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Factors influencing thermal variability and fish distribution in small boreal steams / by Lisa McKee.

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Factors Influencing Thermal Variability and Fish Distribution in Small Boreal Streams

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ABSTRACT

The spatial variability of stream temperature is an important component of habitat within streams providing optimal temperatures for foraging and thermal refugia for sensitive species such as brook trout. Riparian shading and lateral contributions of groundwater through the hyporheic zone are the main contributors to spatial variability in stream temperature. The first two objectives of this study were to quantify thermal variability in stream systems through extensive mapping of streambed temperatures and to evaluate the influence of thermal variability on the stream fish distribution and community structure. The third objective was to examine associations between thermal variability and environmental variables at reach, riparian and catchment scales to identify features that may be used to characterize thermally important stream reaches. A total of 55 sample sites were surveyed during the warmest and driest season for Northwestern Ontario (mid-July - September) in streams from 4 catchments size classes: 1, 3, 5 and 10 km^2. Streambed thermal variability occurred on a sub-metre scale with temperature fluctuating up to 5.8 °C across a transect perpendicular to stream flow. The maximum variability found was 10.1 °C within a 50 m reach and 12.0 °C within a 300 m survey. Thermal variability was driven by cold streambed temperatures; 44 of 55 reaches had larger deviations below the mean streambed temperature than above the mean, which is an indication of cool groundwater entering the streambed. Fish species diversity and brook trout abundance was significantly higher in reaches with high thermal variability, while rainbow trout abundance was significantly lower. Fish species richness within a reach could be predicted as low (<5) or high (>5), with thermal variability as an independent variable using logistic regression. High (>0.10) or low (<0.10) rainbow trout abundance ($fish/m^2$) could also be predicted using thermal variability. Fish size was not found to be associated to thermal variability. Furthermore, thermal variability was correlated with terrestrial variables associated with groundwater movement, including the amount of adjacent land contributing surface and subsurface runoff to the stream, also known as reach contributing area (RCA). Reaches with large RCAs had significantly higher levels of thermal variability compared to reaches with small RCAs. However, the relationship between thermal variability and RCA was only found for reaches in the two largest stream catchment size classes (5 and 10 km^2) due to the dominance of groundwater during base flow of the two smallest catchments (1 and 3 km^2). Areas of low and high thermal variability differed in landscape topography, terrestrial surface roughness, landform geology and streambed permeability, which are all related to groundwater flow. In regions such as Northwestern Ontario, where hydrologic pathways are related to topographic features it is possible to use environmental features, such as RCA, to locate lateral groundwater inputs into streams. This predictive ability allows for identification, management and protection of valued ecosystem components important for the maintenance of ecological integrity of streams.

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During the process of my thesis many steps were taken between the initial question to the final conclusion and many of these steps would have been impossible to complete without the help from some great people. First, I would like thank my supervisor, Rob Mackereth for accepting me into the CAEP lab and for his continuous support throughout the entire process. I worked him hard but he guided my through the process smoothly and made it quite enjoyable. I am very grateful for the experience that Rob has given me and thanks to him, my mind is continuously generating new interesting questions and hypotheses about the biological world. I would also like to thank my committee members Dr. Stephen Hecnar and Dr. Azim Mallik as well as my external reviewer, Dr. Nick Jones, for being patient and flexible with my time line.

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1.0 INTRODUCTION

The distribution of organisms within ecosystems is affected by both biotic and abiotic factors. For aquatic organisms, temperature can have a profound influence on the distribution of individual species, populations and on community structure (Brunke and Gosner 1997; Caissie 2006; Meisner 1990). Thermal influences play a vital role in the composition, development and function of biota throughout a stream system (Vannote and Sweeny 1980). Stream temperature can also regulate food availability for biota such as fish and invertebrates, and growth of aquatic vegetation and algae. The 'Thermal Equilibrium Hypothesis' proposed by Vannote and Sweeny (1980) suggests that temperature is the critical variable in biotic niche differentiation as well as diversity and distribution patterns of fish and invertebrates. Thermal variation within streams allows for diverse community structure based on the conditions necessary for primary production and optimal thermal conditions for organisms (Hynes 1970). The effect of temperature on community structures and health is a combination of specific thermal tolerance levels for individual species and the need for stability in thermal regimes.

Disturbances to the abiotic conditions of a stream system may lead to the dispersal of an organism from one habitat to another, provided adequate connectivity between habitats is available for migration (Power et al. 1999; Fausch et al. 2002; With 2002). The migrations may alter the dynamics of a stream community including the distribution and persistence of organisms, inter- and intrapecific competition or the trophic interactions of the system (Schlosser 1991; Fausch et al. 2002; Brasher 2003; Attrill and Power 2004). Changes in stream temperature may create habitats no longer suitable for the persistence of organisms within them by exceeding the thermal tolerance of species, constricting other physiological important processes or reducing available resources such as food availability along the trophic scale (Wootton 1998).

Water temperature plays a key role in regulating the chemical properties of the ecosystem. Higher stream temperatures decrease the levels of dissolved oxygen and nitrate available to stream organisms (Fry 1971, Duff and Triska 1990). Increases in water temperature increases reaction rates and toxicity of other substances. The impact of higher toxicity levels may be compounded by a decrease in an organism's ability to cope with stressors in warmer conditions (Duffus 1980).

Primary production, such as periphyton growth, can be influenced by stream temperatures both directly; increasing within thermal tolerance levels and decreasing outside of those level, and indirectly; by the availability of nitrate and dissolved oxygen changing with temperature (Triska et al. 1989; DeNicola 1996).

Temperature has a direct affect on aquatic invertebrates by influencing their life cycles and behaviour through alterations in their growth, metabolism, reproduction, emergence and distribution (Vannote and Sweeny 1980). Invertebrate community diversity has been seen to alter with increasing temperatures outside thermal tolerance levels. Sponseller et al. (2001) found that as the maximum stream temperature increased, species richness, diversity and evenness declined and density increased but was attributed to the abundance single, thermally tolerant family, Chironomidae. The reduction of species diversity may have a bottom-up effect on the trophic scale; changes in food availability may influence fish community structure and distribution.

The distribution of fish within stream networks is influenced by individual and population optimal thermal preferences (Power et al. 1999). Many stream fish migrate long distances to find thermal refugia during both summer and winter seasons (Bell 2006; Torgensen et al. 1999). Elevated stream temperatures slow fish growth by affecting activity, appetite, enzyme efficiency, and increasing expenditure of energy on metabolism (Power et al. 1999). While smaller fish can move into the substratum to keep cool, larger fish will move large distances to find cooler reaches and moderate their body temperature (Drake and Taylor 1996).

In Northwestern Ontario stream water temperatures are of particular importance due to the vast network of streams with communities composed of organisms with preferences for colder temperatures. A coldwater stream is defined as a stream that is supporting or capable of supporting coldwater fishes with an upper limit of 26 °C in the summer (OMNR 2008a). Coldwater stream fish species in the region include sculpins and salmonids, which include brook trout (*Salvelinus fontinalis*) and rainbow trout (*Oncorhynchus mykiss*) (Scott and Crossman 1973). Although stream water temperature is most strongly influenced by atmospheric temperature (Poole and Berman 2001), and the amount of solar radiation penetrating the stream (Johnson 2004), groundwater inputs are a significant component in the maintenance of suitable habitat for fish by providing cool upwellings in the summer and warm inputs in the winter (Cunjak 1996).

