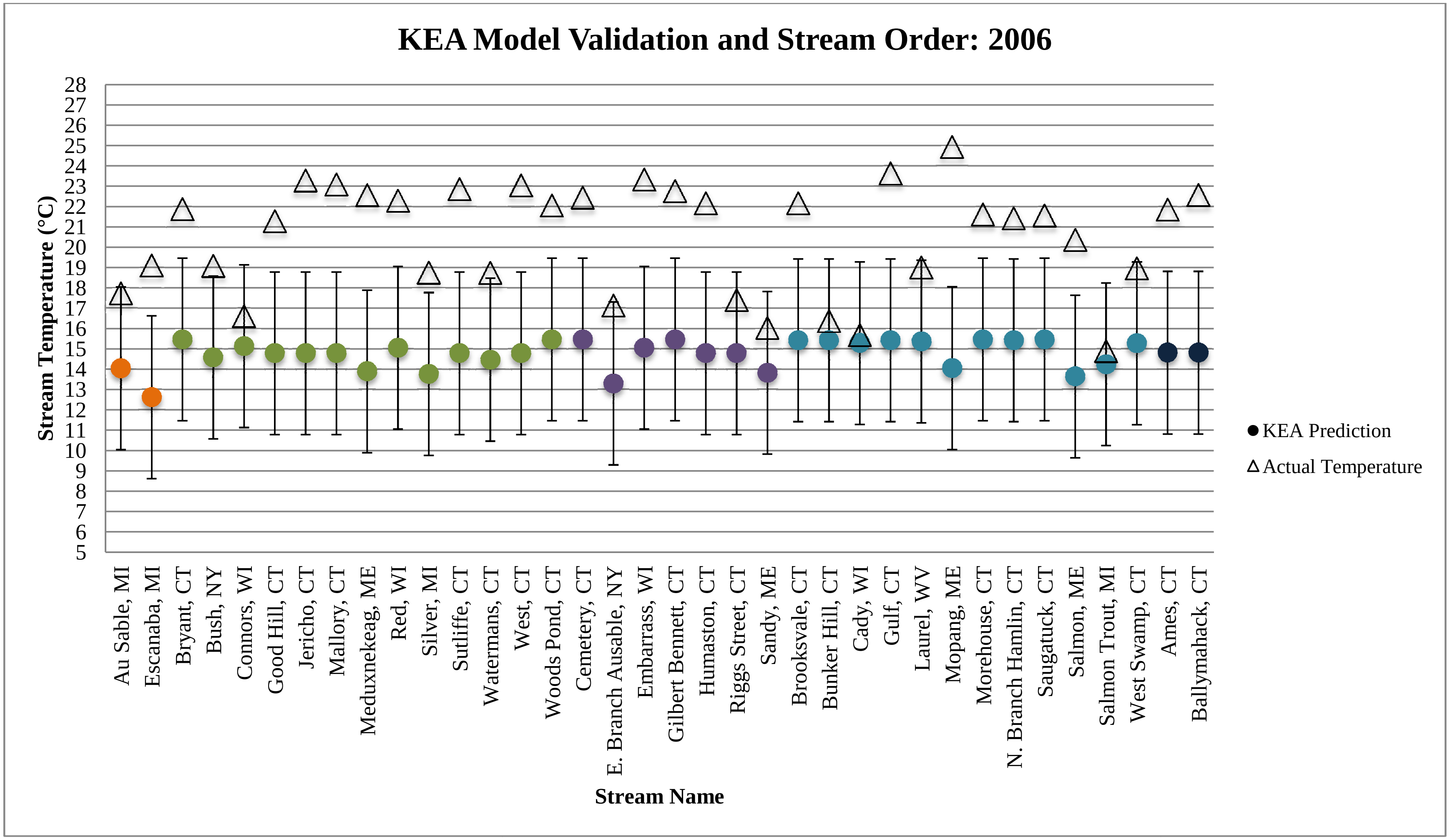


FIGURE 19. Comparison between field measured (actual) stream temperature (°C) data and stream temperature projections made using the Krider et al. (2013) (KEA) model for the year 2012. Data is sorted by percent groundwater contribution to baseflow for each stream from least to greatest.

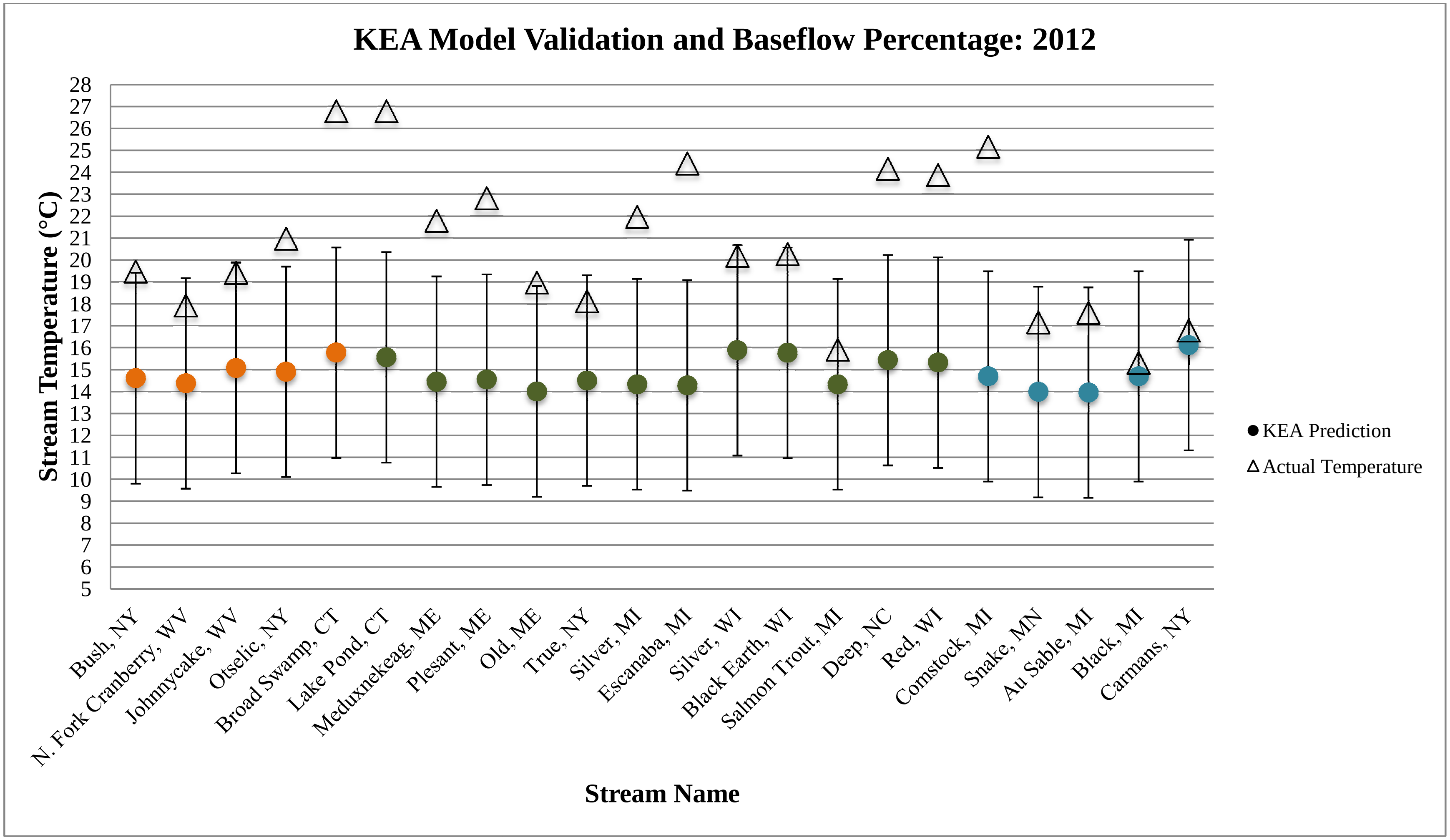


FIGURE 20. Comparison between field measured (actual) stream temperature (°C) data and stream temperature projections made using the Krider et al. (2013) (KEA) model for the year 2012. Data is sorted by the Strahler stream order for each gaged stream, from highest to lowest order.

