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THE INFLUENCE OF GROUNDWATER WITHDRAWAL ON
AVAILABLE BROOK CHARR (*SALVELINUS FONTINALIS*)
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Kerryann Elizabeth Waco

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William W. Taylor
Major Professor's Signature

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# THE INFLUENCE OF GROUNDWATER WITHDRAWAL ON AVAILABLE BROOK CHARR (*SALVELINUS FONTINALIS*) THERMAL HABITAT IN TWIN AND CHIPPEWA CREEKS, OSCEOLA COUNTY, MICHIGAN

By

Kerryann Elizabeth Waco

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# ABSTRACT

# THE INFLUENCE OF GROUNDWATER WITHDRAWAL ON AVAILABLE BROOK CHARR (*SALVELINUS FONTINALIS*) THERMAL HABITAT IN TWIN AND CHIPPEWA CREEKS, OSCEOLA COUNTY, MICHIGAN

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In Michigan, groundwater-dominated streams are currently being impacted by increased groundwater withdrawal and land use/land cover changes which alter stream temperatures and their flow, having the potential to significantly influence brook charr production and behavior. The goal of this study was to quantify the influence of groundwater withdrawal and land cover alteration on thermal habitat availability for brook charr using a groundwater modeling tool that predicted the changes in baseflow due to (1) groundwater withdrawal and (2) changes in rates of recharge due to alteration of land cover, which would result in a change in stream temperatures. Projected stream temperature changes were calculated using a stream temperature modeling tool and compared to the range of temperature preferenda for brook charr in order to evaluate the potential impact of policy decisions regarding water extraction and land use/cover changes. The models predicted relatively small changes in both stream baseflow and consequently, stream temperature, with increased groundwater withdrawal rates. Land use/land cover alterations which we analyzed were shown to either mitigate or enhance the loss of brook charr thermal habitat as a result of groundwater withdrawal. This study emphasizes the importance of collaboration between water, land and fisheries managers to ensure brook charr viability, productivity and sustainability in the face of environmental change, increasing water use and development in the watershed.

# DEDICATION

To my Parents

For your support and advice

And

To Ben

I could not do this without you.

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# INTRODUCTION

Altered stream thermal habitat can contribute to impairment of the physical, chemical and biological processes occurring in aquatic ecosystems (Naiman et al., 1995) as stream temperature is one of the most important environmental factors affecting the physiology, life-history and evolution of stream biota (Wehrly et al., 1998; Allan & Castillo, 2007). As fish are poikilothermic, it is largely their environment that controls their body temperature; thus regulating their production and behavior (Fry, 1971). Fish are most productive when they live in thermal ranges that are conducive to growth and survival, and fluctuations outside of these temperatures may affect their productivity and movement (Fry, 1971). Thus, stream temperature is a key factor limiting brook charr distribution and production (McCormick et al., 1972). Temperatures approaching the lethal thermal level of a fish can result in increased metabolic rates which result in increased food demand, reduction in growth rate due to increased energy needs, and/or an increase in the incidence of disease (Fry, 1971).

## *Thermal habitat and brook charr*

Brook charr (*Salvelinus fontinalis*) are fishes in the genus *Salvelinus* which are a coldwater salmonid species ranging from Newfoundland and Labrador, west to the Great Lakes basin, and south through the Appalachian Mountains (Balon, 1980; Power, 1980; Behnke, 2002). In Michigan, they are a socially and ecologically important species of fish. Brook charr are separated into two principal life history forms, one that is relatively short lived, living approximately 3-5 years, relatively small in size (200-250mm) and typical to smaller coldwater streams and lakes in areas south of the Great Lakes region. The other life history form is a much larger, late maturing, longer lived fish (referred to as “coaster” brook charr) that persists between 8-10 years in age, gets to weights of 4-6 kg and inhabits large lakes, rivers and estuaries (Power, 1980; Raleigh, 1982). Brook charr spawn in the fall from October through November in riffles containing gravel and prefer to spawn in areas of groundwater inflow, or seeps, in streams (Powers 1980, Benson 1953). The summer months are a critical time period for charr growth and stream characteristics in Michigan, such as low flow and high temperatures, can limit trout abundance (Bowlby and Roff 1986). In a study of three Michigan streams, most age 1 brook charr growth occurs in the months of March through June with very little growth occurring from July to September because of increased stream temperatures (>19°C) during those times (Copper 1953).

Brook charr exhibit optimal thermal ranges for growth for all life stages between 12 to19°C (Fry, 1946; McCormick et al., 1972; Cherry et al., 1977) (Figure 1). In Michigan, Wehrly et al. (2003) found the highest brook charr densities in streams during the summer (July) at temperatures between 15 to 19°C. Requirements for brook charr persistence and productivity in Michigan have been demonstrated to be directly linked to relatively stable stream flows and cold temperatures (Wiley & Seelbach, 1997); both conditions of which are determined by the dynamics of the hydrologic cycle and the geologic composition of the watershed and its land cover.

*Hydrologic processes: Groundwater and surface water interactions*

The hydrologic cycle includes the processes and pathways that are responsible for the movement of water on, above, and below the earth’s surface (Brooks et al., 2003). These processes and pathways include evaporation and transpiration of water from the earth’s surface into the atmosphere, precipitation from the atmosphere, infiltration of this precipitation into the groundwater aquifer, runoff of precipitation into surface water, and groundwater input into the surrounding rivers, lakes and oceans (Brooks et al., 2003; Davie, 2003). The hydrologic cycle can be expressed in this basic equation:

$$I - O = S \qquad \text{Eq. 1}$$

where I = inputs, O = outputs and S = storage. Representation of the hydrologic cycle in this manner is a key concept in hydrology. Determining the influence of each process and pathway within different hydrologic units (i.e. a watershed, a stream, and an aquifer) is essential to addressing the interaction between groundwater and surface water (Brooks et al., 2003) which directly relates to fish populations found in these watersheds.

Precipitation which infiltrates the soil surface layer and percolates down through the soil to the underlying groundwater aquifer is known as recharge (Freeze & Cherry, 1979). Recharge increases the amount of groundwater in storage. Groundwater input and surface runoff into streams, as well as aquifer storage capacity and groundwater movement depend, in varying degrees, on local soils and geology, climate, topography and land cover (Brooks et al., 2003) . Consideration of local soils, topography, and climate must be determined and evaluated to assess how changes in land use in a watershed impact ground and surface water resources.

The groundwater contribution to a stream from the groundwater aquifer, baseflow, occurs at various points along a stream reach year-round, fluctuating seasonally depending on the level of the water in the aquifer and flowing in at temperatures of between 8.2 -11.3°C in Michigan (Leverett, 1906). These groundwater inputs, on average, supply approximately 80% of the annual stream flow in streams in the Lower Peninsula of Michigan (Michigan Groundwater Conservation Advisory Council, 2006).

As a result, the groundwater contribution to the stream acts to maintain minimum stream flows and the temperature regimes that in large part determine the biotic community that lives therein. This is particularly true for coldwater streams that provide the thermal habitat needed for coldwater species such as brook charr in low elevation (~150m – 450 m), temperate streams, such as those found in Michigan (USA) (Latta, 1965; Bowlby & Roff, 1986; Wiley & Seelbach, 1997; Zorn et al., 2002).

The thermal regime of these streams is largely a function of the groundwater inputs that provide the ideal conditions for brook charr growth, survival and production throughout the year by providing seasonal protection from elevated summer temperature and cooler stream temperatures incurred throughout the winter months (Hunter, 1991; Wiley & Seelbach, 1997; Power et al., 1999). In addition to being critical for fish thermal habitat, groundwater is a major source of human drinking water in Michigan (Michigan Department of Environmental Quality, 2006) and is used extensively for agricultural irrigation, sanitation and industrial operations. These operations have the ability to directly and indirectly impact aquatic communities through point and nonpoint source effluent and heated discharge.

### *Land use/land cover*

The type of land cover in a watershed influences the levels of evapo-transpiration to the atmosphere, percolation and recharge to the groundwater, and surface runoff to the stream system in the landscape (Dunne & Leopold, 1978; Pringle & Triska, 2000). The rate of infiltration of precipitation at the soil surface, percolation of infiltrated water into the groundwater system, and surface runoff rate is dictated by slope, land cover and the physical characteristics of the soil. The slope of the landscape influences surface runoff rates and the amounts of groundwater influx into a stream system as high sloping landscapes result in increased runoff, causing lower levels of water infiltration to the groundwater aquifer. Vegetative cover provides for higher infiltration rates into the soil layer by providing protective cover against erosion and decreasing surface runoff by slowing lateral movement thus increasing infiltration into the soil (Brooks et al., 2003). Evapo-transpiration is considered a loss from the hydrologic water budget for a watershed and limits recharge to the groundwater aquifer in this region (Dunne & Leopold, 1978). Because land use/cover types dictate the evapo-transpiration, percolation and surface runoff potentials within a watershed, they influence stream baseflows and stream thermal regimes. For example, forested landscape exhibit higher evapo-transpiration rates and impervious surfaces such as roads, rooftops, and parking lots can change surface runoff patterns, both of which decrease levels of infilitration and percolation to the groundwater aquifer. The underlying geology dictates the amount and movement of groundwater in an aquifer. Smaller particles like soil and clay have lower porosity (space between pores) while larger particles like sand and gravel have both higher porosity and permeability. Thus, aquifers consisting of sand and gravel are considered favorable for well development and groundwater production (Grannemann et al., 2000). Therefore, knowledge of the composition and configuration of aquifers indicates the storage and discharge capacity of groundwater to both wells and streams and overall, areas conducive to groundwater exploitation throughout the state.

