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The influence of groundwater withdrawal and land use changes on brook charr (*Salvelinus fontinalis*) thermal habitat in two coldwater tributaries in Michigan, U.S.A.

Kerryann E. Waco · William W. Taylor

Abstract Brook charr (*Salvelinus fontinalis*) is a sentinel fish species which requires clean, cold water habitats. As such, many jurisdictions in the United States where brook charr are present use this species as an indicator of ecosystem health. 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, and thus have the potential to significantly influence brook charr production and behavior. We quantified the influence of groundwater withdrawal and land use alteration on thermal habitat availability for brook charr using a groundwater modeling tool that estimated changes in baseflow to a stream segment based on changes to the groundwater system due to groundwater withdrawal and changes in rates of recharge related to landscape changes within a watershed. 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, depending on its relationship to recharge dynamics. This study emphasizes the importance of collaboration between water, land, and fisheries managers to ensure brook charr population viability, productivity, and sustainability in the face of environmental change, increasing water use and development in the watershed.

Keywords Brook charr · Groundwater withdrawal · Thermal habitat · Land use/land cover alteration · Groundwater and stream temperature modeling

K. E. Waco (✉) · W. W. Taylor
Department of Fisheries and Wildlife, Center for Systems Integration and Sustainability, Michigan State University, 1405 South Harrison, 115 Manly Miles, East Lansing, MI 48823, USA
e-mail: wacokerr@msu.edu

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 (Magnuson et al., 1979; Wehrly et al., 1998; Allan & Castillo, 2007). Fish are most productive when they

live in thermal ranges that are conducive to growth and survival and fluctuations outside of these temperatures may effect their movement, productivity, and ultimately survival (Fry, 1971). 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, or an increase in the incidence of disease (Fry, 1971). Thus, stream temperature is a key factor limiting brook charr distribution and production (McCormick et al., 1972).

The optimal thermal range for all life stages of brook charr is between 12 and 19°C (Fry et al., 1946; McCormick et al., 1972; Cherry et al., 1977) (Fig. 1). In Michigan, USA, Wehrly et al. (2003) found the highest brook charr densities in streams during the summer (July) at temperatures between 15 and 19°C. Requirements for brook charr persistence and high productivity in Michigan are directly linked to relatively stable stream flows and cold temperatures (Wiley & Seelbach, 1997); both conditions of which are largely determined by the dynamics of the hydrologic cycle and the geologic composition of the watershed and its land cover. For instance, precipitation percolates down through the soil to the underlying groundwater aquifer as recharge. 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 and 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 to a 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 ($\sim$150 to 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 high production throughout the year by providing seasonal protection from elevated summer temperature and cooler stream temperatures incurred throughout the winter months. 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, thus contributing to the maintenance of local human health standards and providing economic value. These operations however have the ability to directly and indirectly impact aquatic communities through point and nonpoint source effluent and heated discharge.

The type of land cover in a watershed influences the levels of evapotranspiration 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). Evapotranspiration is considered a loss from the hydrologic water budget for a watershed and limits recharge to the groundwater aquifer (Dunne & Leopold, 1978). Because land use/cover types dictate the evapotranspiration, percolation and surface runoff potentials within a watershed, they influence stream baseflows and stream thermal regimes. For example, a forested landscape exhibits higher evapotranspiration rates and impervious surfaces such as roads, rooftops, and parking lots can change surface runoff patterns, both of which decrease levels of percolation to the groundwater aquifer and thus baseflow.

