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Landscape-Based Models that Predict July Thermal Characteristics of Lower Michigan Rivers

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Abstract.–Water temperature is one of the most important environmental factors affecting the physiology, life-history, and distribution patterns of stream biota. However, the ability to assess the influence of temperature on observed patterns of species distribution and abundance is hampered by a lack of site-specific temperature data collected across relatively broad geographic regions. In this paper, we present 2 models that can be used to estimate July thermal characteristics using landscape attributes for streams in the Lower Peninsula of Michigan.

We used multiple linear regression to construct models that predict July average weekly maximum and minimum stream temperatures from catchment- and local-scale landscape variables. Water temperature data were collected at 171 sites representing 12 major watersheds in Lower Michigan. Catchment- and local-scale landscape variables were obtained from existing maps using a Geographic Information System (GIS).

The best models predicting July thermal characteristics explained from 59-60 % of the spatial variation in stream temperatures. When outlier sites were removed, these models explained from 70-81 % of the spatial variation in stream temperatures. These models suggested that channel morphology, ground water accrual, and riparian forest cover were important variables controlling temperatures in Lower Michigan rivers.

The results of this study illustrate the importance of catchment- and local-scale attributes in controlling instream habitat, especially in heterogeneous landscapes. These models provide a cost-effective method to generate broad-scale temperature information. Such information can provide baseline data environmental impact assessment and can be used to guide management decisions.

Water temperature is one of the most important environmental factors affecting the physiology, life-history, and evolution of stream biota. Consequently, water temperature has been shown to be a key factor influencing the distribution and abundance patterns of both fishes (Huet 1959; Matthews 1987; Cech et al. 1990; Rahel and Hubert 1991) and aquatic invertebrates (Vannote and Sweeney 1980; Ward and Stanford 1982; Haro and Wiley 1992; Hawkins et al. 1997). As knowledge of the effects of temperature on aquatic organisms has grown, interest in the ability to quantify temperature patterns within and among watersheds has increased. This interest results from needs to not only understand present distribution patterns, but also to assess the impacts of human-induced changes on the landscape (e.g. LeBlanc et al. 1997) and to identify potential impacts associated with changes in global climate patterns (e.g. Keleher and Rahel 1996).

Stream temperatures within and among watersheds have traditionally been assessed using maximum-minimum thermometers or continuously recording thermographs. This direct method has contributed to our understanding of the spatial and temporal variation in thermal regimes within certain rivers (Macan 1958; Crisp and Le Cren 1970; Webb and Walling 1986; Webb and Nobilis 1994). However, attempts to assess stream temperatures over relatively large geographic regions have been limited due to high costs associated with acquiring and maintaining a large number of thermometers spread out over many sites. This general lack of large-scale temperature coverage has limited our abilities to quantify the thermal variation that exists within and among catchments and to assess how this variation may influence patterns of distribution and abundance of stream biota.

Spatial variation in thermal regime (both within and among catchments) results from complex interactions between regional meteorological factors (e.g., direct solar inputs, precipitation, or air temperature), catchment characteristics (geology or land use), and local channel features. For example, direct solar radiation is a major source of heat input for streams. The extent to which direct solar inputs influence stream temperatures at a site is controlled by the amount of shade that is provided by topographic relief and riparian vegetation in the upstream catchment. In addition, the volume of water moving in the channel (discharge) and the proportion of that volume recently accrued from ground water inputs also determines the relative influence of direct solar inputs. As a result the thermal properties of streams having relatively large discharges, or receiving significantly large contributions of ground water, are less affected by solar inputs.

The relative importance of regional-, catchment-, and local-scale factors in controlling stream temperatures varies according to geographic setting. When sites are viewed across relatively large gradients of altitude or latitude, climatic-related factors such as solar inputs and air temperature are often important factors controlling the spatial variation in stream temperatures. However, in regions where meteorological factors are relatively uniform, landscape features at the catchment- and reach-scale become the dominant factors controlling the spatial variation in stream temperatures.

In the lower peninsula of Michigan, variation in climate and elevation, within and among catchments, is relatively low. Summer (May-September) average air temperatures range from 15.9 °C to 19.3 °C and total precipitation varies from 360 mm to 440 mm (Albert et al. 1986). Elevation ranges from 177 m to 518 m and 96 % of the peninsula is within 177 m to 366 m (Leverett 1912). The landscape, however, is characterized by a diverse mosaic of surficial deposits including glacial lakeplains, moraines, outwash plains, and tills of varying depths and textures (Farrand and Eschman 1974; Farrand and Bell 1984; Albert et al. 1986). In the Great Lakes Region, variation in surficial geology and topography (through their effect on ground water flow patterns) are important determinants of stream hydrology (Knutilla 1970; Bent 1971; Holtschlag and Crosky 1984; Richards 1990; Wiley and Seelbach 1997; Seelbach and Wiley 1998; Wiley and Seelbach 1998) and consequently, thermal regimes (Hendrickson and Doonan 1972; Dewberry 1980; Haro and Wiley 1992).

In addition to geology and topography, land use and land cover types also vary considerably among catchments. In the Lower Peninsula, the amount of agriculture within the major watersheds ranges from 6 to 92 % and the amount of forest cover in a catchment varies from 2 to 77% (Gooding 1993). Land use practices such as agriculture and urbanization can impact natural thermal regimes through changes in stream flow patterns (Dunne and Leopold 1978), channel morphology (Dunne and Leopold 1978), and the extent of streamside shading (Abell 1996; LaBlanc 1997). The relatively large variation in geology, land use, and land cover across the lower peninsula, suggests that much of the variation in thermal regime within and among catchments, may be attributable to patterns of variation in the landscape.

Regional-, catchment-, and local-scale landscape attributes (e.g., geology or land use) can be obtained from existing maps and data sets using a Geographic Information System (GIS). In addition, other important factors controlling stream temperatures such as channel geometry vary as a function of catchment area (Dunne and Leopold 1978) and can be readily predicted. Regional-, catchment-, and local-scale landscape attributes have been successfully used to develop models predicting hydrology (Bent 1971; Holtshlag and Croskey 1984; Wiley et al. 1997), chemistry (Kleiman 1995; Tompkins et al. 1997) and fish assemblage structure (Zorn et at. 1997) in Michigan rivers, and may be equally appropriate for the development of water temperature models.