The temperature stabilizing influence of groundwater inputs into streams influences habitat suitability for many fish species and plays a key role in habitat choice. The selection of habitat based on the presence of groundwater has been observed in brook trout due to low temperature preference, relatively low upper lethal temperature and their requirement for thermally stable areas for successful reproduction (Blanchfield and Ridgway 1997). Although water depth, stream velocity, substrate composition and cover are important to brook trout spawning site (redds) selection, none are as essential to the preference as the chemical or physical nature of upwelling groundwater (Curry et al. 1994, Curry and Noakes 1995, Blanchfield and Ridgway 1997). The presence of groundwater at redds enhances reproductive success by allowing young of the year brook trout to avoid predation while experiencing optimal temperature and chemical conditions (Power et al. 1999).

In addition to the importance of groundwater in brook trout spawning site selection, cooler temperatures associated with groundwater plays a key role in behavioural thermoregulation for brook trout and other salmonids (Biro 1998). Behavioural thermoregulation involves active regulation of body temperature by behavioural means and occurs when fish avoid water temperatures above their tolerance level to reduce time spent in stressful environments (Reynolds and Casterlin 1979; Tiffian et al. 2009). In warm summer months, brown trout have been observed using coldwater plumes to thermoregulate during the day when stream temperatures are at maximums, suspending foraging until the cooler evening temperatures (Olsen and Young 2009). Breau et al. (2007) found that juvenile Atlantic salmon would aggregate in cool plumes or seeps during daily temperature maximums and disperse as stream temperatures lowered, suggesting that juveniles were actively choosing to occupy higher densities to maintain optimal body temperatures. Observations of juvenile brook trout have noted competitive behaviour for cooler thermal habitat and active avoidance of temperatures over 20 °C (Biro 1998). Juvenile brook trout may also decrease foraging in sub-optimal temperatures (>22 °C) due to the stressful physiological conditions, which amplified when refuge is unavailable (Marchand et al. 2002). Similarly the use of thermal refugia for thermoregulation has been observed juvenile rainbow trout, coho and Chinook salmon (Sutton et al. 2007). Thermal refuge areas for aquatic species produced from groundwater input from springs, tributaries, seeps and plumes and these allow fish to inhabit streams with abundant resources that may otherwise exceed thermal tolerance levels (Sutton et al. 2007).

Water temperatures not only influence the daily distribution and behaviour of stream fish but can have an impact on key aspects of their life cycle such as migration or spawning time. During high water temperatures, Atlantic salmon have been seen to halt their upstream migration, move into cooler tributaries and remain there until the main stream water temperatures are below their upper thermal tolerance level (Goniea et al. 2006).

Regions of cool water from springs, seeps or plumes influence fish distribution within a stream because such features lower the temperatures of the entire stream but rather smaller point locations distributed along a stream (Olsen and Young 2009). In these cool patches the maximum daily temperature is lowered and the diel variation in temperatures is smaller. Ebersole et al. (2003) found a reduction of 5.4 °C in daily maximum temperature and 5.7 °C in diel variation in a groundwater patch compared to the main stream surface water. The quality of groundwater patches is influenced by the surrounding habitat and riparian zone characteristics. Riparian variables such as shading can further lower daily maximum in the cool patches while stream habitat variables such as velocity and substrate composition may increase the utilization of these sites by biota (Ebersole et al. 2003).

The thermal characteristics of streams are important to stream biota and drastic changes in temperature can significantly impede many life stages for these organisms. Heterogeneity in stream temperatures at both a spatial and temporal scale diversifies aquatic communities. According to Townsend's (1989) 'Patch Dynamics' theory, temporal variability in stream conditions provide differing habitat conditions for a diversity of aquatic organisms. A study by Constantz (1998) found that within an annual cycle, temperatures are not only warmer during the summer season due to increase air temperature but are more variable within and between days.

This is complemented by the 'Process Domains Concept' by Montgomery (1999) which suggests that spatial heterogeneity in stream conditions is necessary for aquatic diversity. There are many variables which act upon and regulate stream temperature both at the temporal and multiple spatial scales. At a catchment scale, water temperatures are influenced by the climatic, regional, hydrological and structural conditions within the region (Dallas 2008). Within a catchment, variation between streams or within a single stream is influenced by the hydrological and physical variations among the individual streams (Meisner 1990). During the summer, temperatures are generally cooler in the headwater portion of a stream and warm longitudinally down the system into the lowland areas (Caissie 2006). Many factors have been correlated with the longitudinal thermal gradient in stream systems but perhaps the most recognized are those discussed in the 'River Continuum Concept' by Vannote et al. (1980). The River Continuum Concept suggests that small headwater streams receive only minor longitudinal contributions from upstream sources and are therefore dependent upon water received laterally from the terrestrial landscape in the form of shallow groundwater and surface runoff. During the summer, the groundwater contributing to small headwater streams creates a cooler, stable thermal regime because subsurface groundwater is not influenced by solar radiation and has a temperature that is typically close to the mean annual air temperature of the region (Kalbus et al. 2006; Power et al. 1999).

The lateral inputs of cooler groundwater however are not restricted to the headwater regions of a stream but can be distributed throughout the stream network (Contant Jr. 2004; Freeze and Cherry 1979). Because groundwater emerges from the streambed sediments to mix with the surface water the temperatures of the sediment in groundwater upwelling areas should be variable in comparison to the stream water (Becker et al. 2004).

Sampling of streambed temperatures can be an effective tool to indicate areas of groundwater discharge in streams and lakes (Kalbus et al. 2006). Bustros-Lussier et al. (2007) dragged a thermal sensor (Reelogger Model 2011) along the streambed to measure temperature and found that at low discharge, thermal anomalies were evident and these were attributed these to groundwater upwellings. A different study on streambed temperatures found a thermometer probe inserted directly into the streambed sediments gave a more accurate representation of streambed temperatures and was more effective at locating cooler regions (Bustros-Lussier et al. 2007). Contant Jr. (2004) completed a study by measuring streambed temperatures along transects every metre with a thermometer probe at point locations across each transect for a length of 60 m. A streambed thermal map was then generated showing the spatial distribution of streambed temperatures within a single stream, indicating cooler plumes and groundwater inputs as well as warm shallow regions throughout the stream survey.

The combined influence of groundwater inputs, air temperature and solar radiation on surface water creates heterogeneous thermal patterns, laterally and longitudinally along a stream (Webb and Zhang 1997). These heterogeneous thermal patterns create thermal variability in streambed temperatures where cool groundwater mixes with surface water. The heterogeneous patterns exists because groundwater inputs are not evenly distributed along a streambed and many sections of a stream may only receive minor lateral contributions or none at all, relying only on longitudinal contributions or surface runoff following perception events (Schmidt et al. 2006).