Human activities which alter land cover within a watershed therefore have the ability to 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; Whitledge et al., 2006). Under natural 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 or 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 altering stream temperatures by reducing the coldwater temperature inputs groundwater provides (Hendrickson & Donnan, 1972; Owen,
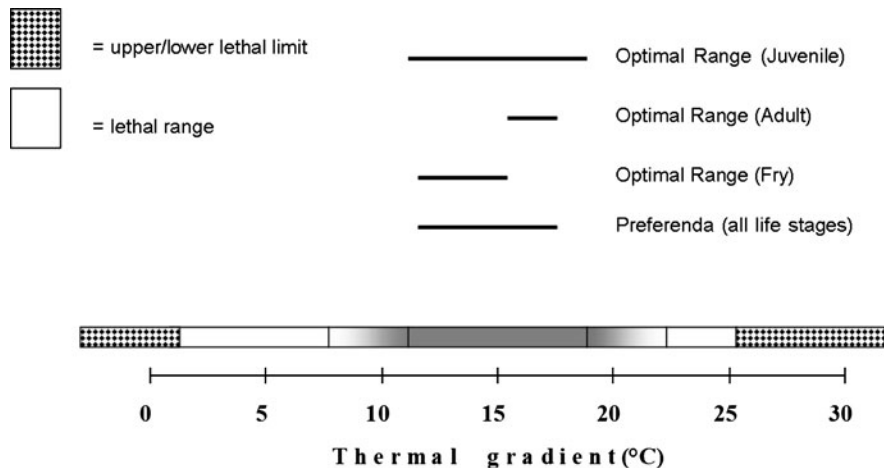
Fig. 1 Gradient of temperature preferenda for brook charr (*Salvelinus fontinalis*) based on data for fry from (Brett, 1940; McCormick et al., 1972; Hokanson, 1973), juveniles from (Fry et al., 1946; McCormick et al., 1972; Cherry et al., 1977), and adults from (Fry et al., 1946; Hokanson, 1973; Cherry et al., 1977). Thermal preferences for brook charr range between 12 and 19°C, with lethal temperatures below 2°C and above 25°C

1991). As such, land cover changes reducing recharge to the groundwater aquifer coupled with large capacity groundwater extraction can act in concert to degrade brook charr thermal habitat as both can reduce the contribution of groundwater input to coldwater groundwater-dominated stream systems that charr depend on for life.

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 objectives 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, U.S.A. and to evaluate groundwater and land use/land cover management strategies for protection of the thermal habitat needs for brook charr within these streams.

Methods

Study site

This study focused on two groundwater-dominated streams in Osceola County, Michigan: Twin and Chippewa Creek; tributaries to the Muskegon River which flows into Lake Michigan (Fig. 2). 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 a 2006 decision by the Michigan Department of Environmental Quality (MDEQ) granted permission to a water bottling industrial operation to place a large capacity 100,000 gallons per day (0.004 m³ s⁻¹) groundwater well in this region. In order to determine the potential effect 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 (Fig. 2). These reaches were chosen based on the abundance of available stream flow, temperature and stream morphological data as well as the proximity of the reaches to the proposed high capacity extraction well. Sampled stream reaches exhibit annual baseflow (m³ s⁻¹) to total average stream flow (m³ s⁻¹) ratios of between 0.81 and 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 comprises mainly forest (73%), principally deciduous in nature, followed by grasslands and shrub land cover (8%), agriculture lands (7%), wetlands (6%), and urban landscapes (4.6%). The predominant soil types (sandy soils, loamy sands) have moderate to high