Human activities which alter land cover within a watershed therefore have the ability to negatively impact the thermal regime of stream ecosystems for brook charr; (Dunne & Leopold, 1978; Bartholic et al., 1983; Wang et al., 2003; Gaffield et al., 2005;

Wang et al., 2006). For instance, development (i.e. agriculture, urbanization) may decrease riparian vegetation and stream shading, which can cause increases in temperature within the stream, thus impacting the cold water refugia needed for fish production (Gaffield et al., 2005; Whitledge et al., 2006). Construction of ditches and use of tile drains for the purpose of agricultural and urban development disrupts the distribution of groundwater recharge and discharge in an area which can ultimately impact stream baseflow, as total recharge to the groundwater aquifer is an indication of baseflow (Winter et al., 1998; Michigan Department of Environmental Quality et al., 2006). In highly urbanized areas, impervious surfaces (e.g., paved roads, buildings) decrease groundwater recharge through decreased infiltration from increased surface runoff to the stream which can result in destabilization of stream temperature and flow (Wang et al., 2003). Under unaltered conditions, the groundwater system is constantly discharging (outflow to lakes, streams and wetlands) and recharging (inflow from precipitation, loss to surface water bodies) to maintain equilibrium however, this natural equilibrium changes when groundwater is withdrawn from the aquifer and land cover alterations reduce recharge rates to the groundwater aquifer. Groundwater withdrawals exceeding natural rates of aquifer recharge result in reduced groundwater input to streams from seeps and springs and alter stream temperatures by reducing coldwater temperature inputs provided by groundwater (Hendrickson & Donnan, 1972; Owen, 1991). As such land cover changes reducing recharge to the groundwater aquifer along with large capacity groundwater extraction act to degrade brook charr thermal habitat and thus their viability as both can reduce the contribution of groundwater input to coldwater groundwater-dominated stream systems that charr depend on for life.

### *Groundwater policy*

In Michigan, the effects of groundwater withdrawals on flows and levels in streams, inland lakes, and wetlands have primarily been ligated in the court system rather than being dictated by policy reflecting knowledge of the groundwater and surface water systems (i.e. *Michigan Citizens for Water Conservation v. Nestlés Waters North America*, Inc., 709 N.W.2d 174 (Mich. Ct. App. 2005)). Prior to lawsuits, there was an overall lack of governance of groundwater withdrawals in the state which ultimately led to legal action. The absence of science-based policy in Michigan created a gap where litigation became the primary decision framework and impeded the ability of decision makers to build consensus on groundwater policy (GWCAC 2006) and natural resource managers to determine management decisions allowing for continued viability of these populations. This lack of science likely created a disconnect between land, water, and fisheries managers with the result being the implementation of incompatible management decisions.

Legislation was implemented in 2006 (PA33-2006) which put limits on new or increased groundwater withdrawals in Michigan and was implemented to prevent large capacity surface or groundwater withdrawals from causing an adverse resource impact (decrease in stream flow during the time it is at its lowest levels, typically during the summer months), thus reducing the stream's ability to support characteristic fish populations (PA 33 2006). This law dictates groundwater withdrawals that can occur based on the withdrawals impact on stream ecosystems, focusing primarily on impacts to charr streams, likely due to their recreational value, status as Michigan's state fish, and fact that most coldwater streams in the state are groundwater dominated. As a result, water quality regulations were designed more strictly for coldwater (10-18°C) streams: However as of February of 2008, the legislation applied to all lakes and streams, likely due to the fact that groundwater contributes/regulates temperatures in warm, cool and coldwater stream systems (Wiley & Seelbach, 1997). According to Karas (1997), "brook trout have been likened to canaries used in mines to detect deteriorating air quality. When brook trout disappears from a stream it's a sign that water quality has deteriorated and the stream is in trouble."

In June 2008, with the passage of the Great Lakes-St Lawrence River Basin Water Resources Compact (June 2008), the Michigan Department of Environmental Quality (DEQ) is now required to assess adverse resource impacts of new groundwater extractions on Michigan's freshwater resources, giving legal protections to all waters within the Great Lakes Basin, and banning large diversions (>70 gpm) of ground and surface water resources. The legislation established in Michigan specified under the Compact requires an assessment of the likelihood of an adverse resource impact by a proposed water withdrawal which specifically addresses impacts to fish species (PA 33 2006). While the controversy surrounding the withdrawal of groundwater commercially in Central Michigan assisted in the passage of the groundwater withdrawal law passed in 2006 and the passage of the Compact in 2008, current groundwater law and management decisions still do not consider the impact of land use/land cover alterations on the groundwater resources nor the coupling of these activities to the potential impacts of groundwater withdrawals on the biotic communities of Michigan's groundwater dependent aquatic systems. Failure to address potential impacts of land use change in the face of increased groundwater withdrawal may prove to be detrimental to the thermal habitat to these communities, particularly those that are coldwater dependent such as brook charr.

### *Goals*

While the relationship between groundwater and surface water systems is generally understood, the exact magnitude of the impact of groundwater withdrawals and land cover change on stream temperatures important for brook charr has been unclear. The goals of this study were to assess the impact of groundwater withdrawal and landscape alteration on available brook charr thermal habitat in two groundwater dominated charr streams in the Lower Peninsula, Michigan, and evaluate groundwater and land use/land cover management strategies for protection of the thermal habitat needs for brook charr within these streams. This was accomplished by integrating models related to land use/cover, the groundwater system, and stream temperature in relationship to brook charr thermal preferences (Figure 2).

### *Study site*

This study focused on two groundwater-dominated streams in Osceola County, Michigan: Twin and Chippewa Creeks; tributaries to the Muskegon River which flows into Lake Michigan (Figure 3). This area was selected for study due to concern about the impact of groundwater withdrawal on the aquatic ecosystems within the state of Michigan after the Michigan Department of Environmental Quality (MDEQ) granted permission to a water bottling industry to place a large capacity (100,000 gallons per day) groundwater well in this region in 2006. In order to determine the potential impairment of this groundwater withdrawal operation on brook charr populations via alteration of stream temperatures in both Twin and Chippewa Creeks, we focused our study on four stream reaches, two within each stream (Figure 4). These reaches were chosen based on available stream flow data, temperature and stream morphological data as well as the proximity of the reaches to the simulated high capacity extraction well. Sampled stream reaches exhibit annual baseflow (cms) to total average stream flow (cms) ratios of between 0.81-0.85, suggesting high levels of groundwater input. Both streams support brook charr as well as other species typical of coldwater stream systems in Michigan; brown trout (*Salmo trutta*), mottled sculpin (*Cottus bairdii*), and brook stickleback (*Culaea inconstans*).

Land cover in the watershed is comprised mainly of forest (73%), principally deciduous in nature (birch, beech and maple), followed by grasslands and shrub land cover (briars, sumac and dogwood) (8%), agriculture land (soybeans and alfalfa) (7%), wetlands (6%), and urban landscapes (4.6%). The predominant soil types (sandy soils, loamy sands) have moderate to high seepage rates yielding high rates of groundwater recharge. The majority of each stream system is covered by deciduous forest canopy with vegetated stream banks. The vegetation helps to stabilize stream banks while the forested canopy aids in maintaining the temperature of these coldwater streams (Malcolm Pirnie Inc, 2006). Groundwater users within the watershed extract groundwater from an unconfined glacial aquifer for either direct consumption or non potable purposes, such as agricultural, commercial, and industrial use.

## METHODS

### *Groundwater system characterization*

The groundwater model, *Interactive Groundwater*, (Li & Liu, 2009) was used to delineate the unconfined groundwater aquifer underlying the study area. This model is a

GIS-enabled hydrology tool which uses existing information on surface water features, geologic material, watershed delineations, elevation and topography in a geo-referenced format that allows for quantification and simulation of groundwater quantity and flow. This tool is a combined research and outreach tool which has been used to create a visual library depicting various dynamics of groundwater flow and contamination transport, examine groundwater influence on stream flow,and establish static water levels for Michigan Well-Head Protection Areas (Bartholic et al., 2007; Li & Liu, 2009). The model uses information within existing groundwater well records detailing the geologic material within the aquifer (i.e. elevation, lithology and specific capacity) and static groundwater levels, to determine aquifer flow boundaries and movement. The tool allows for designation of sources (i.e. recharge areas) and sinks (i.e. streams, wells) using GIS layers characterizing recharge values and the location, geometry and elevation of surface water features (Li & Liu, 2003). Flow and movement in the model was simulated using equations based on Darcy's Law (Bedient & Huber, 1992). Verification and explanation of model equations is detailed extensively by Li et al. (2009). The data used by the Interactive Groundwater are detailed in Table 1.

Using the groundwater model, we first designated an area (approximately 120 $km^2$) within the county surrounding the study watersheds in order to detect regional trends in groundwater movement and examine any hydrologic influences (i.e. rivers, lakes) on the groundwater system that might be affecting the baseflow of the streams in our watersheds. Examination of regional trends in groundwater movement was conducted as aquifer boundaries may not necessarily coincide with surface watershed or jurisdictional boundaries (Dunne & Leopold, 1978). We found little regional influences on groundwater flow from large scale surface water features. Therefore, a sub model was created within the regional boundary at a finer resolution (approximately 120 m x 160 m) in order to more accurately capture local aquifer properties and the subsequent changes in groundwater movement that would occur due to a groundwater withdrawal within the study area. The heterogeneity of the unconfined aquifers throughout the state suggest variability in aquifer properties on the regional level and consequently, site specific aquifer characteristics might differ from data interpolated from regional aquifer characteristics (Malcolm Pirnie Inc, 2006), thereby supporting a more local scale examination. Data from a statewide database of existing groundwater wells from records established at the time of well construction, their location and associated geologic properties were used to determine aquifer elevations and hydraulic conductivity throughout the entire model area using kriging interpolation and variogram analysis (Gringarten & Deutsch, 2001).

Existing groundwater withdrawal wells in the watershed were incorporated into the model using pumping rates from published data (Michigan Department of Environmental Quality, 2006) and previous research conducted within the study area (Malcolm Pirnie Inc, 2006) in order to account for the impact of current groundwater wells on both stream systems. Baseflow measures from seven locations (4 from Twin Creek, 3 from Chippewa Creek) and groundwater monitoring well levels were used as calibration parameters in the model. These measurements were based on an average of existing hydrologic conditions and are representative of a steady state model.