Lateral groundwater contributions into a stream are associated with structural and hydrological characteristics that occur at multiple spatial scales from the entire catchment (km) to instream habitat condition (m) (Dallas 2008). The presence and rate of groundwater flow is determined by the hydrological gradient of local topography and soil permeability (Beven and Kirkby 1979). Steeper topography will have a higher rate of flow compared to low gradient topography due to an increase retention and accumulation capacity (Chang 2003). Fine grain soils such as silt and clay impede water movement and compared to coarse soils like gravel and sand which have high water permeability and allow groundwater to easy flow through (Raymond Jr. 1988). It is these topographical and geological characteristics that determine where groundwater will enter into an aquatic system. Because streams are highly influenced by the landscapes in which they flow (Fausch et al. 2002) there should be topographic, geologic, riparian zone structure and stream morphology indictors that can be used to locate areas of groundwater inflow (Hewlett and Hibbert 1963; Freeze and Cherry 1979; Cey et al. 1998; Raymond Jr. 1988; Borwick et al. 2006).

At this point, there is a need for a better understanding of the hydrological linkage between the terrestrial and aquatic environment due to the vulnerability of the relationship to landscape disturbances. This is of particular importance with disturbances that may potentially alter the quality and quantity of groundwater reaching a stream such as forest management activities (Curry et al 2002), urban development (Taylor and Stefan 2009), road construction (Baxter et al 1999), and agriculture (Scanlon et al. 2005). In Northwestern Ontario, forest management is the most prevalent threat to groundwater pathways. Following tree removal, a reduction canopy interception and evapotransporation may enhance the delivery of water into a stream by increased soil saturation and raise annual stream flow yield (Stednick 1996; Brunke and Gonser 1997; Chang 2003). At the local scale, changes in groundwater delivery after forestry activities may impact stream temperature, chemistry, and nutrient inputs, which may lead to detrimental effects to all trophic levels of the stream biota community from algal abundance to fish community structure (Curry et al. 1994; Allan 1995; Martin et al. 2000).

The common management technique used to mitigate harvesting impacts is to leave undisturbed shoreline zones, or buffers, along streams and lakes. However traditional stream side buffers do not account for the alterations in dynamics or distribution of groundwater inputs and do not consider the hydrological connection of subsurface water from the terrestrial environment (Curry et al. 1994; Buttle 2002). Even with only a small proportion of a catchment harvested there may be increases in stream water temperature in the first few years and has been suggested to be associated with the disturbance to groundwater pathways (Kreutzweiser et al. 2009). In a small

Newfoundland stream, the thermal regime was altered even when a sufficient buffer was left to shade the stream from solar input caused by warmer groundwater discharge entering the stream (Curry et al. 2002). Similarly, Bourque and Pomeroy (2001) reported warming of stream temperature following harvesting because of increased heating of contributing subsurface water from the forest harvesting blocks. The occurrence of stream warming may persist many years after the harvesting disturbance (Carigan and Steedman 2000) which may permanently habitat degrade fish habitat.

It is important to understand the spatial and temporal patterns of variability occurring in a stream and how this thermal variability influences stream fish distribution and community structure. It is necessary to look at the variation in temperatures found laterally and longitudinally across a channel to identify different habitats for fish species (Ebersole et al. 2003). Many studies have focused on point locations of thermal variability or the variability of surface water temperatures rather than subsurface thermal regulation throughout large portions of a stream. My intention was to extensively examine the degree of spatial variability in streambed temperatures as an indication of lateral groundwater contributions into a stream. My study also explored the influence of thermal variability on stream fish characteristics to determine the necessity of thermally diverse habitats for community structure. Furthermore, I attempted to characterize areas of thermal variability using environmental variables at multiple spatial scales. My goals are related to land use implications such as improving the ability of natural resource mangers to easily and quickly identify the terrestrial regions adjacent to streams of thermal importance to minimize the level of disturbance to the natural thermal regime of coldwater streams.

The specific objectives and hypotheses of my study were to:

(1) Investigate the spatial distribution of the thermal characteristics and the degree of thermal variation in streambed temperatures for different stream sizes. I hypothesized that if the contribution of lateral inputs along a stream channel was heterogeneous and this is indicative of cooler groundwater entering the stream then there will be thermal variability in streambed temperatures along a stream channel in association with these areas.

(2) Measure the relationship between stream thermal variability and stream fish abundance, diversity, biomass as well as brook trout and rainbow trout characteristics inclusively. I hypothesized that if thermal variability exists and fish are inhabiting the stream then regions of high thermal variability will have a higher fish abundance, diversity and productivity because they are more diverse and maintain optimal thermal conditions than less thermally variable regions. Furthermore, I predicted that brook and rainbow trout abundance, relative abundance, and productivity will be higher in regions with more thermal variability and cooler temperatures than less variable areas.

(3) Examine the associations between streambed thermal characteristics and environmental variables at multiple spatial scales including the catchment, riparian zone and habitat characteristics. I hypothesized that if stream thermal characteristics are associated with the amount of lateral contribution the stream reach receives then thermal variability will be associated with the size of the area

contributing to it as well as hydrological characteristics that are associated with groundwater flow. I predicted that areas with high thermal variability will have larger contributing areas and different catchment, riparian and habitat characteristics than reaches with less thermal variability and smaller contributions.

2.0 STUDY AREA

The study area was located in Northwestern Ontario in the Nipigon Bay Basin, ~20 km east of the Town of Nipigon, Ontario (UTM 424858, 542992, zone 16). The portion of the basin used for this study consists of 14 sub-watersheds and covers an area of approximately 176800 hectares, all of which drain into the north shore of Lake Superior (Figure 1). This area has an active forest industry in combination vast coldwater stream networks that maintain an abundant fish population.

The ecoregion for the area is a combination of the Superior Highlands in the south and the Lake St. Joseph Plains in the north (Wickware and Rubec 1989). Annual mean temperature is 1.7 °C; the warmest temperatures are in July with a mean of 17 °C and coldest in January with a mean of -16.6 °C. The average annual rainfall is 576.6 mm and the average snowfall is 237.5 cm for a total precipitation of 814.1 mm (Environment Canada 2009).