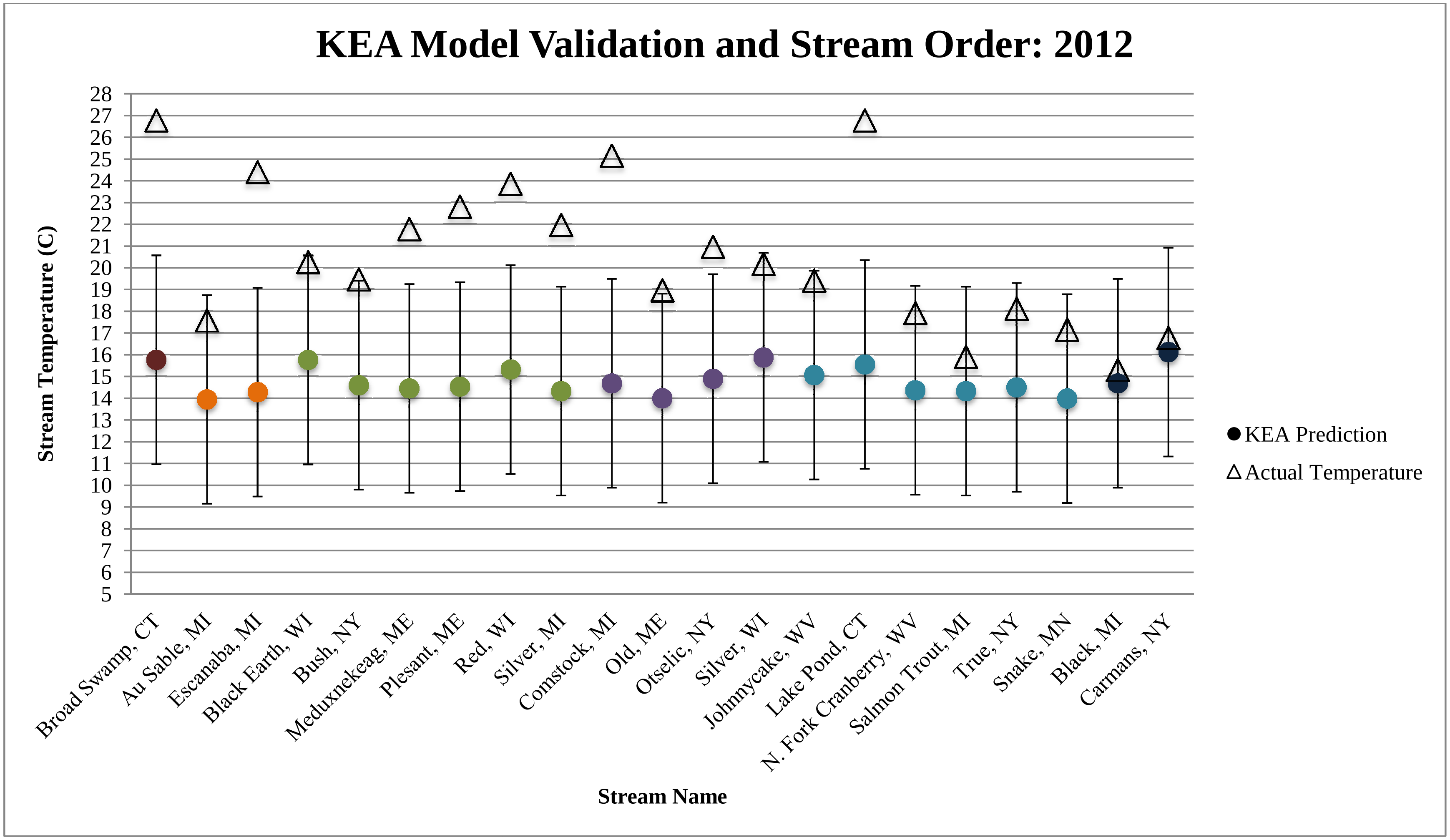


TABLE 8. Average projected stream temperatures for the years 2006 and 2012 using both the air-stream temperature conversion equations, Stefan and Preud'homme's (1993) equation (Pro. SP) and et al. (2013) equation (Pro. KEA), compared with field measured stream temperatures for both years (Actual). The month (Month) projected and actual gage temperatures are provided for is also included. "x" represents no data.

Actual Vs. Projected Stream Temperatures (°C) 2006

Stream Name	Watershed Name	Month	Actual	SP Model	KEA Model	Actual-SP Model	Actual-KEA Model
Good Hill Brook, CT	Housatonic	7	21.27	21.25	14.78	0.02	6.49
Humaston Brook, CT	Housatonic	7	22.15	21.25	14.78	0.90	7.37
Jericho Brook, CT	Housatonic	7	23.27	21.25	14.78	2.02	8.49
Mallory Brook, CT	Housatonic	7	23.08	21.25	14.78	1.83	8.30
Riggs Street Brook, CT	Housatonic	7	17.39	21.25	14.78	-3.86	2.62
Sutliffe Brook, CT	Housatonic	7	22.85	21.25	14.78	1.60	8.07
W. Brook, CT	Housatonic	7	23.03	21.25	14.78	1.79	8.26
Broad Swamp Brook, CT	Lower Connecticut	7	x	22.37	15.27	x	x
W. Swamp Brook, CT	Lower Connecticut	7	18.95	22.37	15.27	-3.42	3.68
Brooksvale Stream, CT	Quinnipiac	7	22.15	22.69	15.42	-0.54	6.73
Bunker Hill Brook, CT	Quinnipiac	7	16.36	22.69	15.42	-6.33	0.94
Gulf Brook, CT	Quinnipiac	7	23.62	22.69	15.42	0.94	8.21
N. B. Hamlin Brook, CT	Quinnipiac	7	21.41	22.69	15.42	-1.27	6.00
Watermans Brook, CT	Quinnipiac	6	18.73	20.54	14.46	-1.81	4.27
Bryant Brook, CT	Saugatuck	7	21.87	22.79	15.46	-0.92	6.41
Cemetery Brook, CT	Saugatuck	7	22.43	22.79	15.46	-0.36	6.97
Gilbert Bennett Brook, CT	Saugatuck	7	22.75	22.79	15.46	-0.04	7.29
Morehouse Brook, CT	Saugatuck	7	21.60	22.79	15.46	-1.19	6.14
N. B. W. B. Saugatuck River, CT	Saugatuck	7	21.55	22.79	15.46	-1.24	6.09
Woods Pond Brook, CT	Saugatuck	7	22.04	22.79	15.46	-0.75	6.58
Ames Brook, CT	Shetucket	7	21.84	21.33	14.81	0.52	7.03
Ballymahack Brook, CT	Shetucket	7	22.56	21.33	14.81	1.24	7.75
Lake Pond Brook, CT	Thames	7	x	21.86	15.05	x	x
Salmon Brook, ME	Aroostook	7	20.35	18.70	13.64	1.65	6.71
Meduxnekeag River, ME	Meduxnekeag	7	22.55	19.26	13.89	3.29	8.66
Sandy River, ME	Lower Kennebec	8	16.02	19.10	13.82	-3.08	2.20
Mopang Stream, ME	Maine Costal	7	24.92	19.62	14.05	5.30	10.87
Old Stream, ME	Maine Costal	7	x	19.62	14.05	x	x
Pleasant River, ME	Maine Costal	7	x	19.62	14.05	x	x
Silver River, MI	Dead-Kelsey	8	18.74	18.88	13.76	-0.14	4.98
Salmon Trout River, MI	Dead-Kelsey	7	14.88	20.04	14.24	-5.16	0.64
Escanaba River, MI	Escanaba	6	19.09	16.40	12.62	2.69	6.47

Table 8 (cont'd).							
Black River, MI	Black	7	x	20.85	14.60	x	x
Comstock Creek, MI	Thunder Bay	7	x	20.75	14.55	x	x
Au Sable River, MI	Au Sable	8	17.72	19.58	14.04	-1.87	3.68
Snake Creek, MN	Buffalo-Whitewater	7	x	22.81	15.47	x	x
Deep Creek, NC	Lower Little Tennessee	8	26.10	23.60	15.82	2.49	10.27
E. B. Ausable River, NY	Ausable	8	17.12	17.91	13.29	-0.79	3.83
True Brook, NY	Great Chazy-Saranac	7	x	19.41	13.96	x	x
Carmans River, NY	Southern Long Island	7	x	23.30	15.69	x	x
Otselic River, NY	Chenango	7	x	20.90	14.62	x	x
Bush Brook, NY	Upper Genesee	7	19.07	20.78	14.57	-1.71	4.50
Embarrass River, WI	Wolf	7	23.32	21.88	15.05	1.44	8.27
Red River, WI	Wolf	7	22.28	21.88	15.05	0.40	7.23
Silver Creek, WI	La Crosse-Pine	7	x	23.00	15.55	x	x
Cady Creek, WI	Lower Chippewa	7	15.67	22.39	15.28	-6.72	0.38
Connors Creek, WI	Red Cedar	7	16.60	22.05	15.13	-5.45	1.47
Black Earth Creek, WI	Lower Wisconsin	7	x	22.78	15.46	x	x
Johnnycake Run, WV	North Branch Potomac	7	x	22.00	15.11	x	x
N. Fork Cranberry River, WV	Gauley	8	x	21.20	14.75	x	x
Laurel Fork, WV	Elk	8	18.99	22.56	15.36	-3.57	3.63

TABLE 9. Average projected stream temperatures for the years 2006 and 2012 using both the air-stream temperature conversion equations, Stefan and Preud'homme's (1993) equation (Pro. SP) and et al. (2013) equation (Pro. KEA), compared with gage measured stream temperatures for both years (Actual). The month (Month) projected and actual gage temperatures are provided for is also included. "x" represents no data.

Actual Vs. Projected Stream Temperatures (°C) 2012							
Stream Name	**Watershed Name**	**Month**	**Actual**	**SP Model**	**KEA Model**	**Actual-SP Model**	**Actual-KEA Model**
Good Hill Brook, CT	Housatonic	7	x	22.28	15.23	x	x
Humaston Brook, CT	Housatonic	7	x	22.28	15.23	x	x
Jericho Brook, CT	Housatonic	7	x	22.28	15.23	x	x
Mallory Brook, CT	Housatonic	7	x	22.28	15.23	x	x
Riggs Street Brook, CT	Housatonic	7	x	22.28	15.23	x	x
Sutliffe Brook, CT	Housatonic	7	x	22.28	15.23	x	x
W. Brook, CT	Housatonic	7	x	22.28	15.23	x	x
Broad Swamp Brook, CT	Lower Connecticut	7	26.77	23.50	15.77	3.28	11.00

Table 9 (cont'd).