The development of temperature models based on landscape attributes would provide a cost-effective tool that could be used by fisheries managers and researchers to evaluate site-specific thermal regimes over a relatively broad geographic region (e.g. Michigan's lower peninsula). The objective of this study was to develop models that would predict July thermal characteristics in lower Michigan rivers, using landscape-scale variables that are readily available from existing maps and accessible using a GIS. We chose to model July thermal characteristics because this is a time when streams in Michigan approach the lethal limit for some taxa and also when differences in thermal behavior among sites are most pronounced (Hinz 1997).

Methods

Water Temperature Sampling

Water temperatures were assessed at 171 sites representing 12 major watersheds in Michigan's Lower Peninsula. Temperature data were collected during the first 3 weeks in July using maximum/minimum thermometers and digitally recording thermographs. Temperature data were collected over several years (1989, 1990, 1994, and 1996), but in this analysis, we used only 1 observation (year) per site. When data for more than one year were available for a site, we arbitrarily chose the earliest record to include in this analysis. For each site, we determined the maximum weekly July stream temperature as the average of the 3 weekly maximum readings and the minimum weekly July stream temperature as the average of the 3 weekly minimum readings.

Air Temperature

Air temperature data for each sampling site were obtained from published NOAA climatological records. For each water temperature record, we matched July air temperatures using data collected from the weather station nearest each site. For each site, we determined the maximum weekly July air temperature as the average of the 3 weekly maximum readings and the minimum weekly July air temperature as the average of the 3 weekly minimum readings.

Landscape Variables

We characterized the landscape associated with each sampling site using existing databases developed as part of the Michigan Rivers Inventory Project (see Seelbach and Wiley 1997). Primary map layers were converted into a 1 hectare rastor format and all landscape data were maintained and accessed using a Geographic Information System (GIS). Buffers and data summaries were generated using ARC/INFO.

In order to characterize the landscape associated with each sampling site, we delineated individual upstream catchment boundaries for each site, and then summarized different land use and land cover data within each catchment. Surficial catchment boundaries were delineated as the divides between stream channels, based initially on subwatershed boundaries developed by the Michigan Department of Natural Resources (MDNR) from United States Geological Survey (USGS) topographic maps at a scale of 1:24,000, and locally modified according to the 3 arc-second digital elevation models (at a scale of 1:250,000). Stream channel network data were based on USGS Digital Line Graph (DLG) data at a scale of 1:100,000. Land use, surficial geology, and ground water movement data were then summarized for each catchment

We also used buffer analysis to evaluate more localized effects of the landscape on stream temperatures. For each site, we created 3 circular buffers of radius 1 km, 2 km, and 4 km, and a 2-km wide (1 km on each side of the stream) corridor buffer for the entire stream network. Land use,surficial geology, and ground water movement data were then summarized for the region of the catchment intersected by the 1 km, 2 km, and 4 km circular buffers; and the region of the catchment intersected by the 2-km corridor buffer.

Land use data for each site were obtained from MDNR (Michigan Resource Information System database) vector format maps developed from 1981-1986 aerial photos at a scale of 1:24,000. For this analysis, we grouped land use coverages into 5 categories: agriculture, barren, forest, urban and wetlands. Land use categories were analyzed as a percentage of the catchment or individual buffer.

To estimate the potential input of ground water to the stream network, we developed a spatial model (map layer) that predicts maximum potential ground water velocity (Wiley et al. 1997). This map was based on Darcy's law which states that ground water velocity is proportional to local hydraulic head (slope) times the hydraulic conductivity of the underlying materials (Dunne and Leopold 1978). Slope data were calculated from USGS Digital Elevation Model (DEM) 3 arc-second data at a scale of 1:250,000. Conductivity values for surficial geology classes were taken from published hydraulic conductivity tables (Rahn 1980; Todd 1980; Bedient and Huber 1988). Surficial geology data were obtained from a digital version of the Farrand and Bell (1:500,000: 1984) map. This representation of potential ground water velocity was summarized as the mean velocity within each catchment or individual buffer.

Reach Variables

Hydrology–We used hydrology data predicted from models that characterize the flow patterns at a specific site (Wiley and Seelbach 1998). These models utilized climate and landscape (geology, soils, and land use) variables to predict flow regimes and explained most (90-99%) of the variation in seasonal and annual hydrologic patterns in Michigan Rivers. For this analysis, we used both mean annual flow and baseflow yield calculated as the 90% exceedence flow divided by the catchment area.

Reach gradient and reach channel morphology–We determined the reach gradient for each site using USGS topographic maps at a scale of 1:24,000. For each site, we located several contour intervals upstream and downstream from the site. Gradient was calculated as the difference between successive contour intervals upstream and downstream of the site, divided by the length of stream between the contour intervals. We estimated stream width, depth, and cross-sectional area at each site using hydraulic geometry equations relating channel characteristics to catchment area

(Dunne and Leopold 1978). Channel measurements used to build these models were taken from existing survey data (MRI, unpublished data) collected at 217 sites in the lower peninsula. These models explained from 77 to 82 % of the variation in channel characteristics.

Model Development

We used multiple linear regression analysis to construct models that predict July average weekly maximum and minimum stream temperatures. We attempted to include variables in the model that have been identified as important environmental factors controlling stream temperatures. For example, shading associated with streamside vegetation has been shown to be a key variable influencing stream temperatures. As a result, we explored the use of the amount of forest within the 2 km corridor buffer in our predictive models. Inclusion of variables in each model was also based on the sign and significance of model coefficients, and the fit (adjusted R^2) and standard error of the resultant models. Where necessary, variables were transformed using the natural log to linearize data. All analyses were performed using SPSS Version 6.0 (1993).