The region is defined by a moderate amount of topographic relief made up of granitic bedrock outcrops which include rock knobs, sheer cliffs and, glacially eroded valleys filled with sandy outwash, lacustrine clay or silt deposits. The region is covered by shallow sandy soils comprised of loamy moraine (Wickware and Rubec 1989). Topographic elevation within the region of the study sites varies from a low of 184 m to a high of 467 m above sea level although the maximum elevation for the region is much higher than these levels and exceeds over 500 m on bedrock bluffs (OMNR 2009). Soil moisture varies from dry and well-drained with humo-ferric podzol soil to low slopes that are poorly drained with organic/peat soils. Stand types vary accordingly to the soil and drainage capacity. In drier well-drained areas there are stands of pure Jack pine (*Pinus banksiana*) or boreal mixed woods consisting of Trembling aspen (*Populus tremuloides*), White birch (*Betula papyrifera*), Black spruce (*Picea mariana*), White spruce (*Picea glauca*), Jack pine and Balsam fir (*Abies balsamea*). In the wetter areas, Black spruce, Tamarack (*Larix laricina*) and Eastern white cedar (*Thuja occidentalis*) stands occur. Under the conifer canopy, the undergrowth consists of feather moss mats and small Jack pine and lichen groundcover in bedrock-dominated regions (Wickware and Rubec 1989). The riparian zones along the stream banks are made up of a variety of small trees, shrubs and herbaceous vegetation. The prevailing riparian species included speckled (*Alnus incana*) and green alder (*Alnus viridis*), mountain maple (*Acer spicatum*), high bush cranberry (*Viburnum trilobum*), red osier dogwood (*Cornus stolonifera*), Labrador tea (*Ledum groenlandicum*) and black ash (*Fraxinus nigra*). The Nipigon Bay Basin has negligible permanent residences or agriculture and primarily land use is recreation and forestry practices (Wickware and Rubec 1989).

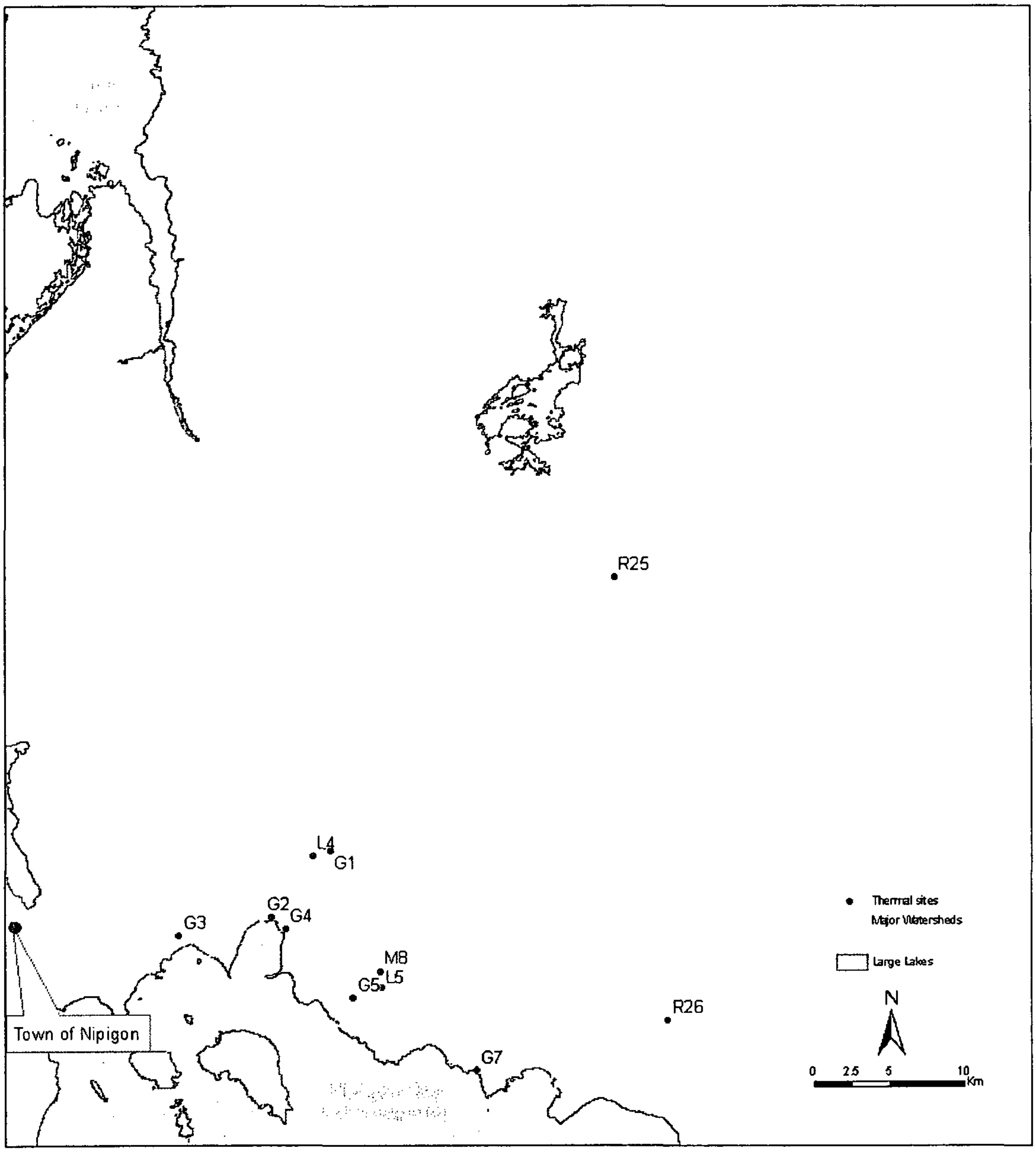


Figure 1. Overview map of the stream survey area located with the Nipigon Bay Basin watersheds.

3.0 METHODS

3.1 Site Selection and Design

In order for a stream site to meet the sampling criteria it needed to fall within 1, 3, 5, or 10 km^2 (+/- 30%) catchment size categories, contain a defined continuous stream channel and have minimal to no recent (>10 years) forest harvesting within the catchment. Catchments were delineated in a GIS using a filled raster-based digital elevation model (DEM) generated with the Environmental Systems Research Institutes (ESRI) ArcMap Spatial Analyst (version 9.2, ESRI 2002). Larger catchment streams (3, 5, 10 km^2) were located in close proximity to Lake Superior and below fish movement barriers to increase the potential for fish presence (Figure 1). Sites were chosen in a non-nested design and were assumed to be spatially independent with each stream on a separate tributary. A 300 m maximum sample unit was established at each site; 300 m was the preferred length for a stream survey but not required due to unavailability of flowing water, undefined upstream channel or a change in catchment size.

To examine the amount of in stream thermal variation each 300 m stream survey section was divided into 6, 50 m reaches. Each 50 m reach survey included streambed temperature measurements along a transect across the width of the stream channel at 2 m intervals; collection of GPS coordinates at each transect; a one-pass electro-fishing survey; 4 habitat assessments; a riparian zone assessment and an evaluation of the catchment scale environmental and geological variables (Figure 2).