Fig. 2 Study area; Twin and Chippewa Creek watersheds Michigan, U.S.A. and sampled stream segments modeled using SSTEMP
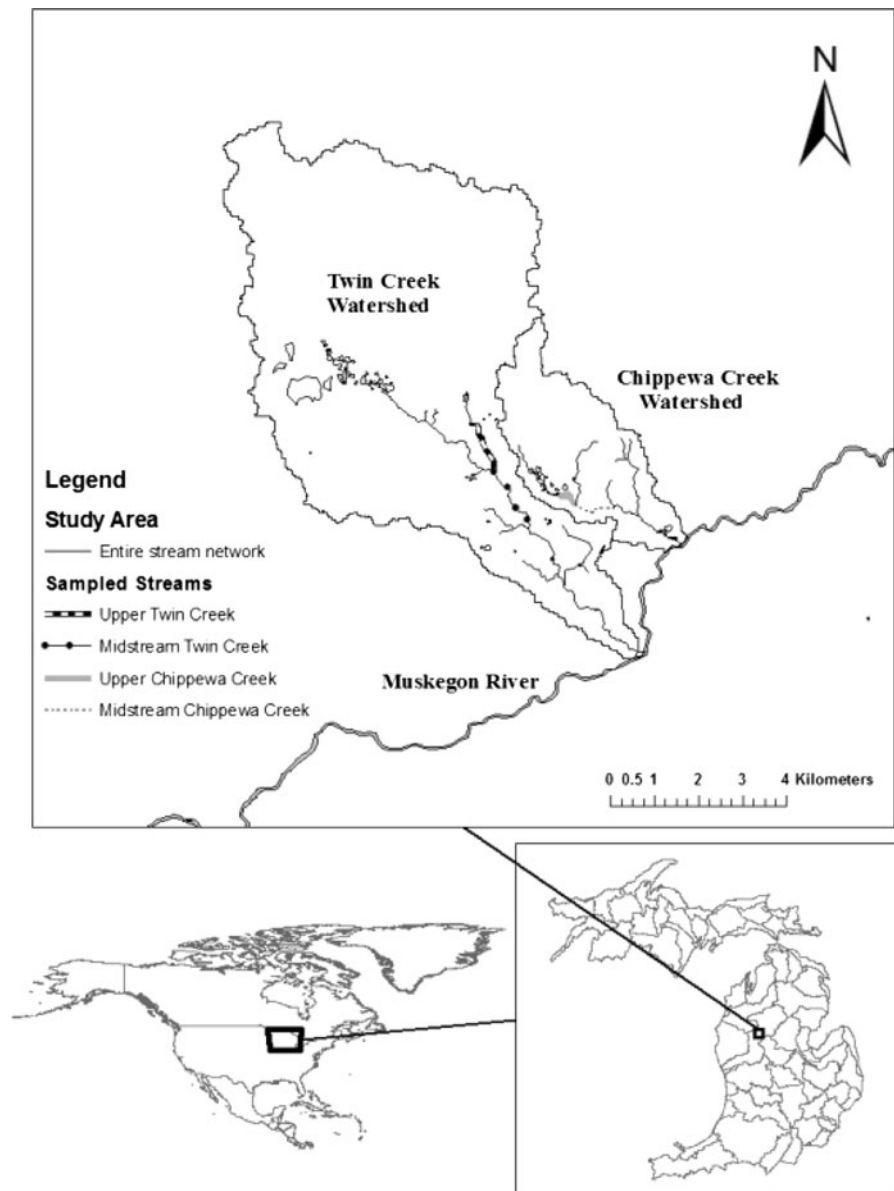
seepage rates resulting in high rates of groundwater recharge. Groundwater users within the watershed extract groundwater from an unconfined glacial aquifer for either direct consumption or non-potable purposes, such as agricultural, commercial, and industrial use.

Groundwater system characterization

The groundwater model, *Interactive Groundwater* (IGW) (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 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 baseflow, and establish static

water levels for Michigan Well-Head Protection Areas (Bartholic & Batie, 2007; Li & Liu, 2009). The data used by the IGW model are detailed in Table 1. 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).