Results

Individual sites used in this analysis represented a large range in catchment area (1-14,270 km^2) and in land use (0-92 % of catchment in agriculture), land cover (from 0 to 99 % of catchment in forest) and hydrologic (baseflow yield from 0 to 2.5 $m^3/s/km^2$) characteristics (Table 1). Observed July stream temperatures also exhibited considerable variation across the Lower Peninsula. Maximum water temperatures ranged from 10.5 °C to 33.3 °C, and minimum water temperatures ranged from 7.8 °C to 23.9 °C (Figure 1). No significant effects of sampling year on stream temperatures were detected (Multiple linear regression, p>0.05). Observed air temperatures were much less variable ranging from 28.0 °C to 34.6 °C for maximum air temperature and from 6.3 °C to 13.3 °C for minimum air temperature (Figure 1).

Multiple linear regression analysis revealed that channel characteristics, ground water inputs, and riparian forest cover were important variables controlling stream temperatures in lower Michigan. Air temperature did not dramatically improve model fit but we chose to include this variable in the final models. Maximum and minimum stream temperatures responded differently to these variables reflecting the different mechanisms controlling the gain and loss of heat. As a result, we developed 2 structurally different models.

The best model for July average weekly maximum temperature was:

$$\begin{aligned}\ln(Tmax) &= \ln(a_1) + b_1 \cdot \ln(CW) \\ &\quad + c_1 \cdot \ln(NGW) + d_1 \cdot \ln(Amax) \\ &\quad + f_1 \cdot \ln(NFOR) + g_1 \cdot \ln(RG) \\ &\quad + h_1 \cdot LGW + i_1 \cdot CA\end{aligned} \tag{1}$$

where Tmax = maximum July stream temperature, CW = channel width, NGW = ground water in the network buffer, Amax = maximum air temperature, NFOR = % forest cover in the network buffer, RG = reach gradient, LGW = local ground water in the 4-km buffer, CA = channel cross-sectional area, and a, b, c, d, f, g, h, and i are coefficients derived from regression analysis. Values for model coefficients are given in Table 2. This model was highly significant ($p < 0.001$) and explained 60 % (adjusted R^2) of the statewide variation in July average weekly maximum temperature (Table 3).

Standardized regression coefficients for the model predicting maximum stream temperature provide a measure of the relative influence of each independent variable in the model (Table 4). Stream width had the greatest influence on maximum temperature followed by channel cross-sectional area, % forest cover in the network buffer, local ground water inputs (4-km buffer), stream gradient, network ground water inputs, and maximum air temperature. The total effect of ground water (local ground water coefficient + network ground water coefficient = -0.293) was slightly greater than the effect of forest cover. Both stream width and maximum air temperatures had positive relationships with maximum water temperature while the remaining variables had negative relationships with maximum water temperature.

The best model for July average weekly minimum temperatures was:

$$\begin{aligned}\ln(\mathrm{Tmin}) &= \ln(a_2) + b_2 \cdot \ln(\mathrm{CW}) \\ &\quad + c_2 \cdot \ln(\mathrm{Amin}) + d_2 \cdot \ln(\mathrm{Tmax}) \\ &\quad + f_2 \cdot \mathrm{LFOR}\end{aligned} \tag{2}$$

where Tmin = minimum stream temperature, CW = channel width, Amin = minimum air temperature, Tmax = maximum stream temperature, LFOR = local forest in the 4-km buffer, and a, b, c, d, f are model coefficients. Values for model coefficients are given in Table 2. This model was highly significant ($p < 0.001$) and explained 59 % (adjusted R^2) of the statewide variation in minimum July temperature (Table 3).

Standardized regression coefficients for the model predicting minimum stream temperatures are listed in Table 4. Stream width had the greatest influence on minimum temperatures followed by maximum water temperature, percent forest cover in the 4-km buffer, and minimum air temperature. Percent forest cover in the 4-km buffer tended to be negatively related to minimum stream temperatures while the remaining variables were positively related to minimum stream temperatures.

Predicted temperatures were plotted against observed temperatures to evaluate the performance of each model (Figures 2 and 3). Both models tended to overestimate at colder temperatures and underestimate at warmer temperatures. The standard error of the difference between predicted and observed values was 0.18 °C for maximum temperatures and 0.15 °C for minimum temperatures.

For a few sites the difference between predicted and observed values was greater than 5 °C. Closer inspection revealed that many of these sites were either channelized or located directly below lake outlets or impoundments. Removal of such outlier sites from the analyses resulted in models explaining 70 % (maximum temperature) to 81 % (minimum temperature) of the variation in stream temperature (Table 5). Coefficient values for models without outlier sites are listed in Table 6.

Removal of outlier sites did not dramatically effect the relative influence of the independent variables on July average weekly maximum stream temperatures (Table 4). Maximum water temperature and minimum air temperature, however, had greater influence on July average minimum stream temperatures when outlier sites were removed from the analysis.

Discussion

Other Temperature Models

Our models can be used to generate estimates of summer stream temperatures throughout Michigan's Lower Peninsula. Despite their obvious utility, few investigators have developed models to predict site-specific temperatures across relatively broad geographic regions. Stefan and Preud'homme (1993) used air-water temperature relationships to develop a model predicting weekly temperatures in 11 streams across the Central United States and Hawkins et al. (1997) used channel reach characteristics to develop models predicting July thermal characteristics in 45 montane streams in California. We are not aware of other landscape-scale models for use in glaciated landscapes.

More accurate estimates of stream temperatures at a particular site can been obtained using heat budget models (water temperatures estimated using heat budget models typically result in standard deviations (SD) between predicted and observed temperatures of 1 °C or less, in this study SD ranged from 2.0 – 2.3 °C; see citations in Stefan and Preud'homme 1993) or empirical models based on air-water temperature relationships (R^2 from 83 to 99%) (Crisp and Howson 1982; Mackey and Berrie

1991; Newcomb and Coon 1997). These models however, are site- or catchment-specific and, in the case of heat budget models, can require extensive site-specific data inputs. In addition, these models are typically developed to predict temporal changes in temperature at a site rather than spatial variation in temperature across multiple sites. Predicting site-specific temperatures across a broad region (especially in exceptionally diverse landscapes such as Lower Michigan) using a heat budget or air-water temperature approach would require the development and calibration of multiple models. As a result, these types of models have limited utility in generating large-scale temperature coverage.