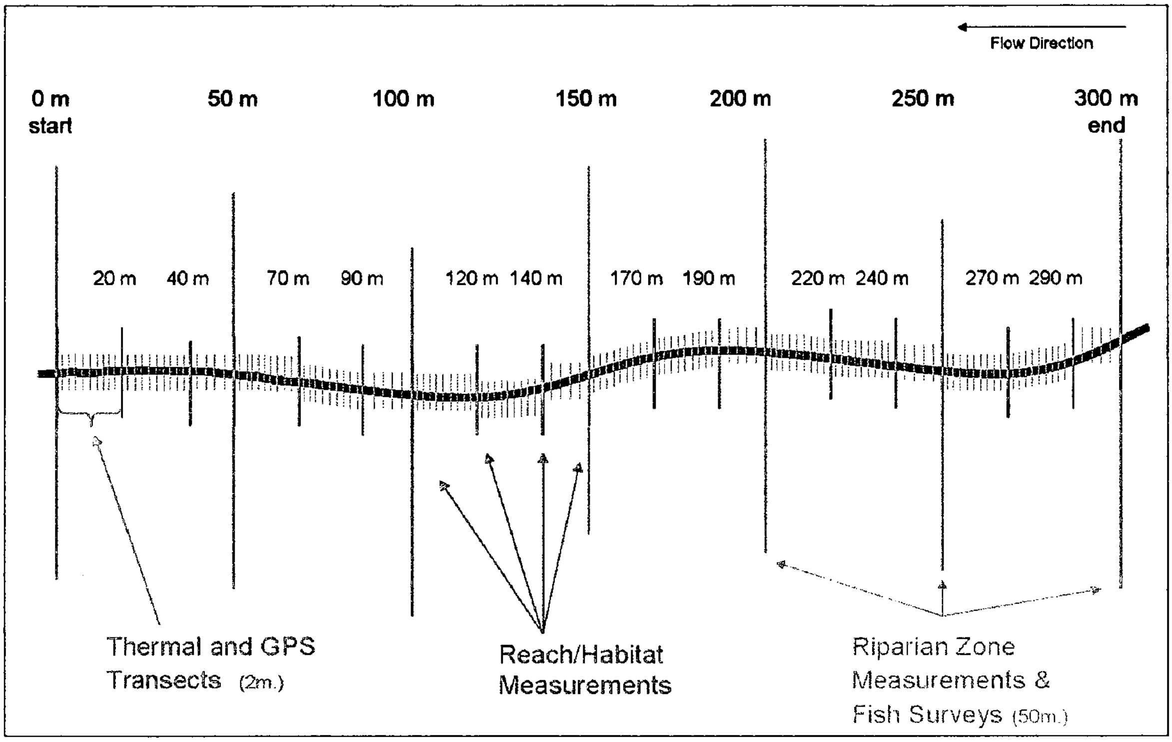


Figure 2. Field sampling design for the streambed thermal mapping, fish surveys and environmental measurements.

3.2 Thermal Characteristics

3.2.1 Streambed thermal mapping

Streambed thermal sampling were conducted on 11 streams and occurred between July and September during periods of base flow when precipitation in the region is low in order to increase the probability of detecting hyporheic influences and to reduce the influence of surface water. Two sites were sampled from each of the 3, 5 and 10 km^2 catchment categories and five from the 1 km^2 catchment category. The thermal data was measured using a waterproof heavy-duty, K-type digital thermocouple thermometer with an accuracy of 0.1°C (Hanna Instruments). Transects were set across the stream channel perpendicular to stream flow and across each transect 5 evenly spaced streambed temperatures and depth measurements were taken (Figure 3). Streambed temperatures were measured by inserting the thermometer probe into the streambed to a maximum depth of 10 cm and allowing the digital reading to stabilize before recording (~5 sec). Stream surface water temperature was measured in the middle of each transect in the middle of the water column.

Stream channel morphologies were generated from GPS points collected with a Trimble Pro XRS (sub-metre accuracy) and a Recon handheld PDA equipped with ArcPad software (ESRI version 7.1.1). GPS location data were collected at the centre of every 2 m transect for a maximum of 300 m (Figure 3). Real time differential correction was applied using a Coast Guard beacon and post-processing was completed using the Centre for Northern Forest Ecosystem Research (CNFER) base station located at Lakehead University. Along with GPS points, the wetted width of the stream channel was also recorded at each transect.

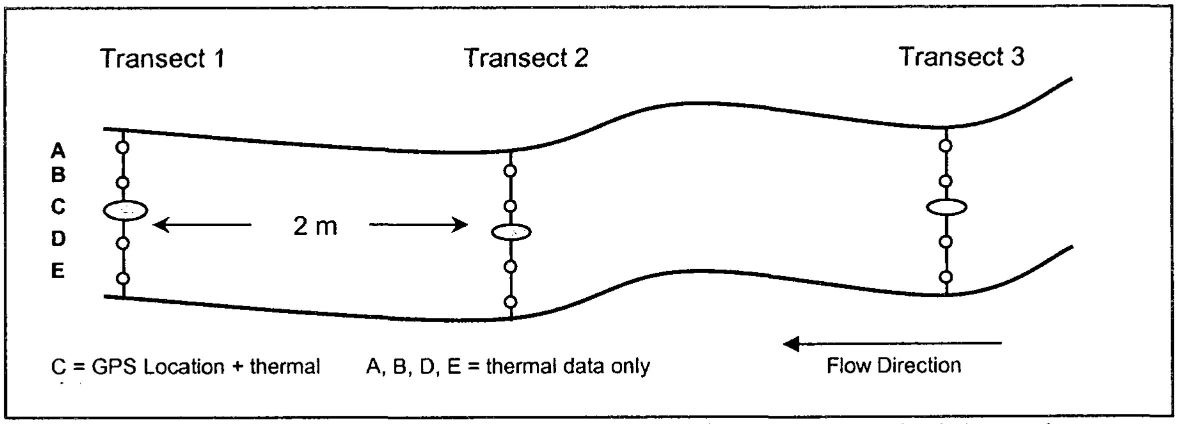


Figure 3. Streambed temperature and GPS point locations for streambed thermal mapping methods. Stream depth was also collected at each point (ABCDE) and wetted stream width for each transect.

The thermal maps for each stream were created individually using a combination of ESRI GIS software packages ArcMap and ArcInfo with the Tools for Graphics and Shapes extension, version 1.1.85 (Jenness 2008) and Microsoft Excel and Access software. Thermal maps were generated by reconstructing the stream channel into a multipart polygon vector and using recorded streambed temperatures for the interpolation of the thermal raster grid (Appendix I).

3.2.2 Statistical analyses - Thermal variability

The streambed thermal data used in analyses was standardized to account for surface water differences within and among days. Standardization included calculating the difference between individual transect surface water temperature and the coldest surface water transect within the entire reach. The difference in surface water temperatures was subtracted from each streambed temperature within each individual transect for the reach.

To reduce the effect of diurnal temperature variation between site survey dates standardization included calculating the deviation of individual streambed temperatures from the overall mean streambed temperature. Streambed temperatures that were warmer than the mean were positive and temperatures that were cooler were negative. Thermal variability within a 50 m reach was summarized as the range between the maximum positive and negative deviations from the mean stream reach temperature. Differences in thermal variability among streams catchment size classes was analyzed by using nested design, analysis of variance (ANOVA). Due to the non-independent nature of reaches within streams, a nested design was used to control within site variability with catchment size as the main fixed factor, stream site as a random nested factor and reach as the sampling unit (Krebs 1989). The ANOVA was used to establish a difference between means among catchment sizes and a least square difference (LSD) post-hoc method was used to interpret how the means differed among catchment size classes.