W. Swamp Brook, CT	Lower Connecticut	7	x	23.50	15.77	x	x
Brooksvale Stream, CT	Quinnipiac	7	x	23.73	15.88	x	x
Bunker Hill Brook, CT	Quinnipiac	7	x	23.73	15.88	x	x
Gulf Brook, CT	Quinnipiac	7	x	23.73	15.88	x	x
N. B. Hamlin Brook, CT	Quinnipiac	7	x	23.73	15.88	x	x
Watermans Brook, CT	Quinnipiac	7	x	23.73	15.88	x	x
Bryant Brook, CT	Saugatuck	7	x	23.77	15.90	x	x
Cemetery Brook, CT	Saugatuck	7	x	23.77	15.90	x	x
Gilbert Bennett Brook, CT	Saugatuck	7	x	23.77	15.90	x	x
Morehouse Brook, CT	Saugatuck	7	x	23.77	15.90	x	x
N. B. W. B. Saugatuck River, CT	Saugatuck	7	x	23.77	15.90	x	x
Woods Pond Brook, CT	Saugatuck	7	x	23.77	15.90	x	x
Ames Brook, CT	Shetucket	7	x	22.50	15.33	x	x
Ballymahack Brook, CT	Shetucket	7	x	22.50	15.33	x	x
Lake Pond Brook, CT	Thames	7	26.77	23.00	15.56	3.77	11.22
Salmon Brook, ME	Aroostook	7	x	20.07	14.25	x	x
Meduxnekeag River, ME	Meduxnekeag	7	21.78	20.52	14.45	1.26	7.33
Sandy River, ME	Lower Kennebec	7	x	21.02	x	x	x
Mopang Stream, ME	Maine Costal	7	x	20.72	14.54	x	x
Old Stream, ME	Maine Costal	8	18.96	19.50	14.00	-0.55	4.95
Pleasant River, ME	Maine Costal	7	22.81	20.72	14.54	2.08	8.26
Silver River, MI	Dead-Kelsey	7	21.96	20.25	14.33	1.72	7.63
Salmon Trout River, MI	Dead-Kelsey	7	15.90	20.25	14.33	-4.35	1.57
Escanaba River, MI	Escanaba	7	24.39	20.13	14.28	4.26	10.11
Black River, MI	Black Watershed	7	15.30	21.06	14.69	-5.76	0.61
Comstock Creek, MI	Thunder Bay	7	25.15	21.06	14.69	4.09	10.46
Au Sable River, MI	Au Sable	8	17.58	19.39	13.95	-1.81	3.63
Snake Creek, MN	Buffalo-Whitewater	6	17.15	19.46	13.98	-2.31	3.17
Deep Creek, NC	Lower Little Tennessee	7	24.15	22.73	15.43	1.42	8.72
E. B. Ausable River, NY	Ausable	7	x	19.96	14.20	x	x
True Brook, NY	Great Chazy-Saranac	7	18.11	20.62	14.50	-2.51	3.62
Carmans River, NY	Southern Long Island	7	16.77	24.28	16.12	-7.51	0.65
Otselic River, NY	Chenango	7	20.96	21.53	14.90	-0.58	6.05
Bush Brook, NY	Upper Genesee	7	19.46	20.85	14.60	-1.38	4.87
Embarrass River, WI	Wolf	7	x	22.47	15.32	x	x
Red River, WI	Wolf	7	23.86	22.47	15.32	1.39	8.54
Silver Creek, WI	La Crosse-Pine	7	20.18	23.73	15.88	-3.55	4.30

Table 9 (cont'd).

Cady Creek, WI	Lower Chippewa	7	x	23.21	15.65	x	x
Connors Creek, WI	Red Cedar	7	x	22.86	15.49	x	x
Black Earth Creek, WI	Lower Wisconsin	7	20.26	23.47	15.76	-3.20	4.50
Johnnycake Run, WV	North Branch Potomac	7	19.41	21.92	15.07	-2.51	4.34
N. Fork Cranberry River, WV	Gauley	7	17.91	21.06	14.37	-3.15	3.54
Laurel Fork, WV	Elk	7	x	22.56	14.37	x	x

were and to determine whether or not using generally applied models is an effective way to predict stream temperatures. The slope values for the I-models ranged from 0.47 to 1.10 and y-intercept values ranged from 0.84-11.61 (Table 10; Figures 21-28).

TABLE 10. Individualized linear regression models for eight streams created using August monthly air temperature averages collected from NOAA's National Climatic Data Center (http://www.ncdc.gov) and August monthly stream temperature averages from the USGS's National Water Information System (http://waterdata.usgs.gov/nwis). All available air and stream temperature data from the year 2000 to 2014 was used. R^2 values for each individualized linear regression model are also included in the table.

Individualized Linear Regression Models		
Stream Name	**Linear Regression Models**	**R^2**
Broad Swamp Brook, CT	1.10x+0.84	0.87
Meduxnekeag River, ME	0.87x+4.04	0.80
Silver River, MI	0.94x+1.60	0.89
Escanaba River, MI	0.47x+11.61	0.40
Au Sable River, MI	0.63x+6.08	0.74
Deep Creek, NC	0.88x+2.85	0.68
Embarrass River, WI	0.53x+10.65	0.50
Red River, WI	0.92x+2.58	0.96

I compared the outputs of these I-models to field measured stream temperatures in 2006 and 2012, using air temperatures projected by the CCMs as the input values. Of the five streams with field measured stream temperature data in 2006, four were over predicted and one was under predicted by the models. Field measured temperatures for the over predicted streams were

FIGURE 21. Individualized air-stream temperature (°C) linear regression model for Broad Swamp Creek, Connecticut (CT).

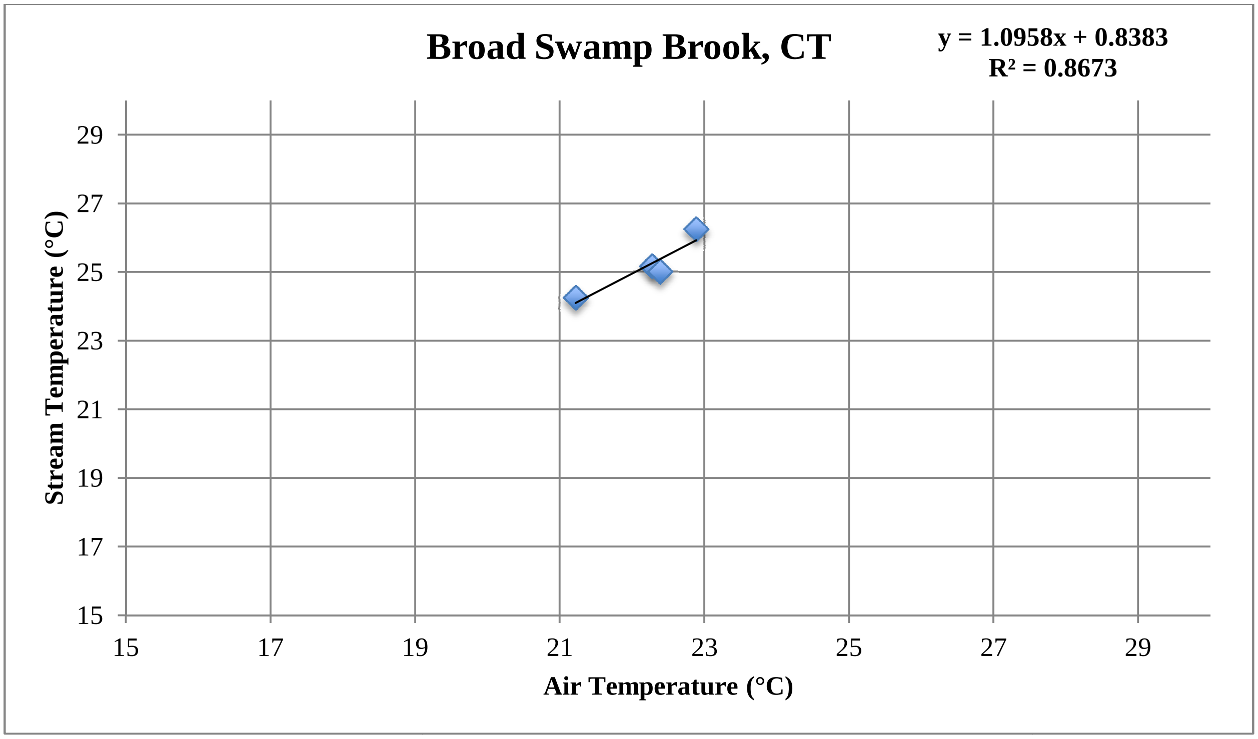


FIGURE 22. Individualized air-stream temperature (°C) linear regression model for Meduxnekeag River, Maine (ME).

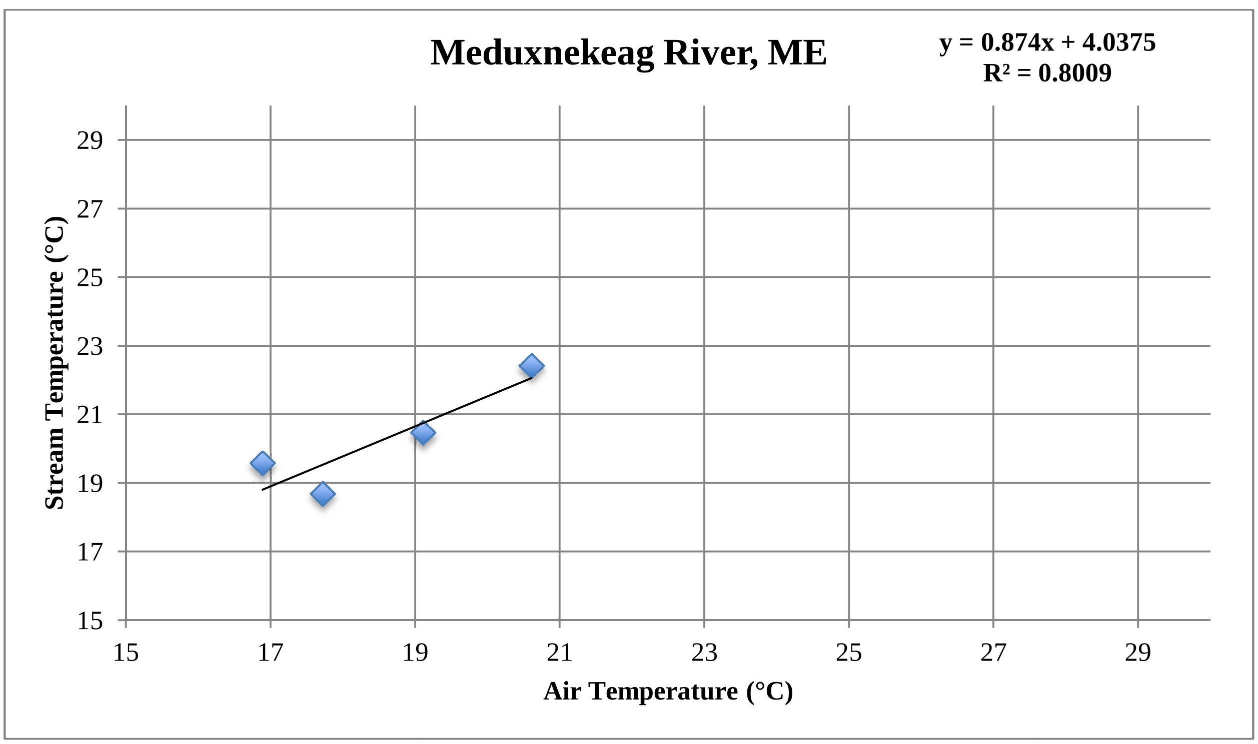


FIGURE 23. Individualized air-stream temperature (°C) linear regression model for Silver River, Michigan (MI).

