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# Simulating the effect of climate change on stream temperature in the Trout Lake Watershed, Wisconsin

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## HIGHLIGHTS

- A stream temperature model was calibrated for three streams in northern Wisconsin.
- The effect of climate change on stream temperature was simulated in each stream.
- Annual average stream temperature was projected to rise from 1 to 3 °C by 2100.
- Forecasts of stream temperature exceeded optimal ranges for brook trout.

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## ABSTRACT

The potential for increases in stream temperature across many spatial and temporal scales as a result of climate change can pose a difficult challenge for environmental managers, especially when addressing thermal requirements for sensitive aquatic species. This study evaluates simulated changes to the thermal regime of three northern Wisconsin streams in response to a projected changing climate using a modeling framework and considers implications of thermal stresses to the fish community. The Stream Network Temperature Model (SNTEMP) was used in combination with a coupled groundwater and surface water flow model to assess forecasts in climate from six global circulation models and three emission scenarios. Model results suggest that annual average stream temperature will steadily increase approximately 1.1 to 3.2 °C (varying by stream) by the year 2100 with differences in magnitude between emission scenarios. Daily mean stream temperature during the months of July and August, a period when cold-water fish communities are most sensitive, showed excursions from optimal temperatures with increased frequency compared to current conditions. Projections of daily mean stream temperature, in some cases, were no longer in the range necessary to sustain a cold water fishery.

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## 1. Introduction

Thermal regimes in stream ecosystems are fundamentally important to fish and other aquatic organisms, especially those with low tolerances for extended periods above or below optimal thresholds (Isaak et al., 2012). In many cases, changes to the thermal regime can be attributed to anthropogenic drivers such as removal of riparian vegetation, thermal effluent from powerplants, water storage in reservoirs, and urbanization. While these alterations to flow and temperature are deleterious to receiving waters, they are generally restricted in spatial scale, allowing for aquatic communities to shift towards more suitable habitat (Wenger et al., 2011). These opportunities for relocation are lessened as stresses to the ecosystem become more pervasive. Climate change is one such stress that can strongly dictate the distribution and abundance of individual species because changes in air temperature, atmospheric radiation, and the timing and magnitude of precipitation patterns can affect entire ecosystems and river networks. While previous studies have considered the potential effect of climate change on the distribution of fish in North America, the majority have been relatively coarse in scale that focus on broad landscapes or large spatial catchments greater than 500 km$^2$ (Lyons et al., 2010). While these studies yield important insights, they represent a small fraction of total stream habitat available. Other studies are more regional, focusing on changes in stream temperature in relation to elevation or latitude. For example, Null et al. (2013) showed an overall reduction in viable coldwater habitat in California's Sierra Nevada, shifting more towards higher elevations. Relatively few studies have emphasized the variation in thermal conditions in a smaller geographical context, or individual streams (Lyons et al., 2010; Steen et al., 2010; Williams et al., 2009). A better understanding of small-scale thermal response to the potential warming effects of climate change will better direct the managerial decision-making process.

The potential for increases in stream temperature across many spatial and temporal scales poses a challenge for environmental managers. Streams that may currently be suitable as a recreational cold-water

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sport fishery could become increasingly fragmented as fish find refuge in less impacted areas. Furthermore, as climate change advances, aquatic communities already constrained by warmer stream temperatures could result in net losses of habitat or a generalized shift in fish assemblages towards more tolerant species (Mohseni et al., 1998; Wenger et al., 2011; Isaak et al., 2012). Increases in stream temperature as a result of climate change could also result in changes to water quality, such as dissolved oxygen (Ficklin et al., 2013). An important step in understanding the importance of climate change on sensitive aquatic resources is describing rates at which suitable metrics might change given variations in projected climate forcings. Given the uncertainty associated with long range projections, the exact consequences of a warming climate on stream temperature could vary depending on several factors, such as precipitation patterns and seasonality of temperature shifts (Nelson and Palmer, 2007).

Several studies have characterized the response in stream temperature to changing climate variables either through examination of historical trends [for example Isaak et al., 2012] or by forecasting through model simulation. A variety of stream temperature models are available, ranging from complex advection/dispersion models (Stefan and Sinokrot, 1993) to more simplistic linear regression models that incorporate one or more climate variables, such as air temperature (Stefan and Preud'homme, 1993; Nelson and Palmer, 2007). However, these models often ignore or approximate complicated interactions between groundwater and surface water systems neglecting important feedback loops with other dynamic hydrologic processes such as evapotranspiration, soil-zone flow, and surface runoff (Ficklin et al., 2013; Hunt et al., 2013). For example, a decreasing snowmelt contribution to streamflow from less snowfall will reduce the amount of cold-water inputs resulting in warmer winter, spring, and early summer stream temperatures (Ficklin et al., 2013). Thus, forecasts of stream temperature should account for both the atmospheric and coupled groundwater/surface water hydrologic system responses to climate change.