Factors Controlling Temperature

One advantage to using a multi-scale approach to modeling spatial variation in temperature is the ability to explore the relative importance of various landscape attributes that influence stream temperatures. Our data suggested that channel characteristics, riparian forest cover, and ground water contributions are important environmental factors controlling July thermal characteristics in lower Michigan rivers. However, maximum and minimum stream temperatures responded differently to this suite of variables indicating that fundamentally different heat budgets exist for daytime (heating) versus nightime (cooling) conditions.

Channel characteristics–Channel width had a relatively strong influence on both maximum and minimum stream temperatures. This is attributed to the fact that heat flux due to radiation, convection, and evaporation takes place at the air-water interface (Barthalow 1989). Therefore, as channel width increases more surface area is exposed to these various heat flux components. As a result, stream reaches having greater widths tend to gain and lose heat more readily than relatively narrower stream reaches of similar cross-sectional area (LeBlanc et al. 1997).

However, the volume of water in the channel (discharge) can moderate the influence of channel width on increases in stream temperatures. Channels having greater volumes have higher heat storage capacity and respond more slowly to changes in ambient conditions (Smith and Lavis 1975). In the present study, channel cross-sectional area served as an index of volume. Our models indicate that sites having a relatively large cross-sectional area tend to have lower maximum temperatures presumably because the rate of change per unit heat input is slower at larger volumes.

Reach gradient also influenced stream temperatures. It is correlated with velocity and serves as a proxy for the amount of time that water spends in the channel as it flows downstream. The time it takes water to move downstream is the time a unit volume of water is exposed to heat exchange with the atmosphere (Smith and Lavis 1975; Theurer et al. 1984; Bartholow 1989). In general, as travel time increases, streams accumulate heat and gradually approach an equilibrium temperature; the point where net heat exchange with the atmosphere is zero (Brown 1969; Theurer et al. 1984; Bartholow 1989). Factors that reduce travel time (such as reach gradient) reduce the amount of time a unit volume of water is exposed to sources of heat. In our analysis, sites having relatively higher reach gradients had cooler summer temperatures.

In the present study, channel characteristics were determined using reach (approximately 1-5 km) level data taken from field surveys or from topographic maps. Average channel characteristics, for the entire network upstream from each site, may also be important factors controlling stream temperatures (Theurer et al. 1984; Bartholow 1989). Nonetheless, in our analysis, reach level channel descriptors were good/useful predictors of stream temperature.

Forest cover–Local forest cover and forest cover in the 2 km corridor buffer were included in our models. The importance of riparian vegetation in moderating natural stream temperatures is well documented (Brown 1969; Burton and Likens 1973; Barton et al. 1985;

Abell 1996; LeBlanc et al. 1997). During the day, riparian vegetation intercepts direct solar radiation that would otherwise be absorbed at the stream surface and is therefore important in reducing maximum temperatures. At night, riparian vegetation back-radiates heat energy and can reduce heat loss from the stream surface, maintaining relatively warm minimum temperatures. However, in our analysis, sites having a greater percentage of local forest cover had lower minimum stream temperatures. The reason for this effect is not known.

Channel orientation or aspect has been shown to influence the extent that riparian shading intercepts direct solar inputs and thereby influences stream temperatures (Abell 1996; LeBlanc et al. 1997). Our models did not account for the effect of stream aspect.

Ground water–Mean ground water velocity in the 4km site buffer and in the 2km corridor buffer were important variables in our models. This suggests that local ground water accrual near a site as well as ground water accrual along the entire stream network are important factors controlling stream temperatures.

Ground water velocity at the catchment level, however, was a relatively poor predictor of stream temperature. This is likely due to the fact that only a proportion of the ground water delivery to surface systems in the catchment is actually intercepted by the stream network, and that lakes and wetlands are competing sinks for this ground water.

For a given latitude, the temperature of ground water is typically within 1 °C of the local mean annual air temperature (Collins 1925), and streams receiving relatively large contributions of ground water are buffered against the effects of seasonal and daily fluctuations in air temperature (Hendrickson and Doonan 1972). As a result, ground water fed systems tend to be cold in the summer and warm in the winter. In Michigan and in other portions of the upper Midwest, ground water inputs have been shown to be critical in the maintenance of appropriate thermal habitat for cold adapted fish and aquatic invertebrates (Ricker 1934; Latta 1965; Hendrickson and Doonan 1972; Bowlby and Roff 1986; Meisner et al. 1988; Meisner 1990; Wiley et al. 1997; Zorn et al. 1997).

In lower Michigan, ground water temperatures vary from 8.2 °C in the north to 11.3 °C in the south (Leverett 1906). We did not account for this difference in ground water temperature in the present analysis. In addition, our models do not account for the actual volume of ground water that is delivered to the channel. Rather, the spatial model provides an estimate of potential ground water accrual based on ground water velocities near the stream network. Calibration of the spatial ground water model with actual ground water temperatures and volumes could improve the predictive abilities our models.

Air temperature–Air temperature did not dramatically improve the predictive ability of our models indicating that the variation in air temperature across the Lower Peninsula is relatively low compared with variation seen in other environmental variables (e.g. ground water inputs). Air temperature can be an important factor controlling stream temperatures if measured over larger latitidinal (e.g. Stefan and Preud'homme 1993) or altitudinal (e.g. Keleher and Rahel 1996) gradients, or at specific sites in relatively homogeneous catchments (e.g. Crisp and Howson 1982; Mackey and Berrie 1991; Newcomb and Coon 1997). It is expected that air temperature would become a better predictor of stream temperature if the present analysis were extended to Michigan's Upper Peninsula.

Landscape-Scale Influences

It is important to highlight the role of landscape-scale features that influence the factors controlling stream temperatures (Figure 4). Catchment physiography (geology + topography) is important in controlling recharge and delivery of ground water, stream flow patterns, and land use/land cover attributes. Stream flow patterns are themselves influenced by patterns of ground water flow and can be modified by changes in the hydrologic cycle associated with land use practices such as agriculture and urbanization. Channel morphology (width, cross-sectional area, gradient) is largely controlled by bankfull flows and can be locally modified by human activity such as channelization. Because the factors that control stream temperature are so closely linked to landscape attributes, human activity within the catchment can impact multiple factors and ultimately alter natural thermal regimes.