3.3 Thermal and Fish Relationships

3.3.1 Stream fish surveys

Stream fish surveys were conducted in 7 sites during the 2008 field season by OMNR fishery technicians using a single pass method with a backpack electrofisher unit (Smith-Root inc. 1992, Model 15-B). All of the reaches in the 3, 5 and 10 km^2 catchment size categories were sampled and one 1 km^2 stream catchment, the remaining 1 km^2 streams were upstream of barriers to fish movement or had water level conditions to low to conduct an electrofishing survey. The stream electrofishing surveys were divided into 50 m reaches which corresponded with reaches surveyed during the streambed thermal mapping surveys (Figure 2). Prior to electrofishing, block nets (4.57 m. 0.6 cm seine mesh) were set in the stream at the upstream and downstream ends of the survey to prevent fish movement between reaches. At the end of the 50 m survey, captured fish were identified to species, counted and batch weighed (g) by species except for brook and rainbow trout which were weighed (g) and measured for total length (mm) individually. Fish were released below the upstream blocker net in the same reach in which they were collected.

The data collected from the electrofishing survey for each 50 m reach was summarized into 3 categories: total fish community, brook trout populations and rainbow trout populations (Table 1). The total fish community variables included abundance (fish/m^2), biomass (g/m^2), species richness, and species diversity, a measurement of species evenness determined using the Simpson Diversity Index (1-D). The species specific variables for both brook trout and rainbow trout were the same as the total fish variables but also included relative abundance and mean length (mm). Relative abundance was used to examine the dominance of the two salmonid species of interest within a reach and refers to the abundance of an individual species divided by the total abundance of all species combined (Krebs 1989).

3.3.2 Statistical analyses – Fish characteristics

The relationship between stream thermal variability and fish community characteristics was assessed by examining associations between independent variables describing the thermal, habitat and catchment characteristics and 14 dependent variables describing the fish community (Table 1). Differences in fish community structure among different catchment size classes were analysed using a series of nested univariate ANOVAs. The nested design was used to control within stream site variability by subgrouping stream site within catchment size class and using the 50 m reaches as the sampling unit. A LSD post-hoc comparison analysis was used to interpolate any significant differences revealed between catchment size classes. Collinearity between the dependent fish variables was tested using a Pearson correlation matrix and one variable from highly collinear pairs ($r > 0.5$, $p < 0.05$) was omitted from the multivariate analyses.

Associations between streambed thermal variability and fish community variables were examined to investigate the presence and strength as well as the nature of the relationship, whether positive or negative between the variables. The presence of a significant relationship ($p < 0.05$) and strength of an association from the coefficient of determination (r^2) was used to explain the influence thermal variability may have on stream fish community structure and which community variable is most related to it. The correlation between the 14 dependent fish community variables and thermal variability was tested using univariate linear regressions.

To determine if fish distribution was associated with stream thermal characteristics I examined the association between thermal variability and the probability of fish presence. Fish presence was characterized by binary, categorical variables for several measures of the fish community based on frequency distribution curves to evenly distribute the numbers into categories (Table 2). Logistic models were developed using logistic regression to use thermal characteristics to predict the probability of each class.

Stream habitat variables (Table 1) were added to thermal variability as independent variables to look for associations between the stream habitat condition and the fish community structure as well as the strength of these variables in comparison to thermal variability. The intention was to find out if stream habitat had a stronger influence on community structure than thermal variability or if variables in the habitat increase previous associations found between thermal variability and the fish community. Stream width was not used in the multivariate analyses for the abundance (fish/m^2) or biomass (g/m^2) which included area within the variable. To assess how stream habitat characteristics contribute to the association between the thermal characteristics and the structure of the stream fish communities, a multiple regression was used as an additive linear model. Using forward stepwise regression the thermal and habitat variables were added to the model for each fish community variable until the r^2 variable was no longer improved.

I also examined whether the abundance or characteristics of the two salmonid species was associated with one another, which may over shadow any associations seen between the two species and thermal variability. To test for correlations between the two species, brook trout abundance, relative abundance, biomass, and mean length measurements were regressed against the equal variables for rainbow trout using simple linear regression for each set of variables.

Table 1. Independent and dependent variables used in analyses.

Independent	Units	Dependent	Units
Thermal Variables		**Total Fish**	
Thermal variability	°C	Total fish abundance (density)	fish/m^2
Stream Habitat Variables		Species richness	
Width	m	Species diversity	1-*D*
Depth	m	Total fish biomass	g/m^2
Slope (gradient)	°	**Brook Trout**	
Percent of porous sediment	%	Brook trout abundance (density)	fish/m^2
Percent of canopy closure	%	Brook trout relative abundance	
Average bank heights	m	Brook trout biomass	g/m^2
		Brook trout mean weight	g
		Brook trout mean length	mm
		Rainbow Trout	
		Rainbow trout abundance (density)	fish/m^2
		Rainbow trout relative abundance	
		Rainbow trout biomass	g/m^2
		Rainbow trout mean weight	g
		Rainbow average length	mm

Note: Average values were used for the habitat variables within the 50 m reach sampled.

Table 2. Binary categorical variables for fish variables in logistic regression analyses.

Variables	Categories	
	Few (1)	Many (2)
Total fish abundance	< 0.20	> 0.20
Species richness	< 5	> 5
Species diversity	< 5	> 5
Total fish biomass	< 1.50	> 1.50
Brook trout abundance	< 0.10	> 0.10
Rainbow trout abundance	< 0.10	> 0.10

3.4 Thermal and Environmental Variables

3.4.1 Habitat characteristics

Stream habitat, riparian zone and catchment scale characteristics were measured for each 50 m reach for all of the 11 streambed thermal mapping sample sites (Table 3). The instream habitat variables were measured at the beginning of each reach, every 20 m within the reach and again at the end of each reach (n= 4/reach) (Figure 2). Stream habitat variables included wetted stream width, streambed substrate, bank heights and percentage of canopy closure. The percentage of canopy closure was collected in 4 cardinal directions during full leaf out using a spherical hand held densitometer and averaged as a representation of the canopy closure from the riparian and upland zone (OMNR 1997). Streambed substrate percent composition was visually estimated using a modified version of the texture classes found in Sims et al. (1997) that included fine sediment (silt and sand), porous sediment (gravel and cobble) and impervious sediment (clay and bedrock). The geomorphic structure of the stream was classified into riffles where the stream flow is rapid and shallow; runs where the stream water was flat but moving and pools where the water is slow and deep (Chang 2003). Stream depth and geomorphic structure, (riffle, run and pool) were recorded at every 2 m transect during the thermal surveys.

Table 3. Summary of the environmental variables collected for each 50 m reach.