Initial aquifer parameters simulated in Interactive Groundwater were compared to known, observed baseflow measurements from these seven locations based on monthly stream flow data collected between January 2001 to September 2007 (stream flow data measures varied for each of the sampling locations) and an average of groundwater level data collected from 38 monitoring wells in the study area from January 2001 to January 2003. Aquifer parameters (i.e. hydraulic conductivity, recharge and stream leakance) were modified until the baseflow and groundwater levels matched that of observed field data as closely as possible. Stream leakance represents the hydraulic connection between the stream bottom sediments and the groundwater aquifer; it is vertical hydraulic conductivity of stream bed sediments divided by the thickness of the sediments (Li & Liu, 2009). Based on past studies, an overall accuracy of 60% was considered to be acceptable for both baseflow and groundwater level for this groundwater modeling environment (Hassan Abbas, Research Hydrologist, Michigan State University, Department of Civil and Environmental Engineering, pers. communication).

The calibrated model was then used to examine the impacts of groundwater withdrawals on baseflow by a high capacity well in the watershed by simulating pumping rates of 70 gpm, 150 gpm, 400 gpm, 700 gpm, 1000 gpm and 2000 gpm and comparing the change in baseflow of the study reaches when the well was not operated to baseflow of the reaches during pumping. The outcomes were then used to examine impacts on stream temperature and brook charr thermal habitat availability. The minimum value (70 gpm) reflects the pumping rate requiring a groundwater withdrawal permit from the MDEQ, subsequent rate increases reflect potential pumping regimes used by industrial and public supply wells in the area. The 2000 gpm extraction rate reflects the potential maximum pumping capacity for this high capacity well.

### *Land use/land cover alteration*

Four different land use/land cover alteration scenarios were simulated to examine the impact of land cover change on baseflow via changes in recharge rates. Aquifer recharge rates were used in Interactive Groundwater as a measure to quantify how changes in land use/land cover alteration within the landscape can affect the dynamics of the underlying aquifer. We used the recharge rates from a U.S. Agricultural Research Service supported soil-water assessment tool (SWAT) (Neitsch et al., 2005) to determine recharge values for the land use/land cover types in the watershed in 2005. SWAT is a public domain watershed modeling tool supported by the U.S. Agricultural Research Service which has been used in water resource and nonpoint source pollution issues (i.e. total maximum daily load analysis) and land management (i.e. effectiveness of conservation practices ) applications (Gassman et al., 2007). SWAT is based continuous time model that uses local soil type, land use/land cover, surface water features, climate data, and topography to determine, for this study, the recharge rates in the study area (Neitsch et al., 2005). Recharge values were designated into 47 different recharge values, comprising 14 different land use/land cover types containing between 1 and 5 different soil types. Average recharge rates by land use/land cover type are detailed in Table 2.

We simulated land cover changes within the study area by altering a 2005 land use/land cover classification using ArcGIS 9.0 Arc Toolbox (ESRI, 2008). The 2005 land use/land cover coverage was classified by Michigan State University Remote Sensing & GIS using ortho-rectified aerial photos from the Michigan Geographic Data Library. These alteration scenarios were based on a qualitative assessment of land use/land cover change noted in the watershed since 1972 as this was the first year aerial photos were available for the watershed. Additionally, we modeled two scenarios that were based on land cover change which the data suggest would result in decreased recharge rates; forest to pasture (approximately 3.33 $km^2$; 10% of total forest), grassland to urban (approximately 1.7 $km^2$; 30% of total grassland), and two scenarios which would likely result in increased recharge rates; agriculture to grassland (approximately 2 $km^2$; 40% of total cropland), forest to shrub land (approximately 6.65 $km^2$; 15% of total forest). This analysis provides insights as to the relative impacts of these specific land use/land cover scenarios on baseflow and stream temperature in order to assess land use/land cover policy changes as conservation strategies that might be used to offset the impacts of groundwater withdrawal on baseflow and stream temperatures, and hence brook charr.

The land cover change scenarios and the amount of land cover that was converted is based on the relative change that has occurred in these two watersheds over the past 37 years while the change in forest land reflects a potential forest management plan or clear-cut for either large scale human development or timber production. The location of each land cover change was determined by (1) proximity to areas with the same land use/cover type (i.e. in order to change grasslands near urban areas into urban land cover), (2) proximity to stream reaches (to assure land cover change was within range of the recharge area contributing groundwater to the stream) and (2) clustered areas of similar land cover types to simulate effects of increasing certain cover types rather than fragmented patches.

### *Stream temperature*

In order to estimate potential changes in stream temperature in the study streams from changes in baseflow due to groundwater extraction and land cover changes, we used a stream temperature model, SSTEMP, developed by and available through the United States Geological Survey (Bartholow, 2002). This allowed for an examination of stream temperature change in relationship to available brook charr temperature in the study stream and brook charr temperature preferenda. SSTEMP was used to predict changes in temperature based on changes in baseflow predicted by the Interactive Groundwater assessment tool. SSTEMP uses stream geometry and hydrology, meteorological data and stream shading to predict changes in stream temperatures for these stream segments for specific time periods (Bartholow, 2002). SSTEMP is a mechanistic, steady state heat transport model which simulates the various natural heat flux processes found in a stream such as air convection, evaporation, conduction through the stream bed, topographic and riparian vegetation shading, streambed friction, back radiation, and long and short wave atmospheric radiation to predict mean daily stream temperatures and estimate daily minimum and maximum temperatures (Bartholow, 2002) SSTEMP assumes that groundwater is gained at a constant rate along each reach and uniformly apportioned throughout the stream segment and air temperature, shade and channel shape are assumed not to change along the stream reach (Bartholow 2002). Data used in the SSTEMP model are detailed in Table 3. Field measurements for each stream reach were used to develop a relationship between channel width and discharge using a power function (Bartholow, 2002). Air temperature was obtained from the closest city with daily air temperature measures (Big Rapids, MI; 24 km). All other meteorological parameters were obtained from the nearest NOAA weather station (Houghton Lake, MI; 72 km), as it was the closest source of comparable and extensive climatological data required for the model. Dust coefficient and ground reflectivity were estimated from values used by Theurer (1984) developed by the Tennessee Valley Authority (1972). Mean annual air temperature was used in lieu of ground temperature as suggested by Bartholow (2002) as no actual ground temperature measures were available. Stream shading percentages were estimated through on-site evaluation.

Components of SSTEMP, which aptly model individual stream reaches, and the more detailed SNTEMP, which allows for modeling of a complex network of many stream reaches, have been used to evaluate the effect of altered flow regimes, stream widths and riparian shading on water temperatures in a Colorado trout stream (Bartholow, 1991), evaluate the importance of groundwater and riparian shading on adequate bass habitat in Ozark streams (Whitledge et al., 2006), and determining the influence of stream shading in maintaining summer temperatures in a brook charr stream (Pajak, 1992). Additionally, Gaffield et al. (2005) used an adapted version of SNTEMP to predict summer temperatures in two Wisconsin streams and was able to illustrate (1) the overall importance of groundwater and riparian shading as controls to summer temperature in small Midwestern streams and (2) the significance of temperature models in facilitating watershed management decisions.

Relative humidity, wind speed and mean annual air temperature were used in SSTEMP model calibration and were adjusted until predicted stream temperatures closely matched observed stream temperature data. The aforementioned parameters were used since the data was collected at a location away from the study reaches and thus not completely indicative of actual site conditions. Groundwater temperature was also used to calibrate the model as groundwater temperatures in Michigan range from 8.2°C-11.3°C (Leverett, 1906). Baseflow output from the Interactive Groundwater model was used in the following equation to determine stream discharge parameters for the model:

$$Q = a + bx \qquad \text{Equation 1}$$

where Q equals stream segment discharge, $a$ equals stream inflow, $b$ equals baseflow and x equals stream length (Gaffield et al., 2005). In this manner, stream inflow minus outflow divided by segment length is equivalent to the baseflow along the reach (Bartholow, 2002). In this model baseflow estimated from stream flow at the sampling points is assumed to be indicative of a culmination of flow along the reach and therefore uniformly apportioned throughout the designated upstream segment (Bartholow, 2002). Stream inflow for both upstream segments was set to zero and it is assumed that all accumulated flow will accrue through accretions of groundwater. The two upstream segments begin at small impoundments (approximately 2.1 acres at Twin Creek and 1.5 acres at Chippewa Creek; High Resolution National Hydrography Dataset, 1:24000 scale, 2004) and were assumed to be a headwater as no data regarding flow above or from the reservoirs exists. However, it has been reported that water levels in these impoundments are constant throughout the year and have short residence times, thereby justifying our assumption of no inflow (Malcolm Pirnie Inc, 2006).

Stream temperature data from July and August were used to calculate mean monthly stream temperatures for each stream reach. From this, we examined the relative change required to alter stream temperatures past the thermal optimum and into the upper lethal temperature for brook charr, and related this to the predicted changes in stream temperature due to groundwater withdrawal and land cover change estimated from the SSTEMP model. We focused on stream temperatures in July and August as these months are the most stressful to brook charr as stream temperatures usually at their highest and flows are at their lowest in Michigan.

## RESULTS

### *Baseflow change predicted from groundwater withdrawal rates*

The groundwater aquifer underlying the study area was depicted as a single unconfined aquifer based on available geologic data in the groundwater well data layer (Michigan Department of Environmental Quality et al., 2006). Bedrock aquifers which underlie the glacial deposits were not modeled as they are not currently used for water supply (Michigan Department of Environmental Quality et al., 2006; Apple & Reeves, 2007). The general movement of groundwater in the system predicted by the model is approximately perpendicular to the surface watershed boundaries, flowing towards the larger river system, the Muskegon, where both creeks drain (Figure 3). This is expected and corresponds to higher elevations in the upper part of the surface watershed and the lower elevations occurring at the Muskegon River (Dr. Shu-Guang Li and Hassan Abbas, Michigan State University, Department of Civil and Environmental Engineering, pers. communication).