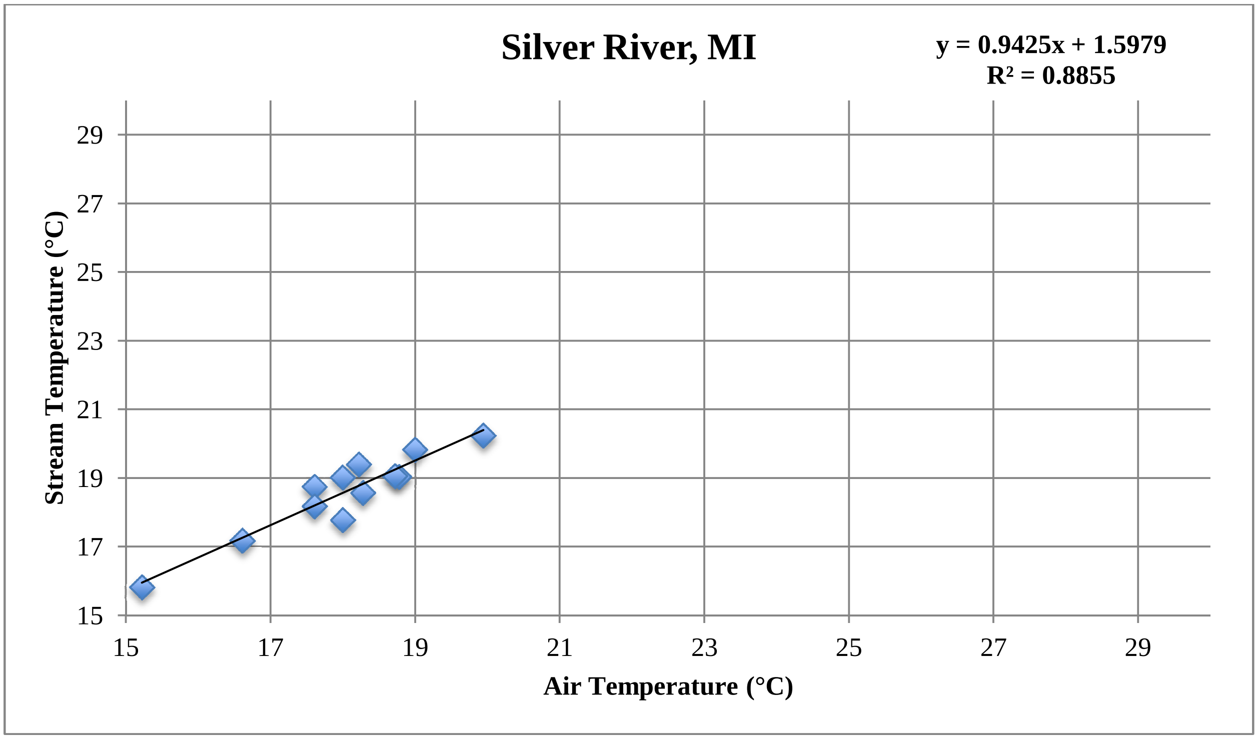


FIGURE 24. Individualized air-stream temperature (°C) linear regression model for Escanaba River, Michigan (MI).

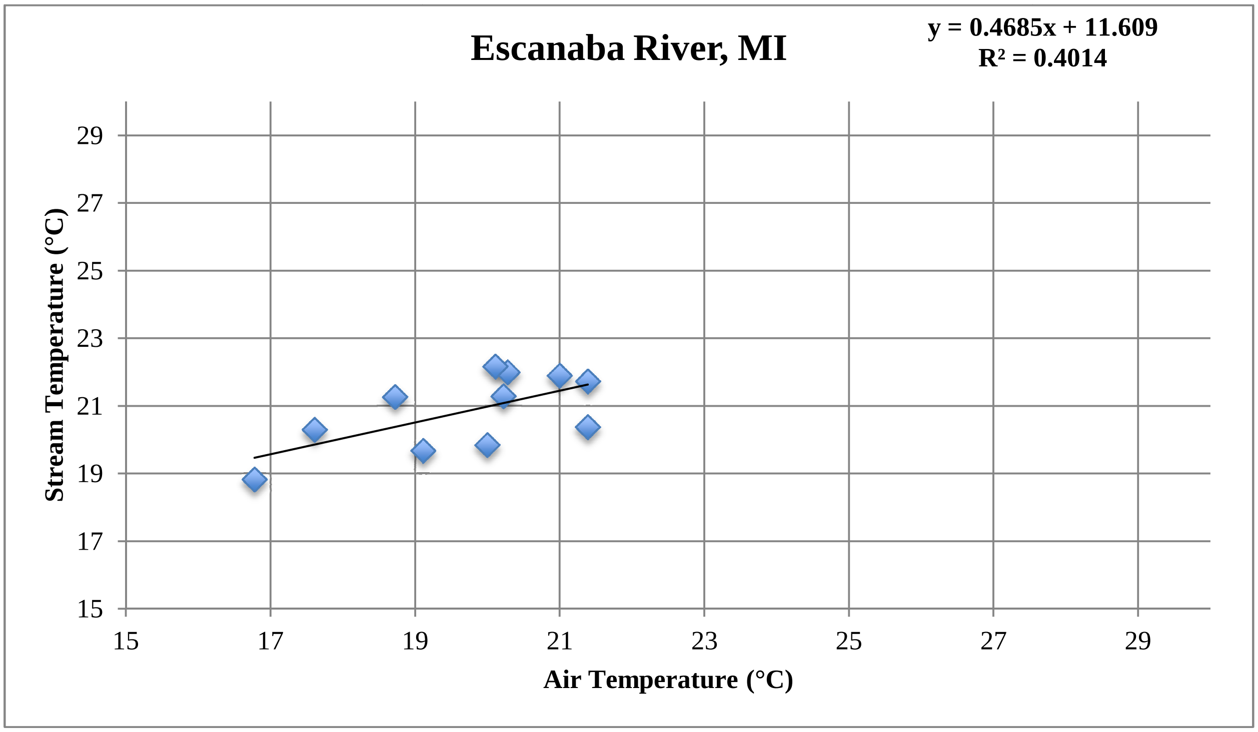


FIGURE 25. Individualized air-stream temperature (°C) linear regression model for Au Sable River, Michigan (MI).

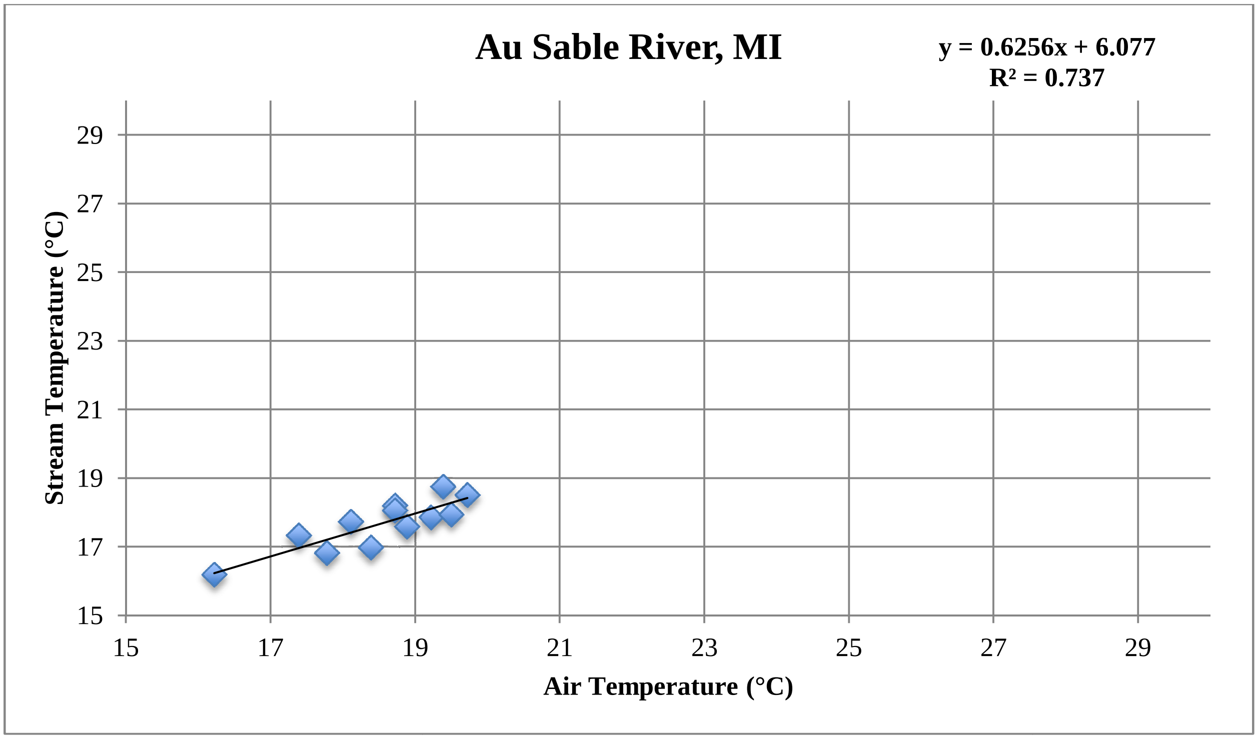


FIGURE 26. Individualized air-stream temperature (°C) linear regression model for Deep Creek, North Carolina (NC).