Stream Habitat	Units	Riparian Zone	Units	Landscape	Units
Depth	m	Stream Slope	°	CV	%
Geomorphic structure		RCA	ha	Landscape slope	°
Wetted width	m	Riparian width	m	Bedrock	%
Bank height	m	Riparian canopy	%	Topographic relief	l/m/h
Fine sediment	%	Riparian slope	°	Soil moisture	w/m/d
Porous sediment	%	Soil moisture	w/d		
Impervious sediment	%	Soil type	1 – 5		
Canopy closure	%	Soil depth	m		
		Wetland type	W-type		

Note: Riparian soil moisture, w = wet, d = dry; Riparian soil type, 1 = organic, 2 = silt, 3 = sand, 4 = clay, 5 = bedrock; Landscape topographic relief, l = low, m = medium, h = high; Landscape soil moisture, w = wet, m = mixed, d = dry

3.4.2 Riparian zone characteristics

Riparian variables were measured at the beginning and end of each reach, or when distinctive changes in riparian zone structure were apparent (Figure 2). Riparian zone variables were measured on both stream banks from the bank edge to the upland forest transition. On each bank side riparian width, riparian zone slope, riparian canopy closure, wetland type and soil characteristics were measured (Table 3). Wetland type was determined using the *Field Guide to Wetland Ecosystem Classification for Northwestern Ontario* (Harris et al. 1996). Soil and canopy closure measurements were taken at 25, 50 and 75% of the riparian zone width. Soil characteristics measured were measured by taking samples using a small, stainless steel auger to a maximum depth of 85 cm. The dominant soil type was categorized into organic, silt, sand, clay or bedrock (Sims et al. 1997). Soil moisture was classified as either wet or dry. Soil depth was quantified by measuring the depth of auger penetration. The percentage of canopy closure within the riparian zone was measured once at each soil sample point, perpendicular to the stream flow. The riparian variables on both bank sides were averaged to summarize riparian zone dimensions, vegetation and soil characteristics within a reach.. Stream gradient measurements were taken using a clinometer in the upstream direction in 10 to 20 m intervals, depending on the line of sight, to find the gradient angle (degrees °). Due to the variation in slope distance lengths (S.D.) in stream gradient measurements (α) within a reach, total slope (°) over an entire reach was calculated using the horizontal distance (H.D.) and the change in elevation (D.E) in flowing equation:

$$\text{Slope} = \tan^{-1}\left(\frac{\text{H.D (S.D.*}(\cos(\alpha))}{\text{D.E (S.D.*}(\sin(\alpha))} \right)$$

Stream slope was not measured for small 1 km^2 streams due to poor sight lines and calculation of it with a GIS using a digital elevation model provided unreliable results and hence was not available for analyses. Riparian gradient was measured using the clinometer and angle readings were taken from the bank edge looking into the riparian-upland transition zone.

3.4.3 RCA delineation

I used Reach Contributing Area (RCA) as a measurement of the lateral terrestrial contribution of surface and subsurface water, organic and inorganic material to a portion of a stream reach. The RCA index was adapted from Beven and Kirkby's (1979) topographical index (*TI*) model. The *TI* is a simple model that uses ln $(a/\tan\beta)$ to predict the contributing area of a basin where a is the contributing upslope area and β is the slope of that area. The *TI* increases as the contributing area size increases and the slope of the land decreases (Buttle et al. 2001). RCA was intended to represent the groundwater pathways based on the assumption that surface topography is similar to bedrock topography in regions of shallow soil depth (Freer et al. 1997) This assumption can be made in the Northwestern Ontario where there is thin glacial till overlaying bedrock (Wickware and Rubec 1989). Similar to the *TI* model, as the amount of land contributing to the portion of the stream increases and the slope of the land decreases, the size of the RCA increases, indicating a larger potential groundwater contribution to a stream reach (Buttle et al. 2001).

The RCA for a stream was determined using GIS with a filled DEM, and the enhanced stream lines created during the construction of the thermal maps. Enhanced flow accumulation and flow direction grids (20 m^2 grid) were created to establish the direction of surface flow on the landscape. The stream line points from the thermal maps were used landmarks, to divide up the stream into discrete sections for the calculation of RCAs. The flow direction grid and stream points were combined to generate RCA polygons (Figure 4) and zonal statistics were used to calculate the number and size of the RCAs contributing to each reach from both bank sides. Road intersections were accounted for raising the DEM values which blocked any subsurface flow, except for where a culvert location was known (Appendix II).