Assumptions and Limitations

In the present study, we did not directly measure the factors that control stream temperature. Instead, we used variables that were highly correlated with stream temperature and where applicable, assumed that a causal relationship existed between each independent variable and stream temperature. For example, we did not directly measure the extent of shading provided by riparian vegetation. Rather, we assumed that % forest cover in the 2-km corridor buffer was directly related to the amount of forest in the area adjacent to the stream and that this was proportional to the extent of riparian shading.

We also did not account for all variables known to influence stream temperatures. Lakes, wetlands and impoundments (because of their relatively large surface areas and high residence times) tend to accumulate heat energy and reduce short-term fluctuations in water temperature. Thus, natural fluctuations would be expected to decrease and water temperatures would be expected to rapidly approach the equilibrium temperature. This is especially important in cold and coolwater systems where an increase in stream temperatures can limit the amount of appropriate habitat available for cold-adapted taxa such as salmonids. Because lakes, wetlands and impoundments are prevalent in Michigan, future model development should incorporate their effects. Other factors we did not account for and that were previously discussed include stream aspect, and the temperature and volume of ground water that is delivered to the stream net.

Our ability to predict stream temperatures at a site is limited by the modeling approach used in this study. We used multiple-linear regression to construct stream temperature models. However, stream water temperatures and meteorological factors (e.g. thermal radiation) are related in a nonlinear way (Stefan and Preud'homme 1993). Although the use of nonlinear techniques may improve the predictive capabilities of our models, the added complexity associated with nonlinear models could limit their use.

Our models provide a rough estimate of July stream temperatures in Michigan's lower peninsula. Temperature predictions represent the average thermal behavior at a site and do not account for year to year variation in stream temperature. It is expected that interannual variation in precipitation and air temperature would lead to variation in stream temperature at a site; sites showing large July variation would also be expected to show the greatest variation in temperature across years.

The use of predictive temperature models developed in this study is limited by a lack of validation. The next step is to test the performance of the models using an independent data set. Future testing and refinement should result in better predictive models.

Management Implications

The results of this study have several management implications. Channel morphology, ground water inputs, and riparian forest cover are important factors controlling stream temperatures in lower Michigan rivers. Land use practices that alter channel shape (channelization, increasing surface runoff), recharge and delivery of ground water (conversion to impervious substrate, well water withdrawal), and riparian forest cover all impact natural thermal regimes. Changes in natural thermal regimes can lead to changes in species composition.

The models developed in this study provide a cost-effective method to generate baseline information that can be used for environmental impact assessment. These models can be used to generate expected (reference) thermal conditions for sites having similar catchment and reach characteristics. Observed temperatures can then be compared to expected temperatures as a means to evaluate present ecological status and to evaluate the impact of specific perturbations (e.g. impoundments).

These models also provide cost-effective tools that can be used by fisheries managers and researchers to evaluate summer thermal regimes at sites across a relatively broad geographic region. Large-scale temperature coverage generated from model predictions can be used to identify the extent of variation in temperature that exists within and among catchments. Such information can be used to classify streams by thermal type (Wehrly et al. 1998). A thermal classification can then be used to identify stream reaches that: 1) should receive special protection (coldwater rivers); 2) are most appropriate for stocking particular species; 3) are most appropriate for habitat rehabilitation; and 4) should fall under similar management regulations.

When matched with existing fish databases (e.g., Seelbach and Wiley 1997; Zorn et al. 1998), large-scale temperature coverage can also be used to determine the influence of temperature on patterns of fish distribution, abundance, and diversity (Wehrly et al. 1998; Zorn et al. 1998). This information will improve our understanding of the processes that control species assemblage structure at a site.

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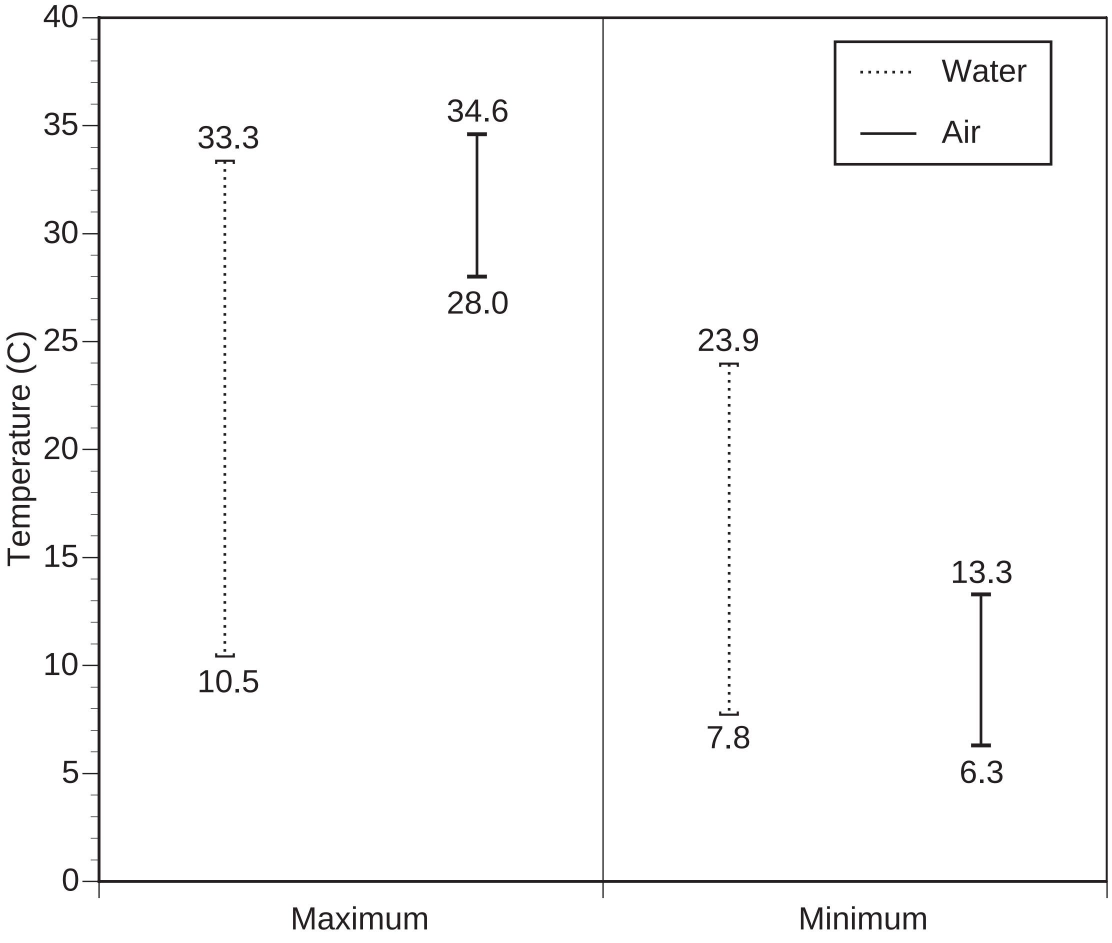