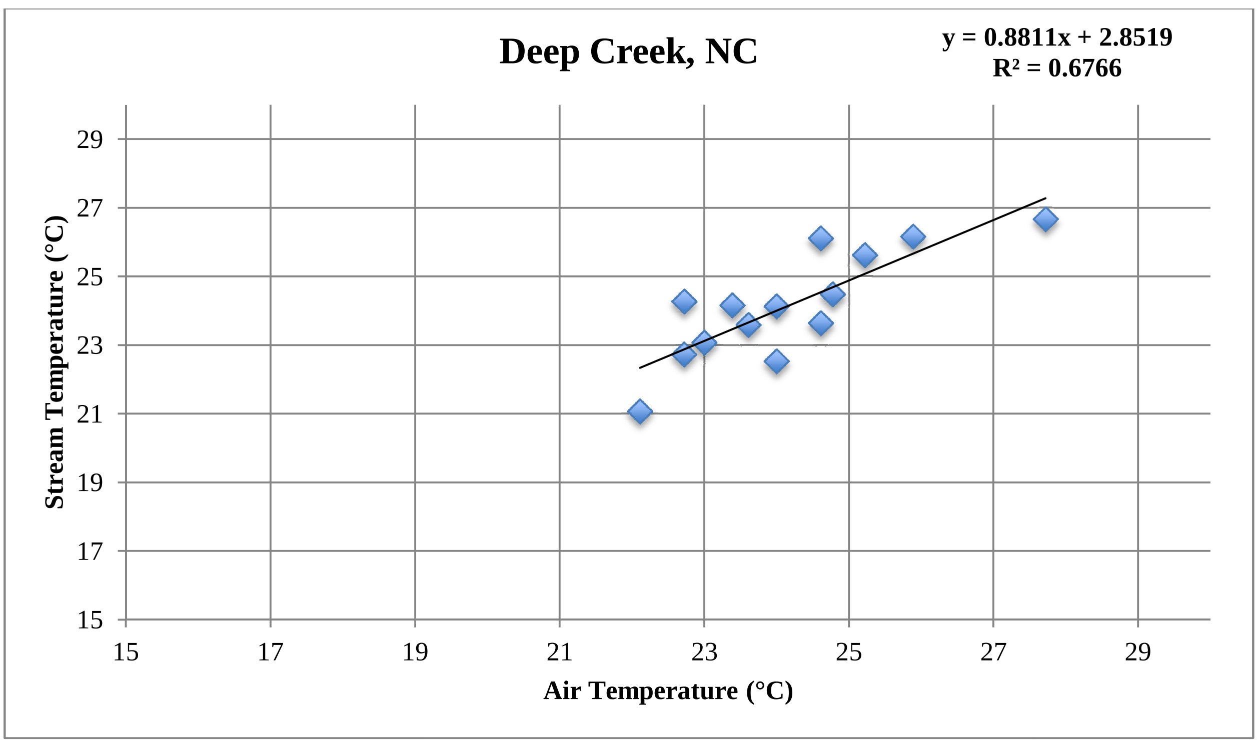


FIGURE 27. Individualized air-stream temperature (°C) linear regression model for Embarrass River, Wisconsin (WI).

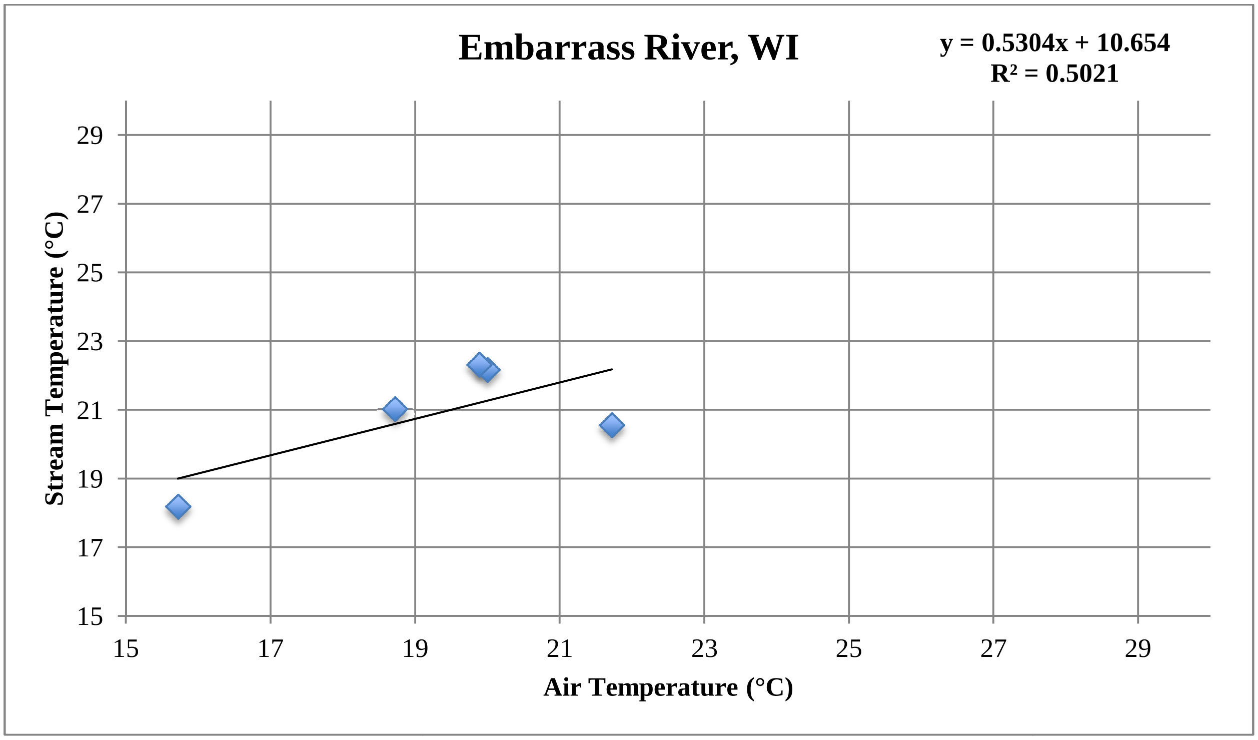
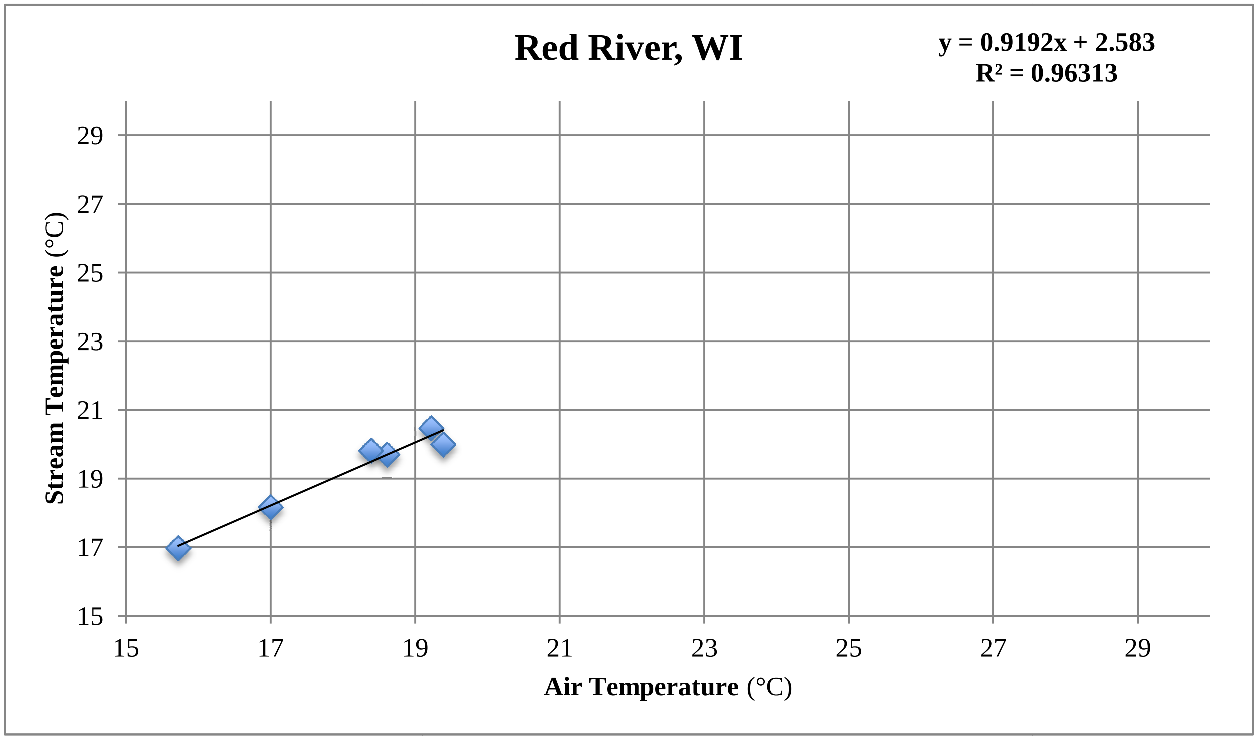


Figure 28. Individualized air-stream temperature (°C) linear regression model for Red River, Wisconsin (WI).



between 0.25°C and 0.87°C cooler than predicted. The over projected stream was warmer than predicted by 2.04°C. Overall, on average 2006 stream temperature predictions were 0.01°C cooler than predicted by the individualized models.

Of the six streams with available stream temperature data in 2012, the temperatures of two streams were over predicted and the temperatures of four streams were under predicted. The two that were cooler than predicted were over predicted by 0.10°C and 0.49°C. Stream temperatures of the four under predicted streams ranged from 0.99°C to 2.73°C warmer than predicted. The average difference between field measured and individualized projections in 2012 was 0.97°C.