Using the groundwater model, we first evaluated an area (approximately 120 km²) 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 influence on groundwater flow from large scale surface water features. Therefore, a submodel was created within the regional boundary at a finer resolution (approximately 120 m × 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 suggests 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 modeled 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 were based on an average of existing hydrologic conditions and are representative of a steady-state model. Initial aquifer parameters simulated in IGW were compared to (1) known, observed baseflow measurements from these seven locations based on monthly stream flow data collected from January 2001 to September 2007 and (2) 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

Table 1 Input parameters and source data for the IGW model

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 2006 (S.S. Papadopulos & Associates, Inc.)
Subsurface lithology, elevation of geologic layers, and hydraulic properties	Wellogic Data Layer
Recharge rates	Soil & Water Assessment Tool, ArcGIS
Calibration	
Baseflow estimates	Derived from stream flow data provided by Malcolm Pirnie Inc.
Static water levels from existing wells at time of construction	Wellogic Data Layer
Monitoring wells water levels (37)	S.S. Papadopulos & Associates, Inc.

that of observed field data as closely as possible. 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 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 ($0.0044 \ \mathrm{m^3 \ s^{-1}}$), 150 gpm ($0.0945 \ \mathrm{m^3 \ s^{-1}}$), 400 gpm ($0.0252 \ \mathrm{m^3 \ s^{-1}}$), 700 gpm ($0.044 \ \mathrm{m^3 \ s^{-1}}$), 1,000 gpm ($0.063 \ \mathrm{m^3 \ s^{-1}}$) and 2,000 gpm ($0.126 \ \mathrm{m^3 \ s^{-1}}$) 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 ($0.0044 \ \mathrm{m^3 \ s^{-1}}$)] reflects the pumping rate requiring a groundwater withdrawal permit from the MDEQ, subsequent rate increases reflect the current potential pumping regimes used by industrial and public supply wells in the area. The 2,000 gpm ($0.126 \ \mathrm{m^3 \ s^{-1}}$) extraction rate reflects the potential maximum pumping capacity for a 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 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. 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. In order to assess land use/cover policy changes as conservation strategies that might be used to offset the impacts of groundwater

Table 2 Recharge rates for land use/land cover types within the watershed from the soil and water assessment tool (Neitsch et al., 2005)

Land use/land cover	Recharge rate in inch/year (cm/year)
Commercial	1.07 (2.72)
Industrial	1.10 (2.79)
Open land	4.01 (10.19)
Pasture	6.33 (16.08)
Residential	6.51 (16.54)
Deciduous forest	7.35 (18.67)
Forested wetland	7.40 (18.80)
Crop land	7.90 (20.06)
Mixed forest	8.49 (21.56)
Non-forested wetland	8.81 (22.38)
Coniferous forest	8.83 (22.43)
Shrub land	11.52 (29.26)
Clear-cut/range brush	11.80 (29.97)
Grassland	14.30 (36.32)

withdrawal, we modeled two scenarios based on land cover change which the data suggest would result in decreased recharge rates; forest to pasture (approximately 3.33 $\mathrm{km^2}$; 10% of total forest), grassland to urban (approximately 1.7 $\mathrm{km^2}$; 30% of total grassland), and two scenarios which would likely result in increased recharge rates; agriculture to grassland (approximately 2 $\mathrm{km^2}$; 40% of total cropland), forest to shrub land (approximately 6.65 $\mathrm{km^2}$; 15% of total forest). 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 since 1972 as this was the first year aerial photos were available for the watershed 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 (2) proximity to stream reaches and (3) clustered areas of similar land cover types to simulate the effects of increasing one particular cover type.