Figure 1.–Range of July maximum and minimum water and air temperatures for 171 sites in lower Michigan.

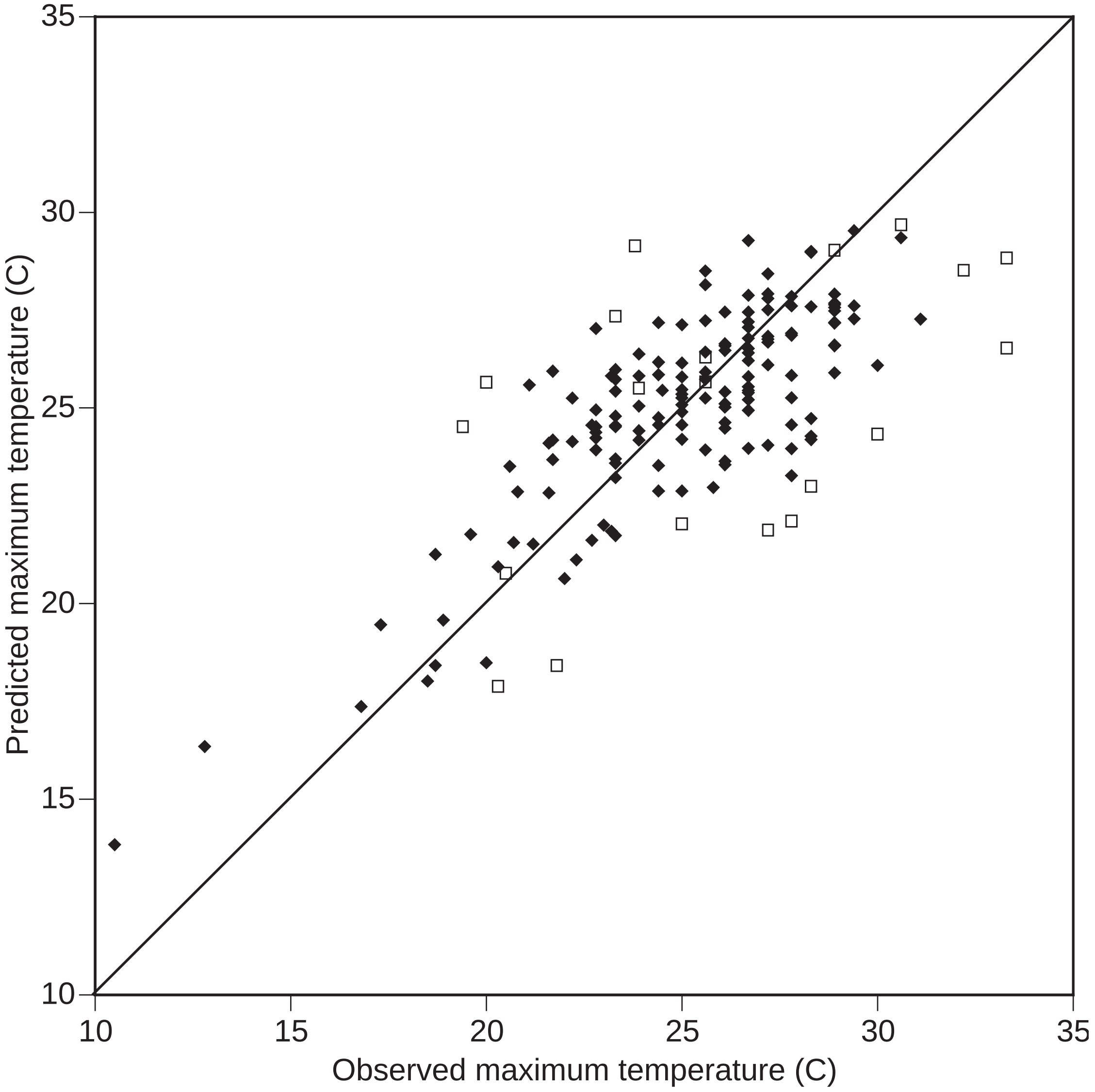

Figure 2.–Predicted (black symbols) and observed (line) average weekly maximum temperatures (July) for 171 sites in lower Michigan rivers. Open symbols indicate outlier sites excluded from second analysis.