In 2006 stream temperature status was consistent for three out of five streams between the status predicted by the individualized model and the status corresponding with the field measured stream temperature. One of the remaining streams was projected to be a status 3 stream (no growth), while the status corresponding with the actual stream temperature was a 4 (extirpation). It is important to note, however, that the predicted stream temperature was 2.04°C cooler than the field measured stream temperature and 1.24°C below the threshold of status 4. The other remaining stream was predicted to be a status 3 (no growth) by the individualized model, but the status corresponding to the field measured stream temperature was a status 2 (reduced growth). The predicted temperature was 0.87°C warmer than field measured stream temperature and 0.06°C above the threshold for status 3.

In 2012, stream temperature was consistent for three out of six streams. Temperature for the remaining three streams were under predicted by the model, meaning the field measured stream temperatures were warmer than those predicted by the individualized models. Two streams predicted to be status 2 (reduced growth), were status 3 (no growth) according to field recorded temperatures. The first of these two streams was 0.99°C warmer than predicted, and the prediction was 0.22°C below the threshold for status 3. The second stream was 2.73°C warmer than predicted, and the prediction was 0.82°C below the threshold for status 3. The third stream with a disparity between the predicted and field measured status was predicted to be a status 3 (no growth) stream, but field measured temperatures resulted in a status designation of 4, with an actual stream temperature 1.53°C warmer than predicted. The prediction was 0.59°C below the threshold for status 4. The stream temperatures project by the I-model projected and SP model are compared with field measured stream temperatures for 2006 and 2012 in Table 11.

I also compared the stream temperature values produced by the individualized air-stream temperature linear regression models and the Stefan and Preud'homme (1993) linear regression model for beginning and end years of the study in 2006 and 2056 to determine how accurately the SP model predicted stream temperatures compared to the I-models. In 2006, the range of stream temperature difference (I-model output – SP-model output) was between -1.37°C and 3.12°C, with an average difference of 0.90°C. In 2056, the range of stream temperature difference between the two models ranged from -2.38°C and 4.01°C, with an average difference of 0.54°C.

Importantly, only two streams in 2006 and two streams in 2056 had discrepancies between the status designations resulting from the individualized model and the SP model. In all four cases, the individualized models predicted a higher status designation than the SP model did. In 2006, two streams designated as status 3 by individualized models were designated as status 2 by the SP model. The individualized models predicted the streams to be 1.13°C and 0.87°C warmer than the SP model did. In both cases the SP model produced stream temperatures 1.31°C below the status 3 threshold. In 2056, two streams designated as status 4 (extirpation) by their individualized models were designated as status 3 (no growth) by the SP model. The individualized models predicted the streams to be 4.01°C and 1.21°C warmer than the SP model did. The SP model produced stream temperatures 0.25°C and 0.17°C below the status 4 threshold. The stream temperatures projected for 2006 and 2056 using the I-models and SP model are listed in Table 12.

Discussion

Changing Stream Temperatures and Brook Trout Thermal Habitat

Based on the results of this study, I predict an increase in stream temperature for all 30 studied subbasins (HUC8s) containing high quality brook trout streams between the years 2006 and 2056. While the magnitude of this change differs between the results produced by the SP model and the KEA model, both predict a general increase in stream water temperatures. The change in temperature between these years ranged from 2.11°C to 4.16°C, with an average change of 3.08°C according to the results of the SP model (Table 6; Figure 10) and ranged from 0.94°C to 1.85°C, with and average change of 1.37°C according to the results of the KEA model (Table 7; Figure 10). While none of the changes in stream temperature were outside of the equation's standard deviation when using the KEA model, they were outside of this range for 29 of the 30 subbasins when using the SP model. These results indicate that rising air temperatures due to climate change will result in warmer stream water temperatures across the brook trout's native U.S. range over the course of the next half-century.

Consequently, increasing stream temperatures over this time period are projected to result in thermal habitat conditions that will be less conducive to brook trout growth and survival than they are currently for 20 of the 30 study subbasins according to the SP model and for 15 of 30 subbasins according to the KEA model. The SP model predicts thermal habitat quality for eight

Table 11. Comparison between stream temperatures and thermal habitat ratings projected by the individualized models (I-models), the Stephan and Preud'homme (1993) model (SP model), and field measured (Actual) temperature for 2006 and 2012.

Individualized Model vs. Stefan and Preud'homme (1993) vs. Field Measured Stream Temperature (°C) Projections												
	2006						**2012**					
Stream Name	**I Model**	**Status**	**SP Model**	**Status**	**Actual**	**Status**	**I Model**	**Status**	**SP Model**	**Status**	**Actual**	**Status**
Broad Swamp Brook, CT	x	x	x	x	x	x	24.71	3	21.64	3	26.24	4
Meduxnekeag River, ME	19.82	2	18.43	2	19.57	2	19.68	2	18.30	2	22.41	3
Silver River, MI	19.19	2	18.96	2	18.74	2	19.11	2	18.88	2	19.01	2
Escanaba River, MI	x	x	x	x	x	x	20.28	2	18.81	2	21.27	3
Au Sable River, MI	18.21	2	19.58	2	17.72	2	18.07	2	19.39	2	17.58	2
Deep Creek, NC	24.06	3	23.60	3	26.10	4	23.01	3	22.57	3	24.15	3
Embarrass River, WI	x	x	x	x	x	x	x	x	x	x	x	x
Red River, WI	20.56	3	20.19	2	19.69	2	x	x	x	x	x	x

Table 12. Comparison between stream temperautres and thernmal habitat ratings projected by the individualized models (I-models) and the Stephan and Preud'homme (1993) model (SP model) for the years 2006 and 2056.

Individualized Model vs. Stefan and Preud'homme (1993) Stream Temperature (°C) Projections										
	2006					**2056**				
Stream Name	**I Model**	**Status**	**SP Model**	**Status**	**I model-SP Model**	**I model**	**Status**	**SP Model**	**Status**	**I model-SP Model**
Broad Swamp Brook, CT	24.93	3	21.81	3	3.12	29.06	4	25.05	3	4.01
Meduxnekeag River, ME	19.82	2	18.43	2	1.39	22.80	3	21.37	3	1.44
Silver River, MI	19.19	2	18.96	2	0.24	23.34	3	22.74	3	0.60
Escanaba River, MI	20.39	2	19.01	2	1.37	22.42	3	22.75	3	-0.33
Au Sable River, MI	18.21	2	19.58	2	-1.37	20.90	3	23.28	3	-2.38
Deep Creek, NC	24.06	3	23.60	3	0.46	27.74	4	27.20	4	0.55
Embarrass River, WI	21.32	3	20.19	2	1.13	24.36	3	25.13	3	-0.77
Red River, WI	21.06	3	20.19	2	0.87	26.34	4	25.13	3	1.21

subbasins will degrade from supporting brook trout growth (status 2) in 2006 to conditions too warm for fish growth (status 3) by 2056. The 12 remaining streams predicted to experience changes in water temperature beyond the equation's standard deviation between 2006 and 2056, will degrade from allowing brook trout survival without growth (status 3) to temperatures beyond the species' upper thermal limits (status 4).

In light of these results, I conclude that climate change will have a considerable impact on the quantity and distribution of thermal habitat available for brook trout in the United States. Other studies related to climate change and coldwater fishes in the U.S. support this conclusion. For example, Steen et al. (2010) produced two models to predict the future thermal habitat available to coldwater fishes in the midwestern state of Michigan. Both models included air temperature as a driver of stream temperature; one assumed a 3°C increase in air temperature by 2100 and the other assumed land cover change and a 5°C increase in air temperature over the same time period. Both models predict substantial reductions in the presence of coldwater fish species within Michigan's Muskegon River watershed by the end of the 21st century and a 90% decrease in the probability of brook trout occurrence in one of the tributary streams studied (Steen et al., 2010). Additionally, Flebbe et al. (2006) predicted a 53% loss of brook trout habitat area along the southern end of the Appalachian Mountains by 2100 using data from climate projections by the more conservative Hadley Centre global circulation model and a 97% loss when assuming the projections of the more severe Canadian Centre global circulation model.

The results from this study also suggest potential shifts in brook trout distribution and productivity, with fewer areas in the U.S. providing for their thermal habitat requirements by mid-century. Brook trout distribution is likely to contract in areas where summer stream temperatures already result in poor or marginal habitat for this species. Near the southern limit of the brook trout's native range, for example, current average summer air temperatures already result in water temperatures near the species' upper thermal limit (Flebbe et al., 2006, Meisner, 1990a). Field recorded stream temperature for Deep Creek (NC), the southernmost stream in this study, provides an example of marginal summer habitat, which is likely to warm past the brook trout's thermal tolerance in the near future. Deep Creek was consistently the warmest stream both in terms of field measured stream temperatures taken in 2006 and 2012 and in terms of stream temperature predictions across all study years.

These potential distributional shifts will be driven by the lethal and sub-lethal effects of the increased metabolic costs associated with increased stream temperatures (Flebbe et al., 2006), including limited growth (Baldwin, 1957). In addition to the impact on growth and survival, I expect the brook trout's reproductive ability will also be compromised at high temperatures because summer water temperatures exceeding 19°C for extended periods have been reported to hinder gametogenesis (Hokanson et al., 1973). According to the results of the SP model, average monthly stream temperature will exceed 19°C in all 30 subbasins during the warmest summer month by 2056.

While the study suggests thermal habitat quality will decline in many portions of brook trout's native range, conversely, thermal habitat could improve for brook trout populations in areas where their growth and reproduction are currently constrained by low temperatures (Meisner, 1990a, Meisner et al., 1988). Stream warming in these cooler regions of North America will increase the potential for brook trout to expand their range and increase productivity.