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

Table 3 Stream Segment Temperature Model (SSTEMP) model parameters

Parameters	Unit	Source
Hydrology and simulation period		
Flow data	$m^3 \, s^{-1}$	Measured (Malcolm Pirnie Inc.)
Stream inflow temperature	°C	Measured (Malcolm Pirnie Inc. & Advanced Ecological Management)
Lateral inflow temperature	°C	Leverett, 1906
Baseflow	$m^3 \, s^{-1}$	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	USGS Topographic Map
Dam at head of segment		Checked for SF-1 & SF-16
Stream segment length	km	USGS Hydrography Dataset
Elevation upstream	m	USGS Topographic Map
Elevation downstream	m	USGS Topographic Map
Stream width coefficient/exponent	m	Derived
Manning's *n*	s/km	Program Default
Meteorological information		
Air temperature	°C	Wastewater Treatment Plant—Big rapids
Relative humidity	%	Calculated (Bartholow, 2002)
Wind speed	mph	NCDC—Houghton Lake (nearest NOAA Weather Station)
Thermal gradient	$j/m^2/s/c$	Program Default
Possible Sun	%	NCDC—Houghton Lake
Dust coefficient	Dimensionless	Theurer et al. (1984)
Ground reflectivity	%	Theurer et al. (1984)
Solar radiation	(Langsleys/day)	Based on dust coefficient and ground reflectivity values
Stream shading	%	Visual estimate

cover changes, we used a stream temperature model, SSTEMP, developed by and available through the U.S. Geological Survey (Bartholow, 2002). This allowed for an examination of stream temperature change in relationship to available brook charr thermal habitat in the study stream compared to brook charr temperature preferenda. SSTEMP was used to predict changes in temperature based on changes in baseflow predicted by the IGW assessment tool. SSTEMP uses stream geometry and hydrology, meteorological data and stream shading to predict changes in stream temperatures (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 convection, evaporation, conduction, 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). 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). Stream shading percentages were estimated through on-site evaluation.

Components of SSTEMP, which aptly model individual stream reaches, and the more detailed SNTEMP, which models a complex network of 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 (*Oncorhynchus mykiss* and *Salmo trutta*) stream (Bartholow, 1991), evaluate the importance of groundwater and riparian shading on adequate bass (*Micropterus dolomieu*)

habitat in Ozark streams (Whitledge et al., 2006), and determine the influence of stream shading in maintaining summer temperatures in a brook trout stream (Pajak, 1992). Additionally, Gaffield et al. (2005) used an adapted version of SNTEMP, to illustrate the overall importance of groundwater and riparian shading as controls to summer temperature in small Midwestern streams while emphasizing 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 were collected at a different location 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 to 11.3°C (Leverett, 1906). Baseflow output from the IGW model was used in the following equation to determine stream discharge parameters for the model:

$$Q = a + bx \qquad (1)$$

where Q equals stream segment discharge, a equals stream inflow, b equals baseflow, and x equals stream length. 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 an accumulation 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, 1:24,000 scale, 2004) and were assumed to be a headwater as no flow data from the reservoirs exist. 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).

Mean monthly stream temperature data from July and August were used for each stream reach. Using this information, we evaluated 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 physiologically the most stressful to brook charr and stream temperatures are 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 in this region (Michigan Department of Environmental Quality, 2006; Apple & Reeves, 2007). The general movement of groundwater in the system is approximately perpendicular to the surface watershed boundaries, flowing toward the larger river system, the Muskegon, where both creeks drain (Fig. 2). This was 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 Liu and Mr. Hassan Abbas, Michigan State University, Civil and Environmental Engineering Department pers. communication). Examination of the difference between observed versus predicted values (residuals) for both groundwater monitoring well levels and baseflow measures 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 the accuracy of our model compared to actual measured data inferred from field data (Anderson & Woessner, 1992). Comparison of observed groundwater levels

Table 4 Percent change in baseflow at pumping rates of 70 gpm (0.0044 m³ s⁻¹), 150 gpm (0.0945 m³ s⁻¹), 400 gpm (0.0252 m³ s⁻¹), 700 gpm (0.044 m³ s⁻¹), 1,000 gpm (0.063 m³ s⁻¹), and 2,000 gpm (0.126 m³ s⁻¹) for Twin and Chippewa Creeks

Stream reach	Baseflow (m³ s⁻¹)	Percent reduction in baseflow					
		70 gpm (0.004 m³ s⁻¹)	150 gpm (0.095 m³ s⁻¹)	400 gpm (0.025 m³ s⁻¹)	700 gpm (0.044 m³ s⁻¹)	1,000 gpm (0.063 m³ s⁻¹)	2,000 gpm (0.126 m³ s⁻¹)
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

and model predictions of water levels in the aquifer revealed a residuals mean of −2.04 m, a mean absolute value of the residuals of 2.80 m and a standard deviation of the residuals of 2.69 m ($R^2 = 0.51$; regression of actual to modeled groundwater level). The RMSE of 3.35 m 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 ($R^2 = 0.88$; regression of actual to modeled baseflow). Most of the values were within the 80th percentile.