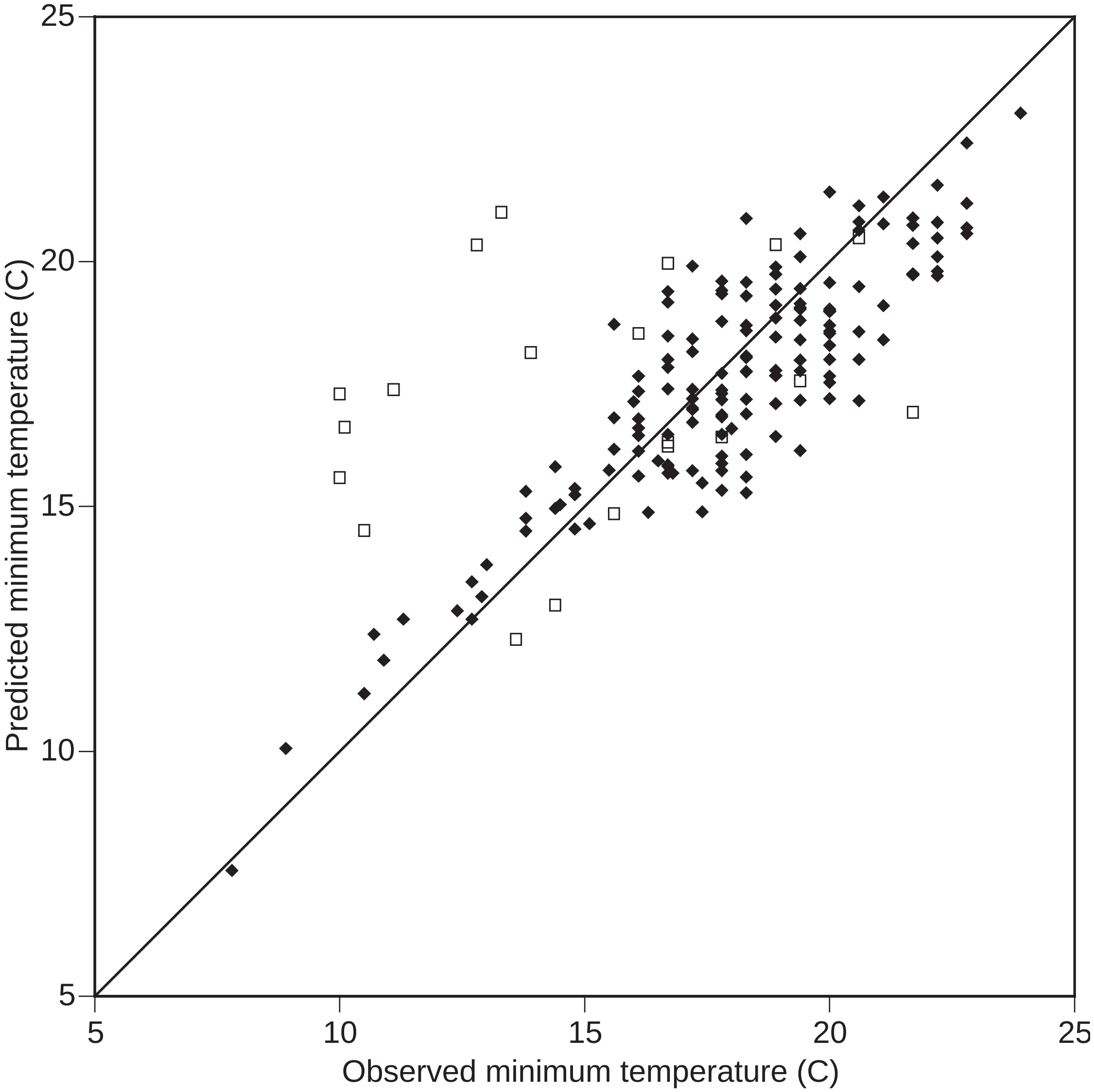

Figure 3.–Predicted (black symbols) and observed (line) average weekly minimum temperatures (July) for 171 sites in lower Michigan rivers. Open symbols indicate sites removed from second analysis.