Stream Temperature Model Validation

The results of the stream temperature model validation portion of this study suggest that the methodology used in this study is a reasonable way to predict current and future stream temperatures. The SP model produced results that were on average 0.60°C warmer than field measured temperatures in 2006 and 0.72°C warmer than field measured temperatures in 2012. The KEA model on the other hand, tended to predict stream temperatures to be cooler than field measured temperatures. Stream temperature predicted by the KEA model in 2006 were on average 5.88°C cooler than field measured stream temperature and were 5.87°C cooler than field measured temperature on average in 2012. The cooler temperatures predicted by the KEA model are not surprising considering that it was developed for streams receiving high levels of groundwater inputs (Krider et al., 2013). High levels of groundwater input tend to maintain streams at more constant temperatures throughout the year (Allan, 1995), making them less responsive to changes in air temperature, as I observed when comparing the results of the KEA model to the results of the SP model, which predicted stream temperatures that were much closer to air temperatures.

While the SP model did over predict stream temperatures for some streams and under predict temperatures for others (Figures 11-14), the KEA model under predicted stream temperatures for all study streams in both 2006 and 2012 (Figures 15-18). This result, in conjunction with the SP model's lower average discrepancy between field measured and predicted stream temperatures in both 2006 and 2012, indicates that the temperatures of my study streams were influenced more strongly by air temperatures than by groundwater inputs. The compelling exceptions to this conclusion were, Carmans River (NY) and Black River (MI), the two 1st order streams with baseflow consisting of ≥80% groundwater input (Figure 13, 14, 17, and 18). Stream temperatures for both sites were well predicted by the KEA model. The stream temperature predicted for Carmans River in 2012 was under predicted by 0.65°C by the KEA model and over predicted by 7.51°C by the SP model. Similarly, in 2012 the KEA model under predicted the temperature of Black River by 0.61°C and the SP model over predicted its temperature by 5.76°C. Perhaps these two streams were predicted more accurately by the KEA model because they more closely resemble the streams found in the karst topography of southeastern Minnesota that the model was originally developed for. In any case, the SP model predicted stream temperatures better than the KEA model for the majority of my study sites. As such, I would encourage management agencies to choose to predict current and future stream temperatures using an air-water temperature linear regression model developed for surface water dominated streams. Since air temperature appears to be the dominant driver of stream temperature, I also suggest that management agencies prioritize strategies to mitigate and reduce air temperature directly above coldwater streams.

Individualized Air-Water Temperature Linear Regression Models

Stream temperature data is often difficult to obtain, since stream gages are often sporadically placed and may not collect data regularly over time. Additionally, maintaining stream gages is costly and lack of funding has recently led to reduced access to current gage recorded data (USGS, 2014). Air temperature data, on the other hand, are readily available and collected by a variety of institutions (weather stations, airports, etc.). The ease of access to air temperature data across the nation makes predicting stream temperatures from air temperatures using linear regression models attractive when actual stream temperature data are scarce. Additionally, the availability of future air temperature projections, like those produced by the three CCMs used in this study, makes the capacity to predict stream temperatures from air temperatures important.

A linear regression model developed by fitting a trend line to a plot of local historical air temperatures and concurrent stream temperature data would likely provide the most accurate means of predicting stream temperatures from air temperatures for a specific stream. The lack of available historical stream temperature data can be limiting in this regard, however, making it difficult to develop linear regression models for each stream of interest in large-scale management or research efforts. Even if the appropriate data were available, compiling air and stream temperature data, creating individualized linear regression models, and then customized future stream temperature predictions on a stream-by-stream basis could be very time consuming. Therefore, a linear regression model capable of predicting future temperatures for a wide range of streams would be a valuable tool for developing future brook trout management plans.

Since I previously concluded the SP model to be more accurate in predicting temperatures for the streams included in this study, I chose to compare the outputs of this model to those produced by the individualized linear regression models. The purpose of this effort was to test the efficacy of the SP model for predicting stream temperatures compared to individualized linear regression models developed for each stream. I compared the values predicted by both models types for monthly average August stream temperatures during the years 2006 and 2056. In 2006 the range of temperature difference between the predictions from the two models was between -1.37°C and 3.12°C, with an average difference of 0.90°C. In 2056, the range of stream temperature difference between the two models ranged from -2.38°C and 4.01°C, with an average difference of 0.54°C.

More biologically significant for brook trout than the differences in predicted stream temperatures between the two model types, are differences in stream temperature statuses predicted by the models. In both 2006 and 2056, two of the eight streams had discrepancies in habitat status predictions between the two models. In all four cases the individualized models predicted a poorer habitat status designation than the SP model did, making the SP model generally more conservative than the individualized models. In 2006, two streams designated as status 3 by individualized models were designated as status 2 by the SP model. The individualized models predicted the streams to be 1.13°C and 0.87°C warmer than the SP model did. In both cases the SP model produced stream temperatures 1.31°C below the status 3 threshold, a value less than the standard deviation (2.16°C) associated with the SP model. In 2056, two streams designated as status 4 (extirpation) by their individualized models were designated as status 3 (no growth) by the SP model. The individualized models predicted the streams to be 4.01°C and 1.21°C warmer than the SP model did. The SP model produced stream temperatures 0.25°C and 0.17°C below the status 4 threshold, again values again less than the standard deviation of the SP model.

Since the SP model did predict the same habitat statuses as the individualized models for six out of eight streams in both 2006 and 2056 and since in those cases when the two models did not predict the same status, the difference between the SP predicted value and the threshold of the status predicted by the individualized model was less than the standard deviation associated with the SP model. As such, the SP model appears to be an acceptable method of stream temperature prediction for those streams assessed.

Factors influencing stream temperature

While the SP and individualized models provide useful tools to estimate the potential effects of increasing air temperature on brook trout thermal habitat, air temperature is only one of a suite of potential factors influencing stream water temperatures. The variability between field measured and SP model predicted stream temperatures in 2006 and 2012 supports this assertion. Field measured stream temperatures differed from the SP predicted values by more than 2.16°C (the equation's standard deviation) for 32% of streams in 2006 and for 55% of streams in 2012, indicating the presence of additional factors influencing stream temperature. The R^2 values of the individualized air-stream temperature linear regression equations also suggest that additional factors influence stream temperature. If stream temperatures were entirely determined by air temperature, then the R^2 values of the equations would be equal to 1.

Other key factors likely influencing stream temperatures include riparian zone shading and the magnitude of groundwater input. Vegetation providing overhead riparian zone shading, for example, can aid in cooling stream water by intercepting ultraviolet rays that would otherwise warm the stream surface on contact (Blann et al., 2002). Groundwater, which often provides streams with a relatively consistent source of water with temperatures generally within 1°C of the average annual air temperature throughout the year provides a thermal buffer, keeping streams warmer during the relatively cold air temperatures of the winter months and cooler during the relatively hot air temperatures of the summer months (Allan, 1995).

Baseflow and Stream Order

Since the SP model predicted temperature for the majority of streams more accurately than the KEA model, we can conclude that while groundwater likely plays a role in determining stream temperature, for the selected study streams air temperature exerted a greater influence on stream temperature than groundwater. Nevertheless, the role of groundwater in determining stream temperature is important and since for majority of streams, field measured stream temperatures were cooler than predicted by the by the SP model in both 2006 and 2012, I hypothesized that the magnitude of groundwater input into the study streams influenced their temperatures.

Percent groundwater contribution to baseflow ranged from 30.27% (Laurel Fork, WV) to 85.02% (Carmans River, NY). I divided the study streams into three categories, low (30.27≤%≤48.52%), medium (48.52<%≤66.77), and high baseflow (66.77<%≤85.02%) relative to the baseflow percentages of the study streams. Then, field measured and predicted stream temperature from both the KEA and SP models were categorized according to baseflow percentage (Figures 11, 13, 15, and 17). If groundwater input were to exert a strong influence on stream temperature, then surface water dominated streams, those with low groundwater inputs, should be better predicted by SP than those streams with high groundwater inputs. Conversely streams with high groundwater inputs should predicted better by the KEA model than the low baseflow streams.

I was unable to discern any clear pattern relating groundwater input percentage with the accuracy of stream temperature predictions from either model. Streams from all three baseflow input categories, low, medium, and high baseflow were under predicted and over predicted by the SP model, showing no clear indication that the percent groundwater input played any role in the efficiency of the model's predictive capacity in either 2006 or 2012 for study streams. The KEA model under predicted temperatures for all study streams in both 2006 and 2012. As such, it was not clear whether groundwater dominated streams (high groundwater input %) were predicted better by this model than surface water dominated streams (low groundwater input %).

I also categorized the field measured a predicted stream temperatures by Strahler stream order (orders 1 through 6) because water temperature tends toward equilibrium with ambient air temperature as the stream departs from its source (Figures 12, 14, 16, and 18) (Hynes, 1970, Ducharne, 2008). Therefore, higher order larger streams are typically warmer than smaller lower order streams. As with baseflow, I did not find any clear indication that the stream order played a role in predicting stream temperatures accurately using either the SP or KEA models.

Therefore, I conclude, that for the streams included in this study, neither percent groundwater input nor stream order substantially influenced the predictive capacity of either the SP or KEA model. The one compelling exception to these findings, mentioned previously, was that the two streams in the high baseflow category (66.77<%≤85.02%) and lowest stream order category (stream order 1), were predicted well by the KEA model, indicating that when percent baseflow contribution is very high and stream order is very low, the combination of these two factors in combination are more influential than air temperature in determining stream temperature.