Examination of the difference between observed versus predicted values (residuals) allows for a quantification of the error in the groundwater model. As such, three different metrics (i.e. mean residuals, absolute value of residuals and root mean square error (RMSE) were calculated in order to determine model error and the accuracy of our model compared to actual measured data at the location of the specified monitoring wells. The statistics and methods used to assess model error were taken from Anderson and Woessner (1992). Comparison of observed groundwater levels and model predictions of water levels in the aquifer reveal a mean of the residuals of -2.04 meters, a mean of the absolute value of the residuals of 2.80 meters and a RMSE of 3.35 meters ($R^2 = 0.5148$). The RMSE of 3.35 meters is within 24% of the range of observed groundwater level measurements that were used as calibration targets in the model. Baseflow measures versus model predicted baseflow values indicate accuracies between the 60th percentile and the 97th percentile ($R^2 = 0.8844$) with the majority being within the 80th percentile.

Groundwater extraction was found to reduce baseflow in Twin and Chippewa Creeks; distances from the pump ranged from 730 m to 1150 m for Twin Creek and 1800 m to 2500 m for Chippewa Creek. When compared to stream baseflow values when the well was not in operation, the predicted reductions ranged from 0.2% at a pumping rate of 70 gpm in the upper reach of Twin Creek to 25.8% at a pumping rate of 2000 gpm at the midstream reach of Chippewa Creek (Table 4). Baseflow reductions were shown to increase with increased pumping rates with overall, larger percentages of change occurring to the stream segments in Chippewa Creek (Figure 5). Therefore, pumping of any magnitude above 70 gpm will have some impact on baseflow in the study stream segments of these groundwater-dominated streams.

### *Stream Temperature*

Stream temperatures predicted by SSTEMP were within 0.11°C - 0.50°C of actual stream temperatures collected at sampled stream segments and reflects the high degree of accuracy of this model. The changes in stream temperature due to the reduction of baseflow as a result of groundwater extraction during midsummer resulted in stream temperature changes ranging from 0 to 0.91°C in both July and August (Table 5). In three out of the four reaches evaluated, all groundwater pumping rates simulated resulted in an increase in stream temperature with the exception of the midstream reach of Twin Creek, which showed no change in temperature at pumping rates of 70 and 150 gpm. The lack of temperature change may be explained by the fact that this reach experienced the lowest percentage change in baseflow (0.20% in July and 0.43% in August) and has the highest baseflow of all four reaches. In general, reduction in baseflow resulted in increases in temperature approximately proportional to the magnitude of pumping (0.38:0.33); hence the greater the pumping rate, the less baseflow and the warmer the water temperature in these stream segments during the summer months of July and August. However, the magnitude of temperature change was, overall, quite small, with increases never projected at more than 1.00°C.

### *Land use/land cover alteration*

Recharge rates from the SWAT model show that grassland provided the highest recharges rate (14.30 in/yr) while both industrial and commercial (urban) landscapes had the lowest recharge rates (1.07 in/yr). Interactive Groundwater predicted higher baseflows when 15% of the land cover was changed from forested land to shrub land; thus resulting in stream temperature decreases of between 0.01°C to 0.09°C in all four stream reaches for both July and August (Figure 6), a result of the recharge rates for shrub land being higher than forested landscapes thus facilitating higher recharge rates and higher baseflows. A 40% change from cropland to grassland resulted in temperature decreases of between 0.08°C to 0.14°C in the upper and midstream reaches of Chippewa

Creek, respectively, however the upstream segment of Twin Creek showed decreased baseflow and increased temperatures of 0.04°C while the midstream segment showed relatively no change in either baseflow or temperature (Figure 6). Land cover alteration of 30% of grassland to urban resulted in increased temperature in both segments of Twin Creek however resulted in increased baseflow and thus decreased temperature in both reaches of Chippewa Creek. A 10% change of forest to pasture resulted in slight changes in temperature in Chippewa Creek reaches (-0.01°C) and the upper reach of Twin Creek (+0.01°C) due to increases and decreases in baseflow respectively, while there was no change in the midstream segment of Twin Creek (Figure 6).

If the area in which a land cover change was applied is relatively small compared to the total area contributing to stream baseflow, the groundwater model may not detect as significant a change in baseflow to the stream (Hassan Abbas, Research Hydrologist, Michigan State University, Department of Civil and Environmental Engineering, pers. communication), thus resulting in little to no change in stream temperature. For instance, the minor change in baseflow, hence lack of impact on temperature, in the upper reach of Twin Creek may be due to the fact that the area of the aquifer contributing baseflow to that reach may only contain 1% of the grassland from the total 10% change from cropland to grassland that was simulated in the watershed, whereas in both reaches of Chippewa Creek, the portion of land changed from cropland to grassland is likely contained entirely within the area in which the aquifer contributing to the baseflow of that system. Additionally the relatively minor differences in recharge rates between forest (7.35 in/yr) and pasture (6.33 in/yr) may explain the relatively minor changes in baseflow and temperature when evaluating these land cover conversion simulations.

### *Brook charr temperature preferenda*

Of the four stream reaches evaluated in regards to the mean July and August monthly temperatures, only the upper reach of Chippewa Creek exhibited temperatures that would rise beyond the temperature tolerances for brook charr (Figure 7a). All other segments had mean monthly temperatures that were within the optimal growth and survival range for brook charr. As such, pumping at 70gpm or greater will result in a loss of thermal habitat for brook charr in midsummer within the upper reach of Chippewa Creek. The magnitude of change required to take brook charr out of their thermal optimum for the other three reaches, which have lower mean monthly temperatures than the midstream reach of Chippewa Creek, will not occur using the pumping rates we examined because of their overall higher baseflows (Table 4) and thus lower mean monthly temperatures in these reaches. A change in these stream reaches to the lethal thermal temperatures for brook charr (>19°C) would require temperature increases in July of at least 0.51°C (Twin Creek) and at least 1.13°C (midstream reach of Chippewa Creek) (Figure 7b). In order for such a temperature change to occur, the baseflow in these streams would need to decrease by 18.8% in July and 22.5% in August in the upper reaches of Twin Creek and by 23.4% in July and 39% in August in the lower (midstream) reaches of Twin Creek. In the midstream reach of Chippewa Creek, baseflow changes of approximately 30% in July and 53% in August would move the stream into lethal temperature limits for brook charr. At no time were brook charr close to the reported upper lethal temperature (25.3°C) in either stream. In order to experience the lethal temperature, the stream segments would need to have temperature changes of at least 5 to 8°C.

# DISCUSSION

Poff et al. (1997) found that stream fish communities are impacted by changes in land use and land cover within a watershed that impact the supply of water to a stream system. Thus, managing aquatic systems in the context of terrestrial landscapes is important to adequately manage fish and fisheries (Taylor et al., 2002). Knowledge of the impact of specific land cover alterations on stream baseflow and temperature can allow for implementation of strategies mitigating the impact of increased groundwater withdrawal in a watershed. The direct linkage between the landscape, surface water and groundwater systems enables one to evaluate the impacts of groundwater withdrawal and land cover changes in a watershed to stream thermal habitat and the production of their fish populations. A study in the Pigeon River, Michigan, U.S.A. found the lack of groundwater to be a limiting factor for brook charr populations (Benson 1953). Groundwater acts to cool and stabilize summer stream temperatures and warm cooler stream temperatures during the winter while land cover determines the levels of groundwater recharge to the underlying groundwater aquifer (Hunter, 1991; Wiley & Seelbach, 1997; Power et al., 1999). Potential for conflict arises when human use of groundwater interferes with groundwater needs for ecological function. Therefore models which facilitate understanding the linkage of the three systems allow fisheries managers and land use policy makers to assess the magnitude of impact that certain anthropogenic activities have on the thermal habitat that brook charr and other biota depend on for survival. By simulating groundwater extraction by a high capacity well and land cover change via changes in groundwater recharge dynamics, we were able to project the degree of impact that such changes would have on brook charr thermal habitat in the study streams, aiding in decisions regarding the suitability of groundwater extraction pumping schedules in relationship to brook charr thermal habitat requirements.

The results of our study showed that all pumping rates evaluated in the Twin and Chippewa Creek watershed resulted in decreased baseflow to every stream reach under study. As such, this pumping removes flow to these streams and overall, will influence groundwater contribution to the Great Lakes. While the magnitude of stream temperature change predicted by this methodology was less than 1°C, the net outcome was a loss of summer thermal habitat for brook charr as summer temperatures were near the maximum optimal growth thermal range for brook charr in these streams. Loss of thermal habitat can equate to reductions in growth and survival of charr in these streams (Power, 1980; Drake & Taylor, 1996). Additionally, reductions in groundwater input may impact brook charr spawning potential as groundwater seeps present potential spawning habitat for brook charr (Power, 1980; Curry & Noakes, 1995). It is important to note, that while water extraction from this high capacity well was only occurring in the Chippewa Creek watershed, impacts of groundwater withdrawal and land use change were evidenced in stream reaches within both watersheds. This emphasizes the fact that aquifer boundaries may not necessarily coincide with surface watershed or jurisdictional boundaries (Dunne & Leopold, 1978). This is significant because groundwater extraction within one watershed can directly impact streams in an adjacent watershed. Therefore, water management agencies which establish water use management plans solely based on surface watershed boundaries may not be adequately addressing the impact of groundwater extraction and land use alteration on aquatic communities in other linked systems.