Groundwater extraction was found to reduce baseflow in Twin and Chippewa Creeks (Table 4). 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 (0.0044 m³ s⁻¹) in the upper reach of Twin Creek to 25.8% at a pumping rate of 2,000 gpm (0.126 m³ s⁻¹) at the midstream reach of Chippewa Creek. Baseflow reductions were shown to increase with increased pumping rates with overall, larger percentages of change occurring to the stream segments in Chippewa Creek (Table 4). Therefore, pumping of any magnitude above 70 gpm (0.0044 m³ s⁻¹) will have an impact on baseflow in the study stream segments of these groundwater-dominated streams.

Stream temperature

Stream temperatures predicted by SSTEMP were within 0.11–0.50°C of actual stream temperatures collected at sampled stream segments and reflect 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 July and August 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 (0.0945 m³ s⁻¹). The lack of temperature change may be explained by the fact that this reach experienced the lowest percentage change in baseflow (0.2% 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/cover alteration

Recharge rates from the SWAT model show that grassland provided with the highest recharge rate (14.30 inches/year; 0.36 m/year) while both industrial and commercial (urban) landscapes had the lowest recharge rates (1.07 inches/year; 0.03 m/year)

Table 5 Stream temperature increase for pumping rates of 70 gpm (0.0044 m³ s⁻¹), 150 gpm (0.0945 m³ s⁻¹), 400 gpm (0.0252 m³ s⁻¹), 700 gpm (0.044 m³ s⁻¹), 1,000 gpm (0.063 m³ s⁻¹), and 2,000 gpm (0.126 m³ s⁻¹) given 2005 land use/land cover in July and August

	Stream temperature change in °C					
	70 gpm	150 gpm	400 gpm	700 gpm	1,000 gpm	2,000 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	0.2	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
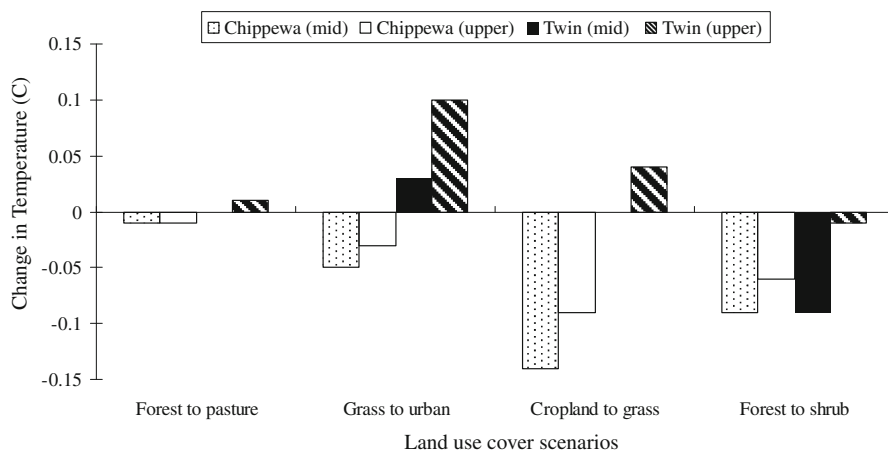
Fig. 3 Land cover alteration scenarios impact on stream temperature in the Twin and Chippewa Creek study stream segments. Alteration scenarios are as follows: forest to pasture (approximately 3.33 km²; 10% of total forest), grassland to urban (approximately 1.7 km²; 30% of total grassland), agriculture to grassland (approximately 2 km²; 40% of total cropland), forest to shrub land (approximately 6.65 km²; 15% of total forest)