Considerations for the future

Air Temperature to Stream Temperature Conversion

Alternative models for relating air temperature to water temperature should be considered for future studies, as linear regression models are not always the most accurate in capturing this relationship. For example, Morrill et al. (2005) found that the stream temperatures of 83% of the geographically diverse study sites assessed did not display a 1:1 relationship with air temperatures. Instead, they determined a non-linear S-shaped function to be a better descriptor of the air-stream temperature relationship (Morrill et al., 2005, Erickson and Stefan, 2000). This seems reasonable, given the fact that for some streams, the relationship between air and stream temperature becomes non-linear after air temperature has reached 25°C, a temperature regularly exceeded during the summer months in the states examined in my study; the reason for nonlinearity is likely related to evaporative cooling of the stream (Morrill et al., 2005, Erickson and Stefan, 2000). However, Morrill et al. (2005) did note that some streams exhibit a strong linear relationship between air and water temperature and that in these cases, using a non-linear model to estimate this relationship may offer little or no improvement (Morrill et al., 2005). Additionally, many other studies have observed streams with nearly 1:1 relationships between water and air temperature for weekly and monthly data making linear regression models an effective way to predict stream temperatures from air temperatures for some streams. For example, Pilgrim et al. (1998) found a near 1:1 relationship between air and stream temperature for 39 Minnesota streams and as did the paper which introduces the linear model used in this study, Stefan and Preud'homme (1993) also found a nearly linear relationship in 11 Mississippi basin streams.

Given that the relationship between air and water temperature seems to be dependent upon the characteristics of the specific stream and surrounding conditions, the most effective way to predict stream temperatures from air temperature would be to investigate the linearity of the relationship between the two variables for each stream and develop a custom linear or non-linear model based on the results.

While this study is based on the premise that air temperature is one of the strongest predictors of stream temperature, the correlation found between low order streams with high levels of groundwater input and the general over prediction of stream temperature by the SP model, suggests that other factors, like groundwater input, also play an important role in influencing stream temperature. In addition to air temperature and groundwater inputs, other drivers of stream temperature include such things as percent riparian zone shading, runoff, ice cover, and the presences of dams. Ideally, these additional drivers of stream temperature would be incorporated into a model to most accurately predict stream temperature.

Climate Models

As mentioned earlier in the methods section of this thesis, the emissions scenario used to project future air temperatures for this study, SRES A1B, assumes a moderate increase in atmospheric CO_2 concentration (700 ppm by 2100) (Meehl et al., 2007). It is possible that CO_2 emissions will follow a different emissions pathway, like the A2 pathway, which assumes CO_2 concentrations of 820ppm by 2100 (Meehl et al., 2007), as a result of continued heavy reliance on fossil fuels to meet energy demands; or the B1 pathway, which assumes substantial reductions in emissions, predicting CO_2 concentrations of 550ppm by 2100. If CO_2 emissions continue along the lower emissions pathway (B1), then stream temperatures could be lower than predicted by this study, resulting in more favorable thermal habitat conditions for brook trout in the future. Conversely, if emissions proceed along the higher emissions pathway (A2), then stream temperatures could become warmer more quickly than predicted in this study, thus reducing thermal habitat for brook trout more rapidly than anticipated. Additionally, as the scientific community's understanding of climate science grows, the latest GCMs and emissions scenarios, and downscaling methods should be used in further studies of the impact of climate change on brook trout habitat.

Additional Effects of Climate Change on Thermal Habitat for Brook Trout

In addition to direct effect that changes in air temperature have on stream temperature, climate change is likely to influence stream temperature indirectly as well. For example, climate change may influence groundwater and riparian zone shading, which are also drivers of stream temperature.

Since groundwater temperatures are ultimately driven by air temperatures, staying within 1°C of annual average air temperature (Allan, 1995), rising air temperatures should result in rising groundwater temperatures as well. The impact of climate change on groundwater temperature has not yet been studied in great depth, however, posing a challenge in projecting future water temperature for groundwater dominated streams (Kurylyk et al., 2013, Mayer, 2012). A study of the effects of air temperature and concurrent ground surface temperature on a small watershed catchment in east-central New Brunswick, Canada, did show that the temperature of shallow groundwater is responsive to seasonal changes in air temperature and the temperature of deeper groundwater is sensitive decadal climate change (Kurylyk et al., 2013). As such, the influence of changing groundwater temperature on stream temperature should be considered when modeling future stream temperature and the buffering effect of groundwater inputs on stream temperature should not be overestimated (Kurylyk et al., 2013).

The riparian vegetation mitigating rising air temperatures by providing shading may also change as incidence of wildfires, droughts, insect, and pathogen outbreaks increase in response to climate change (Melillo et al., 2014), resulting in increasing stream temperatures and further reductions in thermal habitat status for brook trout. A study of the effect of changing vegetation regimes due to climate change on stream temperature in the southeastern United States, concluded that altered stream shading could result in increases in stream temperature of up to 7°C (Cooter and Cooter, 1990). Reductions in riparian vegetation could also lead to increases in the amount of surface runoff entering streams further contributing to stream warming (Hynes, 1970).

In addition to the direct effects that rising stream temperatures are likely to have on brook trout, the effect that elevated stream temperatures will have on other members of the ecological community will influence brook trout indirectly as well. One such concern is changing phenology as a result of climate change (Walther et al., 2002), which may lead to asynchrony between the lifecycle events of brook trout and other species in the aquatic environment. Changes in water temperature may lead to premature hatching of the eggs of fall spawning fish, like brook trout, leading to a mismatch between the pulse of prey species production and the onset of larval fish feeding (Shuter et al., 2012). Changes in the emergence of prey species may also prove problematic for brook trout. For example, the high altitude stream mayfly, *Baetis bicaudatus*, a prey species for trout, emerges as an adult insect earlier as stream temperatures warm (Harper and Peckarsky, 2006), which could result in a mismatch between the availability of mayflies as a prey resource and a critical period for energy consumption for brook trout. Harper and Peckarsky (2006) also note that the size and fecundity of mayflies emerging under increased water temperature conditions may be reduced, which likely means reduced quality of this food resource for trout even in the absence of phonological asynchrony.

Management Implications

In the face of increasing air temperatures due to global climate change, fisheries managers must identify the processes controlling stream temperature and prioritize efforts to mitigate the effects of rising air temperatures to maintain brook trout fisheries within their native range. I suggest that promoting high levels of riparian zone shading, reducing runoff, and protecting the sources of groundwater inputs into these coldwater systems would provide the most effective ways to maintain stream temperatures cool enough for brook trout to persist in United States.

Riparian zone shading should be protected from removal and enhanced in areas where it has been lost to shield streams from direct exposure to ultraviolet radiation. This strategy to reduce stream temperature will be of particular importance for streams receiving little or no groundwater input. Blann et al. (2002) found that suitable thermal habitat for brook trout could be expanded by introducing sufficient shading in previously unshaded stream reaches and indicated that wooded buffer zones produce the most shade, followed by successional vegetation buffers. Loss of riparian shading can also reduce the volume of cold water plumes in areas of high groundwater input, thus reducing important summertime thermal refugia for brook trout (Ebersole et al., 2003).

In addition to reducing stream temperature by providing shading, streamside vegetation also reduces direct water runoff into streams (Hynes, 1970). Reducing runoff is critical for maintaining cool stream temperatures particularly in catchments with high levels of urbanization, because impervious surfaces, like pavement, increase runoff volume and warms water as it washes over these surfaces (Nelson and Palmer, 2007). Nelson and Palmer (2007), concluded that while spikes in stream temperature dissipated in a relatively short amount of time (3 hours), localized rainstorms could causes surges in temperature averaging 3.5°C.

For streams receiving substantial inputs from groundwater aquifers, like those in this study receiving groundwater contributions to baseflow of ≥80%, protecting baseflow is critical. An important approach to maintaining baseflow levels high enough to mitigate increasing air temperatures is to carefully evaluate the effects of groundwater withdrawals for human use and consumption on stream temperature as the demand for this resource continues to increase over time because even slight reductions in baseflow can result in stream temperature increases (Waco and Taylor, 2010).

In addition to directly safeguarding stream baseflow, managers must also be cognizant of the various landscape features promoting groundwater recharge, as these features ultimately determine the amount and rate of groundwater input into streams. For example, streams located in areas with highly permeable, coarse soil types and low gradient topography (Winter, 1999, Stanford and Ward, 1993, Cey et al., 1998, Siitari et al., 2011), are likely to receive higher levels of groundwater input than streams in areas with steep terrain and more impermeable geology. As such, in low lying areas with highly permeable soils, such as those representative of large portions of the brook trout's range in the Midwestern U.S., groundwater is an important factor influencing stream temperature (Siitari et al., 2011).

The amount and rate of groundwater entering riparian systems has also been linked to land cover in addition to geologic structure. Notably, differing land cover types allow for distinctive rates of water percolation into soil, resulting in differing aquifer recharge rates. Grasslands, for example, allow for the highest rates of aquifer recharge followed in descending order by forested lands, croplands, and areas dominated by impervious surfaces, such as concrete (Waco and Taylor, 2010). Therefore, encouraging land cover types that promote higher rates of groundwater recharge and restricting the amount of area within a watershed dominated by impervious surfaces will be important in protecting groundwater quantity and stream baseflow in the future.

Given the increasing temperatures predicted to result from global climate change, it is essential to protect and improve natural stream cooling mechanisms to help sustain brook trout thermal habitat and ultimately brook trout populations across their native U.S. range. Additionally, fisheries regulations must also change in response to rising air temperatures to protect brook trout populations from high angling pressure during thermally stressful events and by protecting the coldwater refugia these fish need to persist under adverse thermal regimes. Lastly, in areas where brook trout thermal habitats and thus populations are likely to be lost, we must prepare to introduce stakeholders to new types of fishing opportunities, and ready ourselves and the public for new warmer water species assemblages as water temperatures become less conducive to stenothermic coldwater species (Lynch et al., 2010).

As the brook trout's range and productivity are impacted by rising air temperatures resulting from climate change, fisheries managers must prepare to address the concerns associated with the changing availability of this recreationally and economically valuable species. The role of coldwater fisheries managers in the future will become increasingly complicated, as the human population increases, land cover changes, competition for ground and surface water accelerates, and the challenges of increasing air temperatures threaten the brook trout's existence across their native range. In order to cope with the complex issue of shifting brook trout range and productivity, resource managers must: identify and prioritize the protection of areas likely to maintain high quality brook trout habitat as air temperatures increase; safeguard and enhance the drivers of stream cooling; and appropriately adjust regulations in accordance with changes in brook trout productivity.

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