The small magnitude in stream temperature change due to pumping that we noted for Twin and Chippewa Creeks suggests that other factors other than groundwater may be influencing stream temperatures in these reaches. When temperature in stream reaches approaches the lethal thermal range of brook charr, we would expect to see lowered abundances due to its impact on their growth and survival dynamics (McCormick et al., 1972; Hokanson, 1973). We found that baseflow reductions ranging from 18.8% to 39% in reaches of Twin Creek and 30% to 53% in the midstream reach of Chippewa Creek would result in stream temperatures that begin to surpass the optimal range for brook charr. In the case of the upper reach of Chippewa Creek, any rate of groundwater withdrawal resulted in temperature changes which shifted the stream farther away from the upper optimal temperature (19°C) and closer to the upper lethal limit (25.3°C) and as such would provide poor thermal habitat for brook charr and reduce overall brook charr productivity for this stream reach (Fry, 1971) unless they could move to more favorable temperature conditions elsewhere in the system. For instance, (Hayes et al., 1998) noted that in the Ford River, Michigan, brook charr were shown to seek refuge in the colder water of a tributary headwater stream to evade summer stream temperatures in the main channel that exceeded 20°C. As headwaters of a stream provide important thermal refugia for brook charr (Hayes et al., 1998), it is important that land use practices in these regions do not degrade headwaters conditions conducive to brook charr productivity.

The small changes in temperature at low pumping rates may likely be masked by variations due to natural annual/seasonal variations in stream flow as well as natural annual/seasonal variability in air temperature that currently occurs in Michigan stream systems. Land use practices occurring within the stream corridor, in addition to those occurring in the landscape may impact stream thermal habitat (Allan & Castillo, 2007), for instance, decreases in riparian shading can result in increased stream temperatures due to increased direct solar radiation and is more pronounced when air temperatures exceed that of groundwater temperature (Power et al., 1999). That said, the influence of air temperatures on stream temperatures coupled with increased groundwater withdrawal and land use change, which reduces recharge, will be important to research as climate change threatens to increase global air temperatures and consequently, thermal habitat for fish (Meisner, 1990; Eaton & Scheller, 1996). Additionally, precipitation changes due to climate change warrant further analysis as precipitation is an important component dictating the level of recharge to the groundwater aquifer and thereby influencing surface watershed and groundwater dynamics.

Likewise, examination of the impact of land cover change can give insight into land use practices which reduce recharge thus exacerbating the changes in thermal habitat due to groundwater withdrawals. A population status assessment of Eastern brook charr and evaluation of watersheds over their native range revealed loss of thermal habitat via increased temperatures from changing land use practices and habitat fragmentation (Hudy et al., 2008). Declines of brook charr in Maryland streams were strongly influenced by land use/land cover causing increased stream temperatures (Stranko et al., 2008). They found increases in water temperature and erosion were associated with increased percentages of urban land and impervious surface and decreased forested land cover. In our study, we found stream temperature similarly increased as a result of reduced recharge from a landscape change to urban. However, unlike Stranko et al. (2008), we projected that decreased forest land cover in our watershed would result in decreases in stream temperatures due to increased recharge to the groundwater aquifer and thus increased groundwater contribution to streams. Our study streams in Michigan were a relatively low elevation system which had a dominance of sandy and gravel soils with high percolation rates and low surface runoff while Maryland streams are typically located in higher elevations, steeper gradient terrains and thus may be influenced more by surface runoff generated from loss of forested land cover. Jacobson et al. (2008) examined the effects of groundwater withdrawals on habitat availability of three freshwater fishes and related it to stream discharge and annual flow regime. While the study by Jacobson et al. (2008) did not specifically address thermal habitat alteration or the influences of land use alteration, they did find that groundwater extraction, through its reductions in stream discharge, reduced available habitat for three distinct species of freshwater fish (brown trout, tessellated darter, and fallfish).

Evaluating the midstream section of Twin Creek only, we found that an increase in stream temperatures of 0.06°C due to a groundwater extraction rate of 700 gpm could be mitigated by implementing a 15% (6.65 $km^2$) change in land cover from forest to shrub land, which provided for an increase in recharge and thus baseflow (Table 6). In this case, the increase in temperature related to groundwater extraction would be ameliorated by the increased recharge rates to the aquifer due to the change in land cover from forest to shrub land. For example, while a high capacity well at 700 gpm may result in increased temperatures at the midstream reach of Twin Creek in midsummer, from 18.47°C to 18.53°C, a land use change would actually result in 18.44°C, thus resulting in stream temperatures lower than the average monthly mean before pumping began. Alternatively, a 30% (1.7$km^2$) change of grassland to urban under a 700gpm extraction rate could potentially result in further loss of thermal habitat (18.53°C to 18.56°C) due to reductions in recharge to the aquifer

The upper section of Twin Creek in midsummer under a groundwater extraction rate of 400gpm pumping rate results in a 0.07°C (18.32°C) change in temperature while a change in land cover from forest to shrub land resulted in a less pronounced decrease in temperature in this reach (-0.01°C), a change in land use from grassland to urban results in a further increase in temperature of 0.1°C (18.42°C) (Table 7). In the upper reach of Chippewa Creek in midsummer, we find that land cover changes from cropland to grassland and forest to shrub land may result in decreases in the rise in temperatures incurred through pumping by -0.09°C and -0.06°C (Table 8), respectively. Therefore, it is important to consider land use practices and their potential impact on stream temperatures as groundwater recharge is influenced by land use/cover and it is the groundwater that provides the needed cool temperatures in streams for coldwater biota such as brook charr.

Our research provides one of the first studies that directly link groundwater withdrawal and land use alterations to impacts on brook charr thermal habitat. The methodology used in this study proved to be an effective way to examine the impact of land cover alteration and groundwater withdrawal on thermal habitat for brook charr. The method uses readily available tools that are easy-to-use and understand, are visual in nature and based on verifiable scientific premises. These methods allow for a linkage of water policy and land use management directly to fish populations and their production dynamics. In Michigan, brook charr are the foundation of an important recreational fishery, which provides a significant amount of revenue to the state from recreational activities by the public. Continued examination and use of this methodology is warranted as groundwater-dominated streams in Michigan and elsewhere will likely continue to be impacted by increased groundwater withdrawal coupled with land use/cover alterations, both of which we have shown to influence thermal habitat of streams and consequently, will impact brook charr viability and productivity. As such, collaboration between water, land and fisheries managers is imperative to optimize the use of our groundwater resource while ensuring brook charr viability and sustainability in the face of increased human demands and global environmental change.

**Table 1**: Input parameters and source data for Interactive Groundwater (Li and Liu 2009).

| Parameters | Source |
|---|---|
| Input | |
| Surface water features, geometries and elevations (stream, lakes, wetlands) | USGS National Hydrography data set |
| Surface elevations and topography | Incorporated within IGW model components |
| Surface watershed divide | Malcolm Pirnie et al. 2006 (S.S. Papadopulos & Associates) |
| Subsurface lithology, elevation of geologic layers and hydraulic properties | Wellogic Data Layer |
| Recharge rates | Soil & Water Assessment Tool, ArcGIS |
| Calibration | |
| Base flow estimates | Derived from stream flow data provided by Malcolm Pirnie In |
| Static water levels from existing wells at time of construction | Wellogic Data Layer |
| Monitoring wells water levels (37) | S.S. Papadopulos & Associates |

**Table 2:** Recharge rates for land use/land cover types within the watershed from the soil and water assessment tool (Available at: www.brc.tamus.edu/swat).

| Land use/Land Cover | Recharge Rate (in/year) |
|---|---|
| Commercial | 1.07 |
| Industrial | 1.10 |
| Open Land | 4.01 |
| Pasture | 6.33 |
| Residential | 6.51 |
| Deciduous Forest | 7.35 |
| Forested Wetland | 7.40 |
| Crop land | 7.90 |
| Mixed Forest | 8.49 |
| Non-Forested Wetland | 8.81 |
| Coniferous Forest | 8.83 |
| Shrub land | 11.52 |
| Clear-cut/Range Brush | 11.80 |
| Grassland | 14.30 |

**Table 3**: Stream Segment Temperature Model (SSTEMP) model parameters (Bartholow, 2002)

| Parameters | | Unit | Source |
|---|---|---|---|
| Hydrology and Simulation period | | | |
| Flow Data | | cms | Measured (Malcolm Pirnie Inc) |
| | Stream inflow temperature | °C | Measured (Malcolm Pirnie Inc and Advanced Ecological Management) |
| | Lateral inflow temperature | °C | Leverett et al. 1906 |
| | Baseflow | cms | Derived from stream flow data (Malcolm Pirnie Inc) |
| | Simulation month and day | | Simulation of a day in July, August, September |
| | Stream Geometry | | |
| Latitude | | decimal degrees | U.S.G.S Topographic Map |
| | Dam at head of segment | | Checked for SF-1 & SF-16 |
| | Stream segment length | km | U.S.G.S. Hydrography Dataset |
| | Elevation upstream | m | U.S.G.S. Topographic Map |
| | Elevation downstream | m | U.S.G.S Topographic Map |
| | Stream width coefficient/exponent | m | Derived |
| | Manning's n | sec/km | Program Default |
| | Meteorological Information | | |
| Air temperature | | °C | Waste Water Treatment Plant – Big Rapids |
| | Relative humidity | % | Calculated (Bartholow 2002) |
| | Wind speed | mph | NCDC - Houghton Lake |
| | Thermal gradient | j/m2/s/c | Program Default |
| | Possible Sun | % | NCDC - Houghton Lake |
| | Dust coefficient | dimensionless | Theurer (1984) |
| | Ground Reflectivity | % | Theurer (1984) |
| | Solar radiation | (Langsleys/d) | Based on dust coefficient and ground reflectivity values |
| | Stream shading | % | Visual estimate |

**Table 4:** Percent change in baseflow at pumping rates of 70, 150, 400, 700, 1000, and 2000gpm for Twin and Chippewa Creeks.

| | | Percent reduction in baseflow | | | | | |
|---|---|---|---|---|---|---|---|
| **Stream reach** | **Baseflow ($m^3s$)** | **70 gpm** | **150 gpm** | **400 gpm** | **700 gpm** | **1000 gpm** | **2000 gpm** |
| Twin Creek (upper) | 0.04723 | 0.47 | 0.96 | 2.52 | 4.41 | 6.27 | 15.22 |
| Twin Creek (mid) | 0.19700 | 0.20 | 0.42 | 1.12 | 1.96 | 2.81 | 6.30 |
| Chippewa Creek (upper) | 0.06400 | 0.69 | 1.46 | 3.85 | 6.75 | 9.66 | 17.32 |
| Chippewa Creek (mid) | 0.13208 | 1.04 | 2.19 | 5.81 | 10.16 | 14.48 | 25.86 |

**Table 5**: Stream temperature change for pumping rates of 70, 150, 400, 700, 1000, and 2000gpm given 2005 land use/land cover in July and August.