(Table 2). IGW 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 and 0.09°C in all four stream reaches in midsummer (Fig. 3), a result of the recharge rates for shrub land being higher than forested landscapes thus facilitating higher recharge rates and hence higher baseflows. A 40% change from cropland to grassland resulted in temperature decreases of between 0.08 and 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 had relatively little change in either baseflow or temperature (Fig. 3). Land cover alteration of 30% of grassland to urban landscapes 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 (Fig. 3).

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 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 inches/year; 0.19 m/year) and pasture (6.33 inches/year; 0.16 m/year) 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, the upper reach of Chippewa Creek was the only reach which exhibited temperatures outside the optimal range temperature tolerances for brook charr (Fig. 4A). All other segments had mean monthly temperatures that were within the optimal growth and

Fig. 4 **A** Mean monthly stream temperatures for Twin and Chippewa Creek stream reaches in July and August and **B** the required change in mean monthly stream temperature (°C) it would take to exceed both optimal range (*left*) and upper lethal limit (25.3°C) (*right*) for brook charr in relationship to the thermal gradient established for brook charr
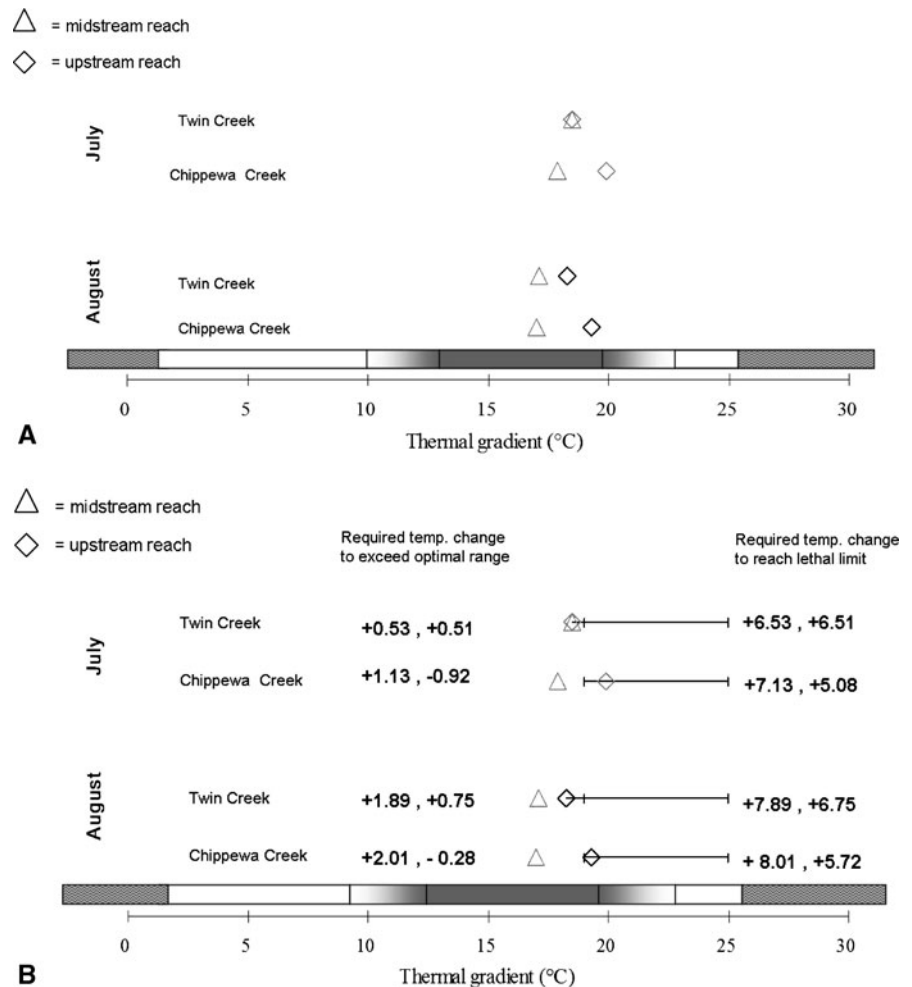
survival range for brook charr. As such, pumping at 70 gpm ($0.0044 \, \mathrm{m}^3 \, \mathrm{s}^{-1}$) or greater will result in a loss of thermal habitat for brook charr in midsummer only within the upper reach of Chippewa Creek. The magnitude of change required to move brook charr out of their thermal 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 generally higher baseflows (Table 4) or higher percentage of forested canopy and riparian shading and thus lower mean monthly temperatures in these reaches. A change in these stream reaches to temperatures outside the optimal growth range for brook charr (>19°C) would require temperature increases in July of at least 0.51°C (Twin Creek) and 1.13°C (midstream reach of Chippewa Creek) (Fig. 4B). 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 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 temperature model predicted the stream segments would need to have temperature increases of at least 5–8°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 impacts the supply of water to the 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 on 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 linkages of the these systems allow fisheries managers and land use policy makers to assess the magnitude of impact that specific 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. While the magnitude of stream temperature change predicted by this methodology was less than 1°C, the net outcome was a loss of certain summer thermal habitat for brook charr as summer temperatures were near the maximum optimal thermal limits 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).