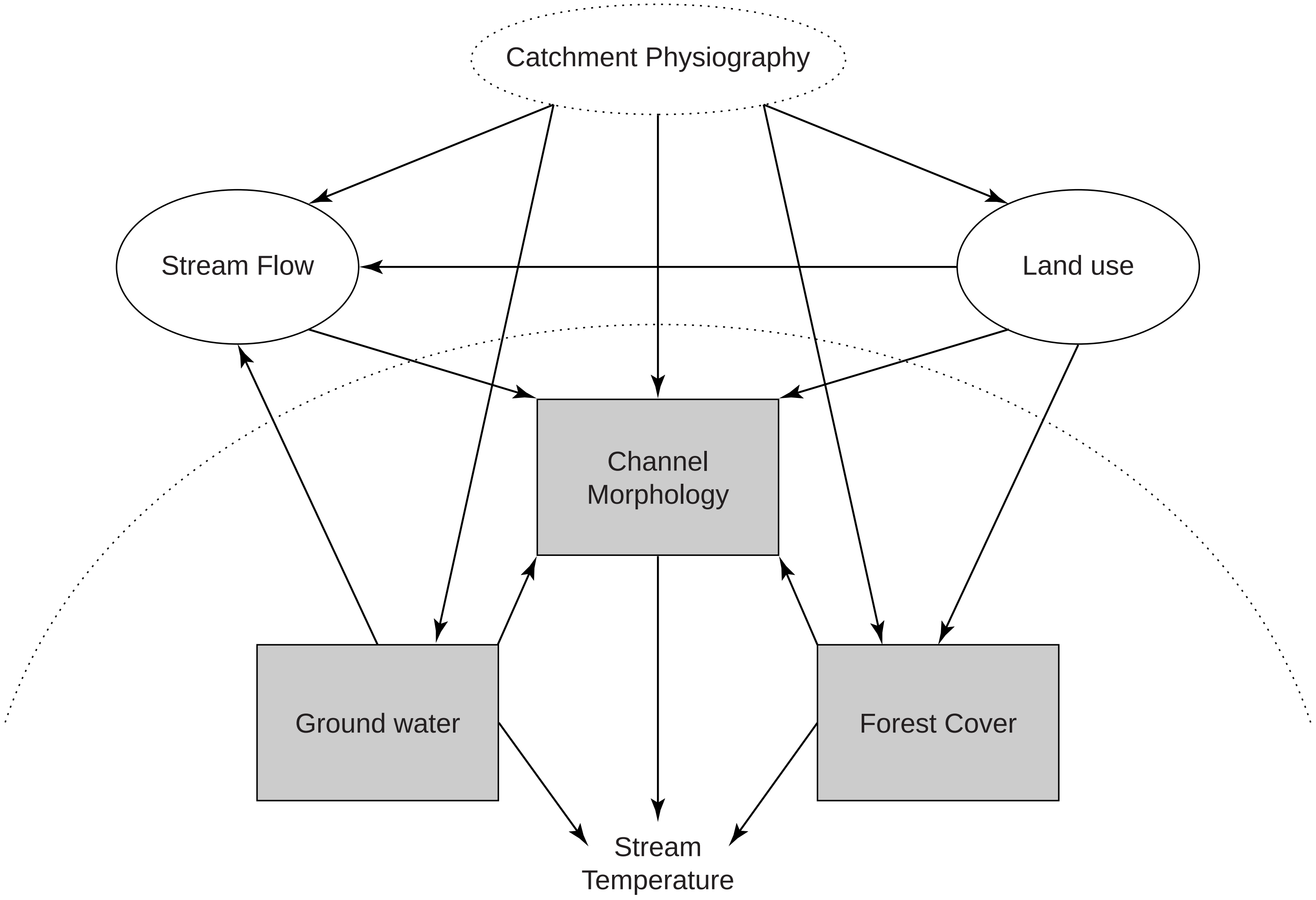

Figure 4.–Path diagram showing the influence of catchment physiography (geology + topography) on, and the interactions of, environmental factors that are important in controlling stream temperatures in lower Michigan.

Table 1.–Mean, standard deviation (SD), and range of catchment and local physical attributes and July water temperatures for 171 study sites in Michigan's lower peninsula.

Variable (units)	Mean	SD	Minimum	Maximum
Catchment characteristics				
Catchment area (km^2)	1,170.8	2,213.6	1.0	14,270.0
Agriculture (%)	50.7	24.9	0.0	92.2
Forest (%)	29.2	23.2	0.0	100.0
Urban (%)	4.7	3.5	0.0	17.5
Outwash and coarse texture till (%)	62.2	35.1	0.0	100.0
Fine and medium texture till (%)	20.7	26.6	0.0	100.0
Lacustrine sand and clay (%)	10.7	23.1	0.0	98.0
Network buffer				
Forest (%)	29.3	22.8	4.0	100.0
Ground water (m/day)	19.8	19.6	0.0	95.3
4-km buffer				
Forest (%)	30.2	23.4	2.5	96.1
Ground water (m/day)	15.2	16.6	0.0	96.5
Reach characteristics				
Cross-sectional area (m^2)	12.9	18.2	0.1	109.1
Depth (m)	0.5	0.2	0.1	1.2
Width (m)	18.9	16.5	0.6	91.1
Gradient (m/km)	1.7	5.5	0.1	50.9
Baseflow yield (m^3/s/km^2)	0.2	0.3	0.0	2.5
Temperature				
Max July stream temperature (°C)	25.1	3.4	10.5	33.3
Min July stream temperature (°C)	17.6	3.1	7.8	23.9
Max July air temperature (°C)	31.7	1.5	28.0	34.6
Min July air temperature (°C)	10.4	1.6	6.3	13.3

Table 2.–Symbols and estimated parameter values for temperature models predicting July thermal characteristics in Michigan rivers. Analysis with all sites included.

Model	Symbol	Parameter description	Parameter value	p
Maximum	a_1	Intercept	2.4722	0.0003
	b_1	Channel width exponent	0.1083	< 0.0001
	c_1	Network groundwater exponent	-0.0136	0.1361
	d_1	Maximum air temperature exponent	0.1371	0.4906
	f_1	Network forest exponent	-0.0417	0.0184
	g_1	Reach gradient exponent	-0.0203	0.0297
	h_1	Local groundwater coefficient	-0.0015	0.0209
	i_1	Channel area coefficient	-0.0026	< 0.0001
Minimum	a_2	Intercept	0.7298	0.0314
	b_2	Channel width exponent	0.0977	< 0 .0001
	c_2	Minimum air temperature exponent	0.0968	0.1936
	d_2	Maximum water temperature exponent	0.5220	< 0.0001
	f_2	Local forest coefficient	-0.1114	0.0467

Table 3.–Summary statistics from multiple linear regression for models predicting July thermal characteristics in Michigan rivers. Analysis with all sites included.

Models	n	R^2	$SE_{y \cdot x}$	p
Maximum	171	0.60	0.095	<0.001
Minimum	171	0.59	0.128	<0.001

Table 4.–Standardized regression coefficients from multiple linear regression models predicting July thermal characteristics in Michigan rivers. For each model, variables are listed in decreasing magnitude of relative influence on water temperature.

Model	Variable	Regression Coefficient[a]	Regression Coefficient[b]
Maximum	Stream width	0.605	0.749
	Cross-sectional area	-0.321	-0.400
	Network forest	-0.206	-0.253
	Local groundwater	-0.169	-0.170
	Reach gradient	-0.153	-0.141
	Network groundwater	-0.124	-0.072
	Max air temperature	0.044	0.032
Minimum	Stream width	0.428	0.439
	Max water temperature	0.398	0.506
	Local forest	-0.131	-0.108
	Min air temperature	0.077	0.126

[a] Results of model run with all data included.
[b] Results of model run with outliers removed.

Table 5.–Summary statistics from multiple linear regression models predicting July thermal characteristics in Michigan rivers. Analysis with outliers removed.

Models	n	R^2	$SE_{y \cdot x}$	p
Maximum	151	0.70	0.081	<0.001
Minimum	151	0.81	0.081	<0.001

Table 6.–Symbols and estimated parameter values for temperature models predicting July thermal characteristics in Michigan rivers. Analysis with outliers removed.

Model	Symbol	Parameter description	Parameter value	p
Maximum	a_1	Intercept	2.5178	0.0001
	b_1	Channel width exponent	0.1301	<0.0001
	c_1	Network groundwater exponent	-0.0083	0.3488
	d_1	Maximum air temperature exponent	0.0993	0.5800
	f_1	Network forest exponent	-0.0517	0.0019
	g_1	Reach gradient exponent	-0.0184	0.0316
	h_1	Local groundwater coefficient	-0.0015	0.0111
	i_1	Channel area coefficient	-0.0031	<0.0001
Minimum	a_2	Intercept	0.3325	0.1413
	b_2	Channel width exponent	0.0896	<0.0001
	c_2	Minimum air temperature exponent	0.1444	0.0036
	d_2	Maximum water temperature exponent	0.6217	<0.0001
	f_2	Local forest coefficient	-0.0822	0.0240

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