Stream temperature change in °C

|  | 70 gpm | 150 gpm | 400 gpm | 700 gpm | 1000 gpm | 2000 gpm |
|---|---|---|---|---|---|---|
| JULY |  |  |  |  |  |  |
| Twin Creek (upper) | 0.01 | 0.03 | 0.06 | 0.11 | 0.15 | 0.38 |
| Twin Creek (midstream) | 0 | 0 | 0.02 | 0.03 | 0.05 | 0.12 |
| Chippewa Creek (upper) | 0.02 | 0.04 | 0.11 | 0.20 | 0.29 | 0.53 |
| Chippewa Creek (midstream) | 0.03 | 0.07 | 0.18 | 0.32 | 0.47 | 0.91 |
|  |  |  |  |  |  |  |
| AUGUST |  |  |  |  |  |  |
| Twin Creek (upper) | 0.01 | 0.03 | 0.07 | 0.13 | 0.19 | 0.48 |
| Twin Creek (midstream) | 0 | 0.01 | 0.03 | 0.06 | 0.09 | 0.21 |
| Chippewa Creek (upper) | 0.02 | 0.04 | 0.1 | 0.18 | 0.26 | 0.49 |
| Chippewa Creek (midstream) | 0.03 | 0.06 | 0.15 | 0.28 | 0.4 | 0.77 |

**Table 6:** Land use/land cover alteration impact on the midstream reach of Twin Creek when land cover is changed from grassland to urban and from forest to shrub land under pumping rates of 150 gpm, 700 gpm and 1000 gpm.

| High Capacity Well Pumping Rates | | 150 gpm | 700 gpm | 1000 gpm |
|---|---|---|---|---|
| Land-use Change | | +0.01°C | +0.06°C | +0.21°C |
| Grassland to urban | +0.03°C | +0.04 | +0.09 | +0.24 |
| Forest to shrubs | -0.09°C | -0.08 | -0.03 | +0.12 |

**Table 7:** Land use/land cover alteration impact on the midstream reach of Twin Creek when land cover is changed from grassland to urban and from forest to shrub land under pumping rates of 150 gpm, 400 gpm and 1000 gpm.

| High Capacity Well Pumping Rates |  | 150 gpm | 400 gpm | 1000 gpm |
|---|---|---|---|---|
| Land-use Change |  | +0.03°C | +0.07°C | +0.19°C |
| Grassland to urban | +0.1°C | +0.13 | +0.17 | +0.29 |
| Forest to shrubs | -0.01°C | +0.02 | +0.06 | +0.18 |

**Table 8:** Land use/land cover alteration impact on the upstream reach of Chippewa Creek when land cover is changed from grassland to urban and from forest to shrub land under pumping rates of 150 gpm, 400 gpm and 1000 gpm.

| **High Capacity Well Pumping Rates** | | **150 gpm** | **400 gpm** | **1000 gpm** |
|---|---|---|---|---|
| **Land-use Change** | | **+0.04°C** | **+0.11°C** | **+0.29°C** |
| **Cropland to grassland** | **-0.09°C** | **-0.05** | **+0.02** | **+0.20** |
| **Forest to shrubs** | **-0.06°C** | **-0.02** | **+0.05** | **+0.23** |

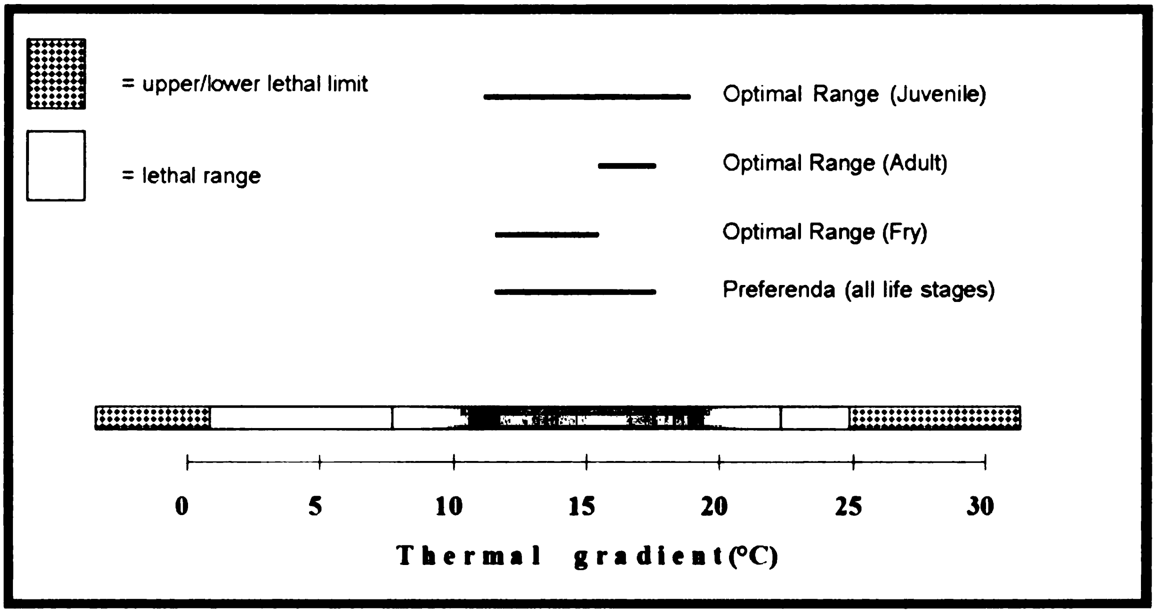


**Figure 1:** Gradient of temperature preferenda for brook charr (*Salvelinus fontinalis*) based on data for fry from (Brett, 1940; McCormick et al., 1972; Hokanson, 1973) , juveniles from (Fry, 1946; McCormick et al., 1972; Cherry et al., 1977) and adults from (Fry, 1946; Hokanson, 1973; Cherry et al., 1977) . Thermal preferences for brook charr range between 12-19°C, with lethal temperatures below 2°C and above 24-25°C.

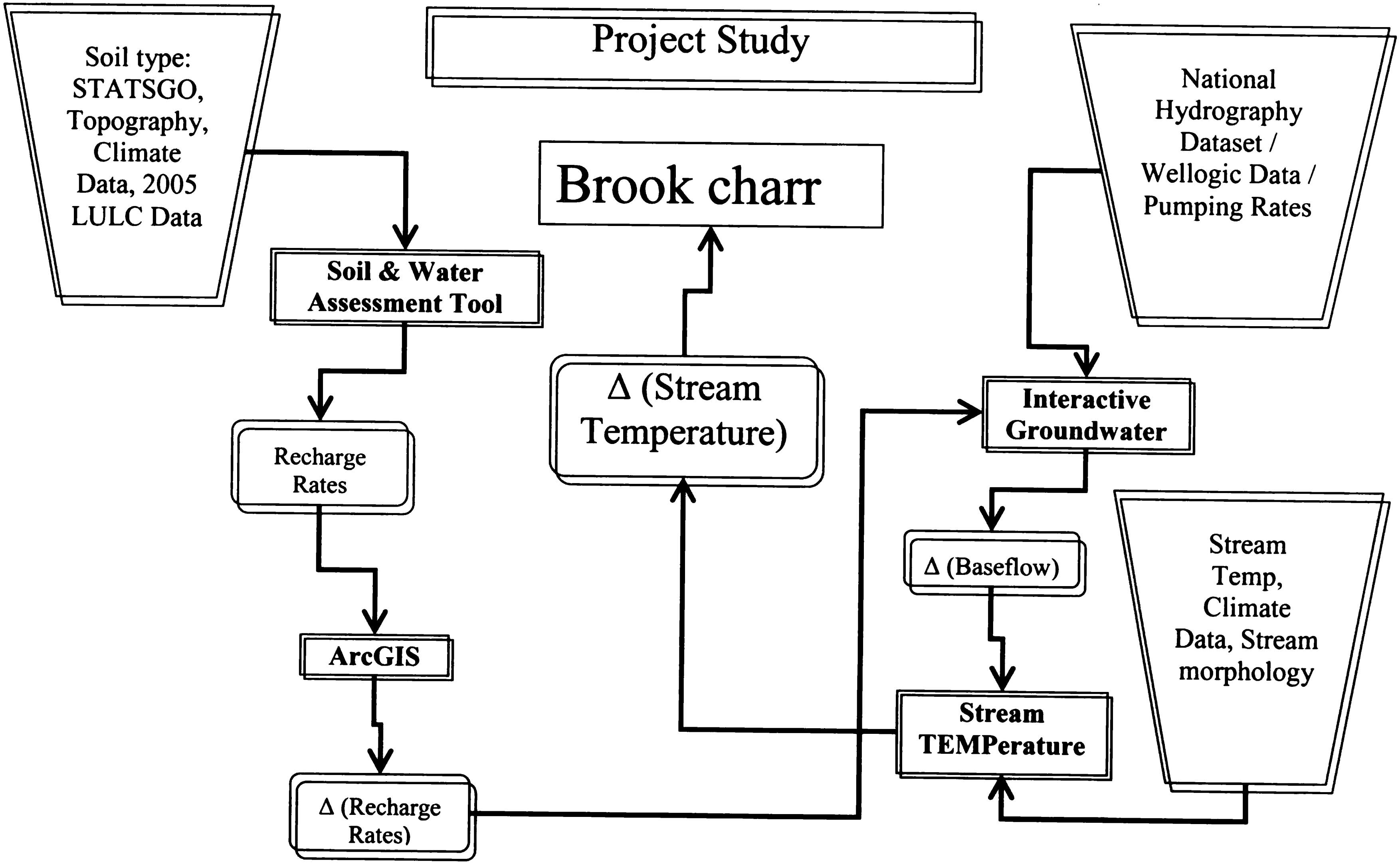


**Figure 2**: Schematic describing linkages between land cover alteration, groundwater production, stream temperatures and brook charr