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 lethal limit 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 conditions 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 high 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 occur in Michigan stream systems. Land use practices occurring within the stream corridor, in addition to those occurring in the landscape may also 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). As such, the influence of air temperatures on stream temperatures coupled with increased groundwater withdrawal and land use change, which reduces recharge, will be important to understand as climate change threatens to increase global air temperatures and consequently, will alter the 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 changes in land use/land cover which caused increased stream temperatures (Stranko et al., 2008). These investigations 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 from grassland 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 an increase in 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 Jacobson et al. (2008) study 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 (*Salmo trutta*), tessellated darter (*Etheostoma olmstedi*), and fallfish (*Semotilus corporalis*).

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

Table 6 Land use/land cover alteration impact on the mid-stream 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 (0.0945 m³ s⁻¹), 700 gpm (0.044 m³ s⁻¹), and 1,000 gpm (0.063 m³ s⁻¹)

Land use change	High capacity well pumping rates (°C)	150 gpm +0.01°C	700 gpm +0.06°C	1,000 gpm +0.21°C
Grassland to urban	+0.03	+0.04	+0.09	+0.24
Forest to shrubs	−0.09	−0.08	−0.03	+0.12

of 700 gpm (0.044 m³ s⁻¹) could be mitigated by implementing a 15% (6.65 km²) 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 pumping at 700 gpm (0.044 m³ s⁻¹) may result in increased temperatures at the midstream reach of Twin Creek, from 18.47 to 18.53°C, a land cover change in addition to pumping would actually result in a temperature of 18.44°C, thus resulting in stream temperatures lower than the average monthly mean before pumping began (Table 6). Alternatively, a 30% (1.7 km²) change in this area of grassland to urban under a 700 gpm (0.044 m³ s⁻¹) extraction rate could potentially result in further loss of thermal habitat (18.53–18.56°C) due to reductions in recharge to the aquifer.

The upper section of Twin Creek in midsummer under a groundwater extraction rate of 400 gpm (0.0252 m³ s⁻¹) 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). In the upper reach of Chippewa Creek, we found that land cover changes from agriculture to grassland and forest to shrub land reduced the increase in temperature incurred through pumping by 0.09 and 0.06°C, 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 links 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 an essential component of the ecological system and are also the foundation of an important 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 to ensure brook charr viability and sustainability in the face of increased human demands and global environmental change.

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