The goal of this study was to simulate the historic and potential future stream temperatures in three select streams in the Trout Lake watershed in Vilas County, Wisconsin. While there have been many other studies examining the response of stream temperature to climate change, most make use of regional models that are too coarse for meaningful management options, or use surrogates, such as air temperature, as predictors of stream temperature and do not include the dynamic hydrological processes at the local scale. This study made use of a coupled surface water and groundwater model called GSFLOW. GSFLOW is an integration of the U.S. Geological Survey's Precipitation-Runoff Modeling System (PRMS) and MODFLOW. The objectives for the model described in this paper included forecasts of the effects of climate-change scenarios on streamflow and stream temperature. Therefore, streamflow results from the coupled GSFLOW model were linked to the Stream-Network TEMPerature model (SNTEMP) (Bartholow, 1991). This approach allows propagation of potential temperature changes in the atmosphere to coldwater streams and informs questions related to projected impacts on stream ecology and the potential risk to fish communities. The following is a partial digest of a previously published U.S. Geological Survey Scientific Investigations Report. Full details of the study can be found in Hunt et al. (2013).

### 1.1. Site description

The Trout Lake watershed (105 $km^2$) is in Vilas County, Wisconsin, USA (Fig. 1). The basin is comprised of many small lakes with watersheds that are completely forested with a mixture of coniferous and deciduous species. The poorly drained glacial landscape has resulted in numerous wetland areas, ranging from bogs to fens (Hunt et al., 2006). Lakes are well connected to the groundwater system and many lakes are flow-through lakes with respect to groundwater. Streamflow in the area is dominated by groundwater which can account for over 80% of total streamflow; however, surface runoff can be appreciable during spring snowmelt (Gebert et al., 2009). Annual precipitation averages about 81.5 cm/years (National Climatic Data Center, 2014); average groundwater recharge is estimated to be 27 cm/years (Hunt et al., 1996), and has been estimated to range from about 15 to 50 cm/years at local areas within the basin (Dripps et al., 2006). Mean monthly temperatures range from $-18$ to $-7$ °C in January to $+12$ to $+25$ °C in July (National Climatic Data Center, 2014).

Three mainstem and associated tributaries to Trout Lake were selected for measurement and simulation of stream temperature: North Creek, Stevenson Creek, and Upper Allequash Creek (Fig. 1). Mean baseflow at the mouth ranged between 0.09 $m^3/s$ at Stevenson Ck. and 0.13 $m^3/s$ at Allequash Ck. (Hunt et al., 2006). Channels are widest and more diffuse near the headwaters as each stream becomes integrated with a larger wetland system. Channel widths range from approximately 30 m near the headwaters of both Upper Allequash and Stevenson Ck. to less than 3 m near the mouth of Upper Allequash. Topography surrounding each stream consists primarily of wetland and forested lowlands.

## 2. Methods

### 2.1. Description of temperature model

The instream water temperature model SNTEMP, developed and supported by the U.S. Fish and Wildlife Service, was selected to predict stream temperatures in the Trout Lake stream network. A modified version of SNTEMP called TRPA Stream Temperature for Windows (http://trpafishbiologists.com/sindex.html) provided a graphical user interface to simplify data entry and export. SNTEMP is a steady-state, one-dimensional heat transport model that predicts daily mean and maximum temperatures as a function of stream distance and environmental heat flux (Bartholow, 1991). A heat-transport equation describes the downstream movement of heat energy in the water and actual exchange of heat energy between the water and its surrounding physical environment (Theurer et al., 1984). Net heat flux is calculated by parameter inputs describing the meteorological, hydrological, stream geometry, and shade setting for a network of stream segments that define North, Stevenson, and Upper Allequash Creeks.

Each stream was discretized into two or more segments. Each segment is considered constant and represents uniform width, groundwater accretion rates, and relatively homogeneous topographic and riparian vegetation conditions. As such, major transitions in any of these categories would support creation of a new stream segment. Final versions of conceptual models created for North, Stevenson, and Upper Allequash Creek, resulted in 7, 3, and 4 stream segments, respectively. Each stream segment requires a physical description of stream geometry, hydrology, and shading variables. Meteorological variables, on the other hand, are considered more global in nature and were applied to all stream segments equally. SNTEMP assumes that all input data, including meteorological and hydrological variables, can be represented by 24-hour averages (Bartholow, 1991).

#### 2.1.1. Data collection and field measurements

Data used to calibrate SNTEMP came from a variety of sources. Meteorological data came from publicly available historical datasets for the modeled region, hydrologic data were provided by previously calibrated hydrologic models, and field measurements of stream geometry and riparian shading were done by using methods described in Bartholow (1989). Some parameters, such as dust coefficients, ground reflectivity, and Manning's n values were not measurable and were supplemented by published data sources.

#### 2.1.2. Hydrology

Hydrologic data consists of stream discharge and water temperatures. SNTEMP requires both upstream discharge and temperature data for each modeled stream segment. For calibration, daily mean discharge data was based on a coupled groundwater-surface water flow model called GSFLOW (Markstrom et al., 2008). GSFLOW is an