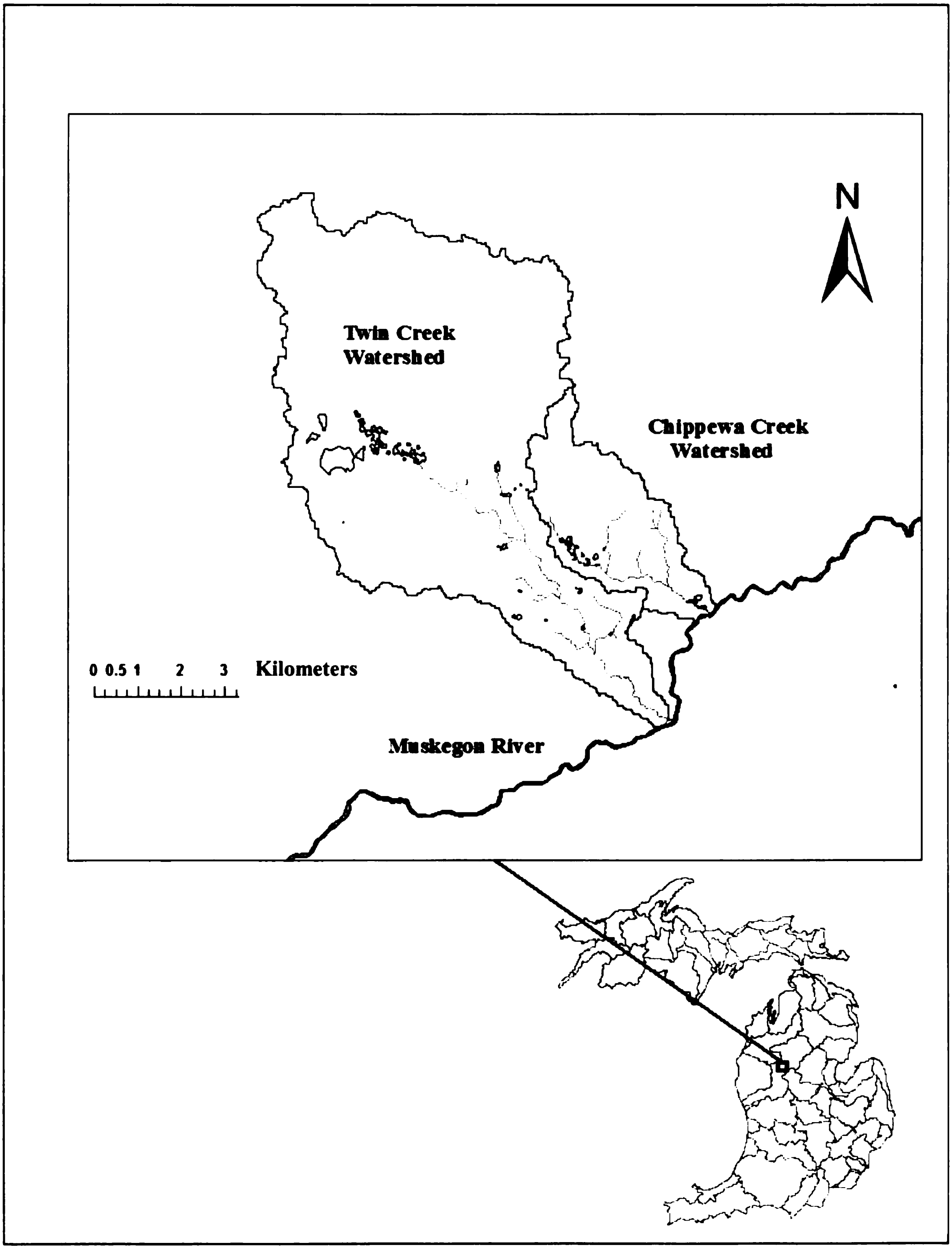


**Figure 3:** Study area; Twin and Chippewa Creek Watersheds, located within the Muskegon River Watershed, Michigan, U.S.A.

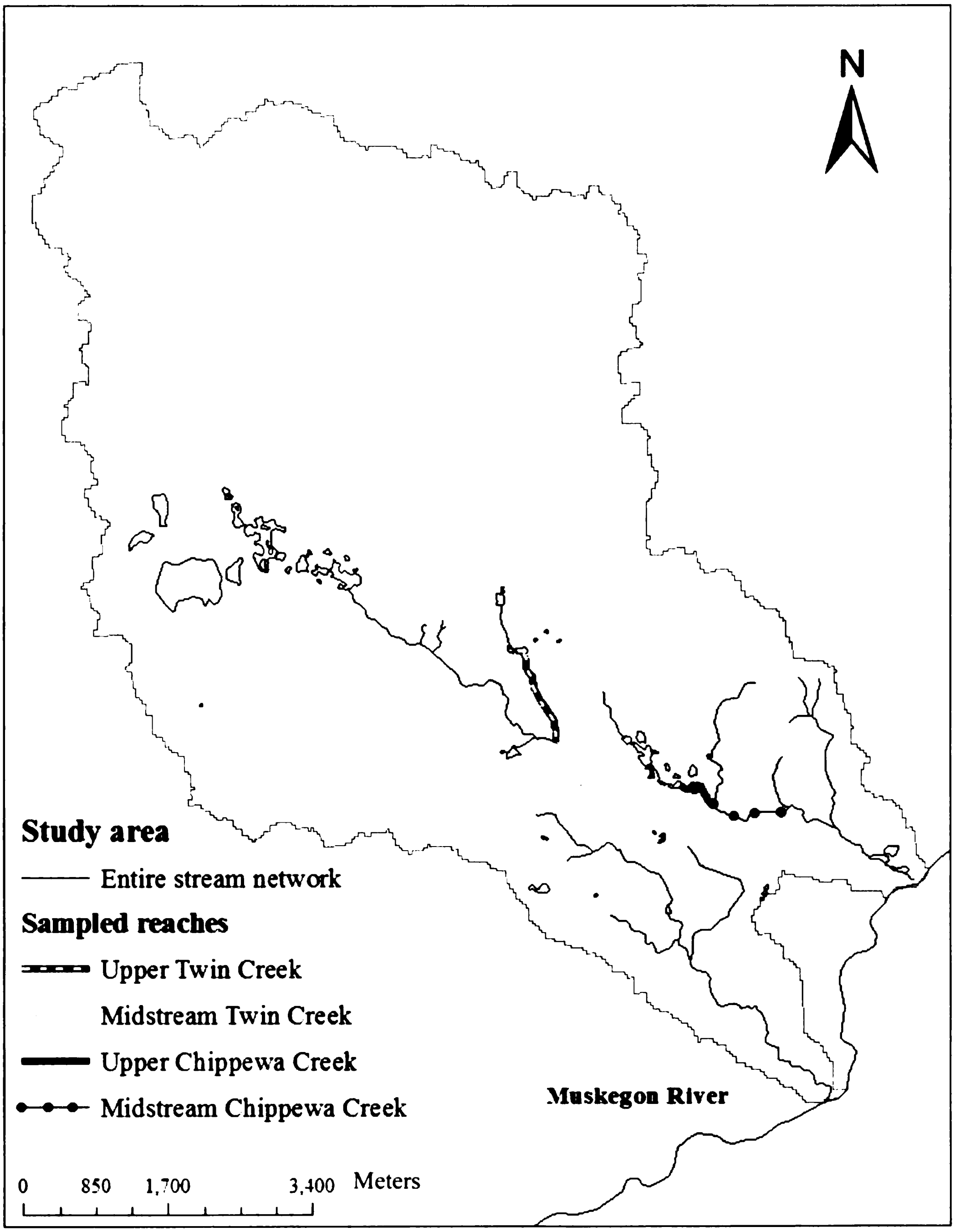


Figure 4: Stream reaches modeled with SSTEMP

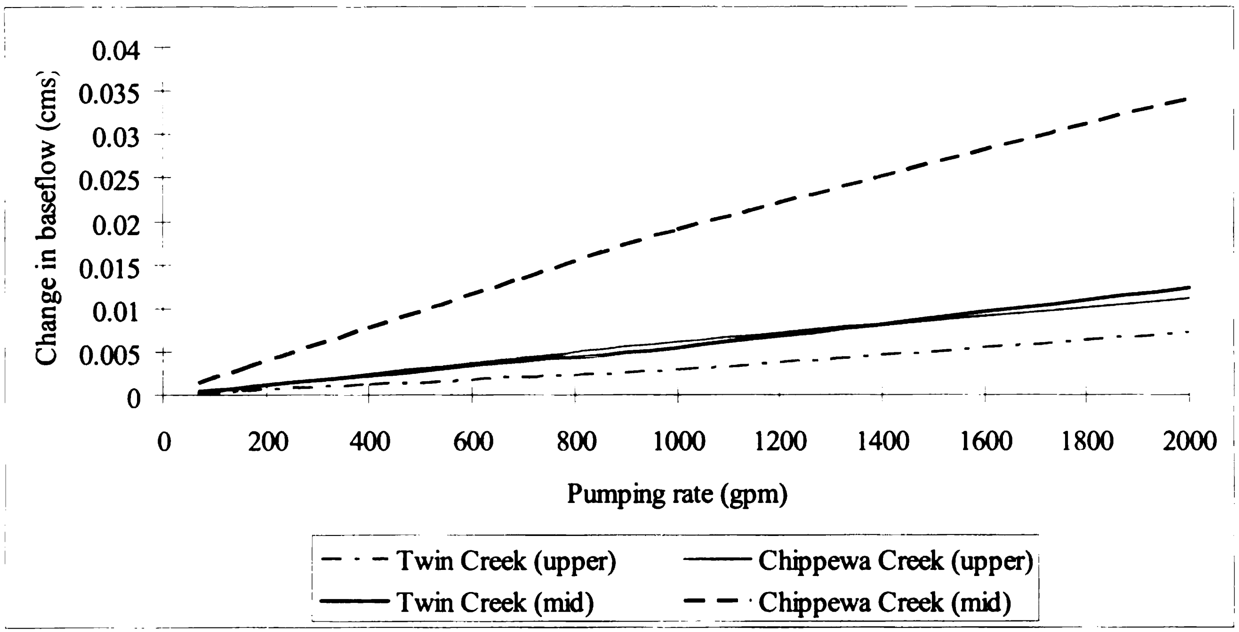


**Figure 5:** Change in baseflow for each sampled stream segment in Twin and Chippewa Creeks at groundwater withdrawals of 70, 150, 400, 700, 1000, 2000 gpm.

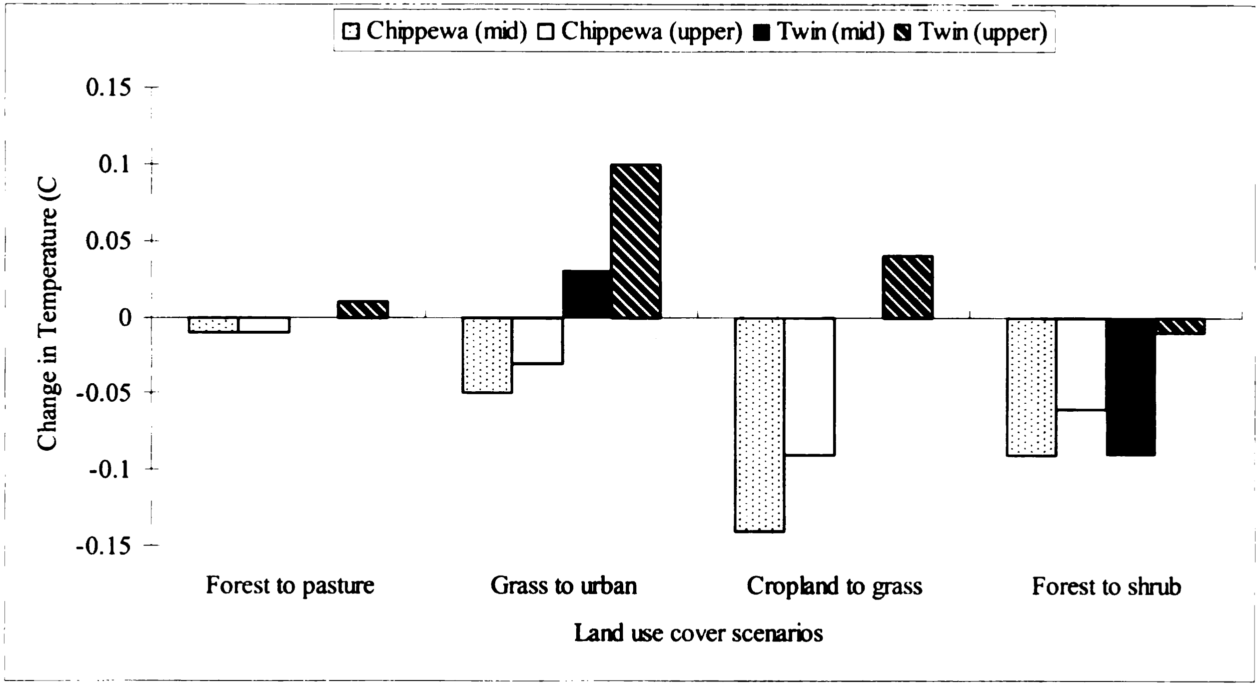
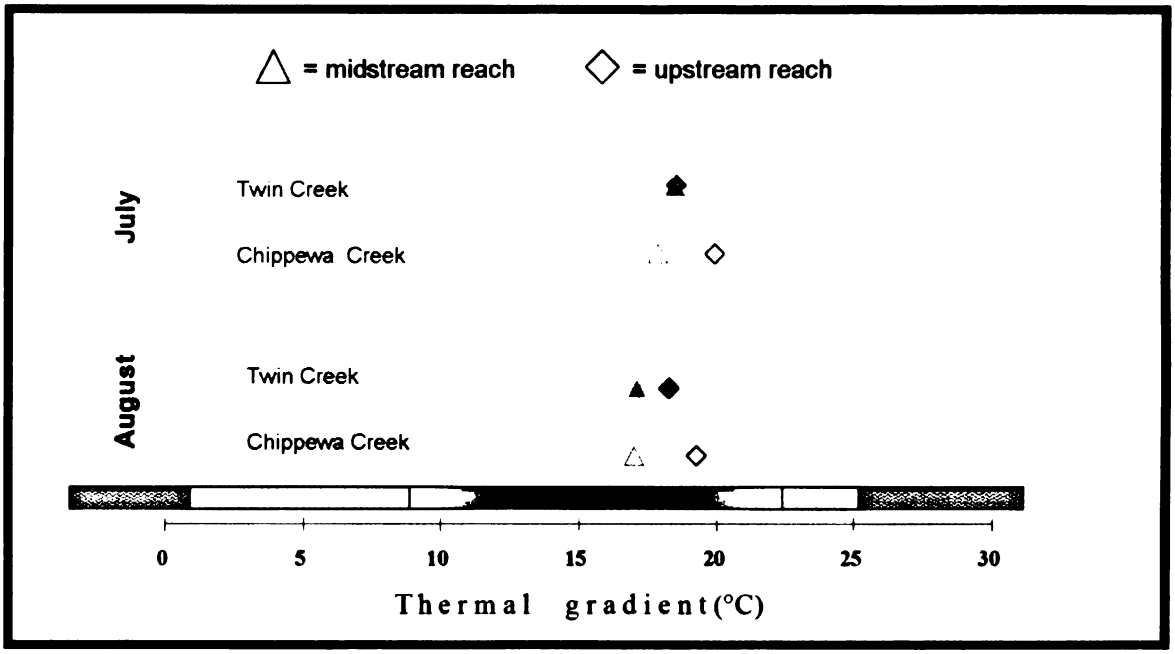


**Figure 6:** Land cover alteration scenarios impact on stream temperature in the Twin and Chippewa Creek study stream segments. Alteration scenarios are as follows: forest to pasture (approximately 3.33 $km^2$ ; 10% of total forest), grassland to urban (approximately 1.7 $km^2$; 30% of total grassland), agriculture to grassland (approximately 2 $km^2$; 40% of total cropland), forest to shrub land (approximately 6.65 $km^2$; 15% of total forest).

A



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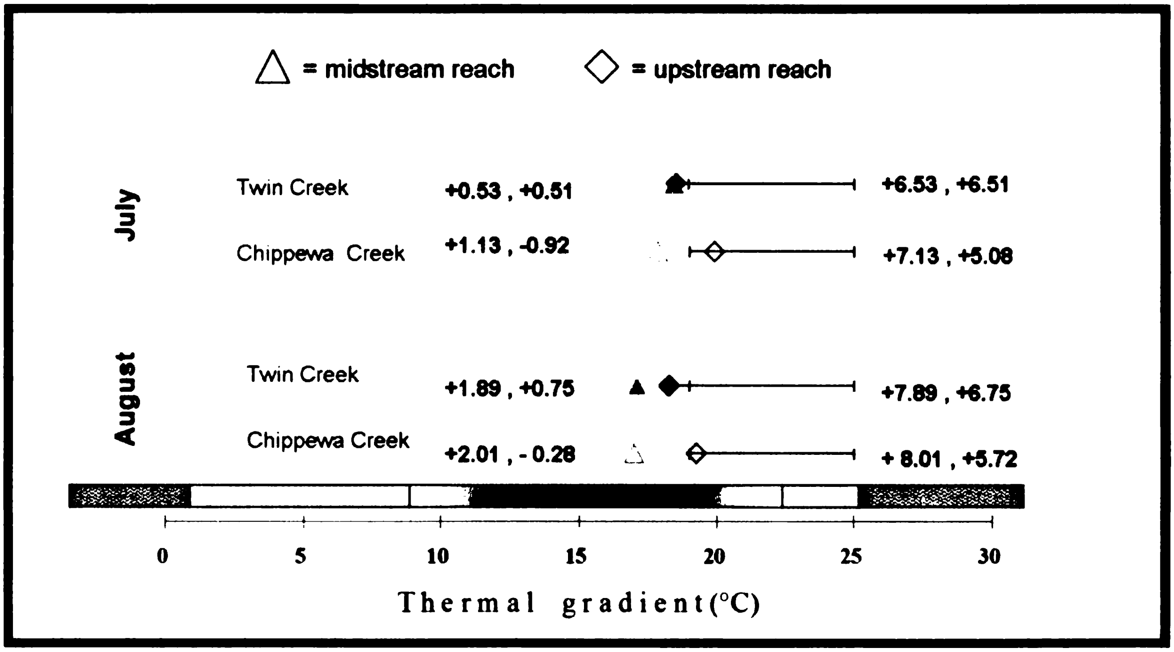

**Figure 7:** Mean monthly stream temperatures for Twin and Chippewa Creek stream reaches in July and August (A) and the required change in mean monthly stream temperature (°C) to exceed both optimal range (right) and upper lethal limit (25.3°C) (left) for brook charr (B) in relationship to the thermal gradient established for brook charr.

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