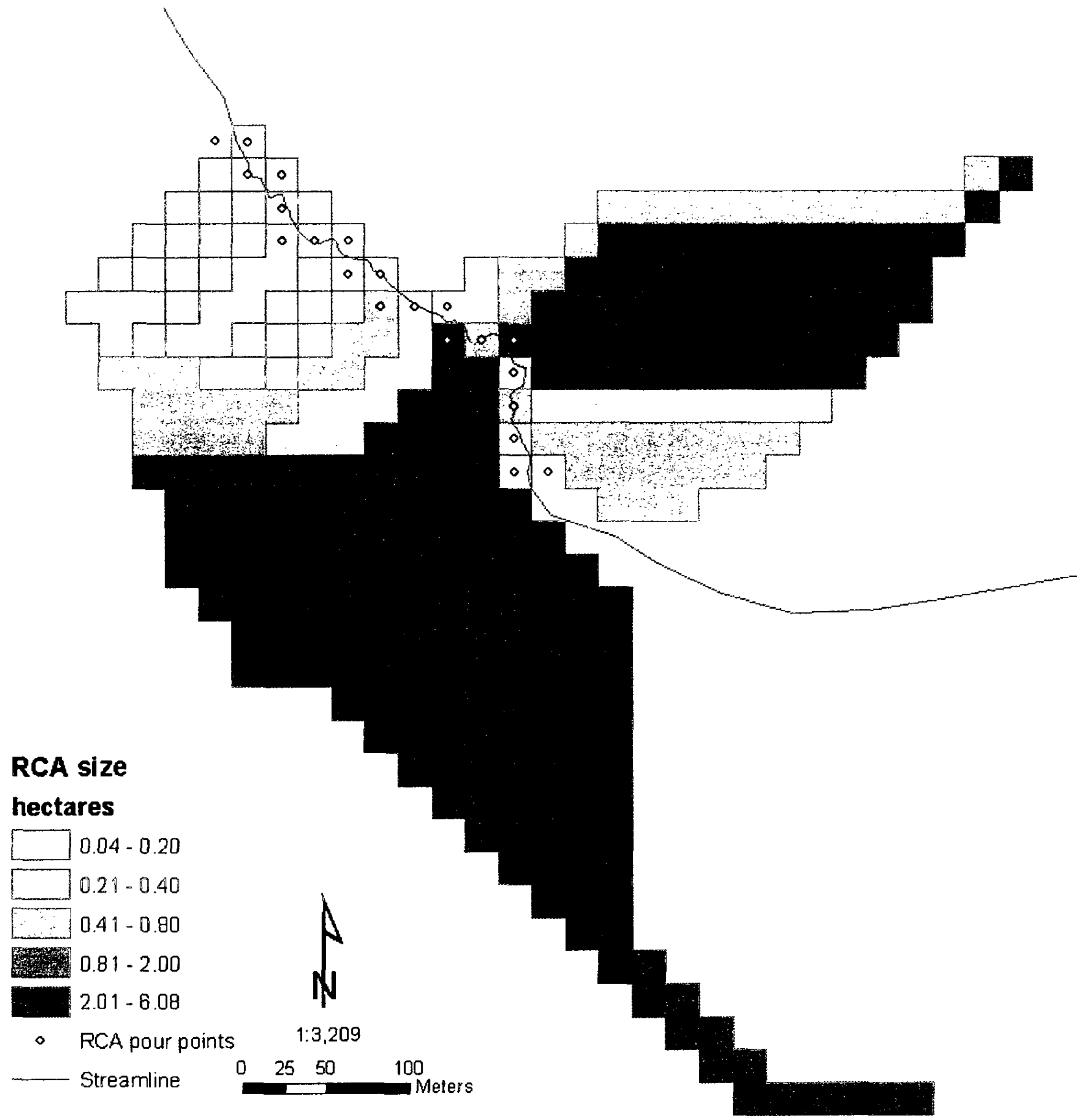


Figure 4. Schematic of Reach Contributing Area (RCA) polygons. Each polygon represents the amount of terrestrial land that in contributing to a specific portion of the stream, as indicated by the RCA pour points. The size of the contributing area is symbolized by the size of the individual polygons and the colour gradient from light to dark. Larger RCAs are represented by larger polygons size and darker shading.

3.4.4 Catchment characteristics

Terrestrial landscape characteristics were measured within the boundaries of each RCA contributing to a survey reach (Table 3). Upland vegetation was measured in the field using visual assessment of the dominant upland stand type and categorized into conifer, conifer mix, mixwood, hardwood mix and pure hardwood according to the *Terrestrial and Wetland Ecosites of Northwestern Ontario Field Guide* (Racey et al. 1996). The coefficient of variation in elevation (CV) as well as the slope, geology and amount of topographic relief for each RCA contributing to a survey reach was calculated using zonal statistics in a GIS. The CV summarizes the amount of variation in elevation within a RCA and is an index of roughness. The landscape data for the zonal statistics was from Natural Resources and Values Information System (NRVIS) (OMNR 2008b) and included the provincial DEM (OMNR 2005a) as well as the Digital Northern Ontario Engineering Geology Terrain Study (NOEGTS) (OMNR 2005b). The CV in elevation is the standard deviation divided by the mean value of the elevation for each 20 m^2 grid cell in a RCA catchment.

The geology of the landscape was summarized to the percent of landscape dominated by bedrock materials which includes plateaus, knobs and plains which are typically covered by a thin mantle of drift no more than 1 m (Gartner et al. 1981). Topography relief was defined into three NOEGTS categories: low relief (L), a difference of >15 m in local elevation, moderate (M); a difference between 15 m and 60 m and high (H) with differences in local elevation over 60 m. Surface soil moisture was also defined into three categories by the NOEGTS as wet, dry and mixed (Gartner et al. 1981).

3.4.5 Statistical analyzes – Environmental variables

The environmental variables from the 3 spatial scales were tested for collinear relationships using a Pearson's correlation matrix. Relationships were deemed highly correlated with two-tailed significance at the 0.01 level and r >0.5. For each collinear relationship one variable was omitted from the analyses. RCA was $\log_{(10)}$ transformed were transformed appropriately to improve normalility as necessary.

To examine whether there was a relationship between thermal variability and the amount of lateral contributions a stream receives, the association between RCA and reach thermal variability was tested using simple linear regression with all catchment sizes pooled together. The coefficient of determination (r^2) was used to determine the strength of the association and relationships of $p < 0.05$ were deemed significant.

The thermal variability data was separated into normal and extreme categorizes based on a frequency distribution curve. The categories were divided using 1 standard deviation above the mean thermal variation value. Reaches thermal variability above one standard deviation were classified as extreme variability and reaches with thermal variability below one standard deviation were classified as normal variability. The proportion of normal and extreme thermal categories were then compared based on catchment size to look at the distribution of the thermal categories amongst the of 1, 3, 5 and 10 km^2 catchments.

The relationship between thermal variability, based on catchment size, and RCA was examined to look for associations between lateral contributions and streambed temperatures for different catchment size classes. This was completed using univariate linear regressions in which the strength of the correlations as well as the direction of correlation were considered to interpret the relationship between temperature and lateral inputs.

To examine whether there were correlations between thermal variability and the habitat, riparian and catchment scale variables, univariate linear regressions were performed on each variable. The strength of the association was determined using the coefficient of determination (r^2) and the significance was used to test the relationship ($p < 0.05$). The direction of the relationship was also considered using the standardized beta coefficient (β) and regression line to examine the influence of the environmental variables on thermal variability.

4.0 RESULTS

4.1 Thermal Characteristics

4.1.1 All streams

A total of 11 stream sites were surveyed, 5 with a catchment of 1 km^2 and 2 each for catchment sizes of 3, 5, and 10 km^2 (Table 4). A total of 55, 50 m reaches were sampled, 23 reaches in the 1 km^2 catchment class and a 32 in the 3, 5 and 10 km^2 catchment classes. Over the entire field survey season, 33 055 streambed thermal points were measured within 6611 transects. Mean temperatures varied widely both within and between streams and catchment size classes. Mean streambed temperatures ranged from 7.4 °C in R25 to 16.6 °C in G3 (Table 4). The maximum streambed temperature was 19.4 °C, recorded in G4 while the minimum temperatures 2.9 °C in R26.

Thermal variability is defined as the difference between maximum and minimum streambed temperatures within the 11 streams ranged from 1.6 °C in L4 to 11.9 °C in G7. In most streams the largest deviations from the mean streambed temperature were those below or colder than the stream mean (Figure 5). Larger streams tended to have a greater range of streambed temperatures. Streams within the 4 catchment size classes differed significantly in the level of thermal variability measured within them ($F_{(3, 7)} = 4.992$, $p = 0.039$). The variability was due to the differences between catchment size classes and not due to the variability among stream sites within the catchments. The streams with catchment sizes of 5 and 10 km^2 had, on average, approximately twice the thermal variability as the 1 and 3 km^2 streams (Figure 6). The highest total thermal variability was seen in the 10 km^2 catchments and was incrementally lower in each catchment size class, however, there was no significant difference between 1 and 3 km^2 or the 5 and 10 km^2

size classes. The significant differences in thermal variability were found between the 1 km^2 and 5 km^2 ($p = 0.02$), and 10km^2 ($p < 0.01$) as well as the 3km^2 and the 5km^2 ($p = 0.009$) and 10km^2 ($p < 0.01$).

Table 4. Summary of the streambed temperatures for all survey sites in 2008.

Site	Catchment size	# of Reaches	Mean of Stream (°C)	Max. of stream (°C)	Min. of stream (°C)	Thermal variability	Deviation range from mean
L4	1	2	10.4	11.3	9.7	1.6	0.9 – (-0.7)
L5	1	5	11.2	12.1	8.5	3.6	0.9 – (-2.7)
M8	1	6	10.1	10.6	8.2	2.4	0.5 – (-1.9)
R25	1	4	7.4	8.4	6.4	2.0	1.0 – (-1.0)
R26	1	6	8.0	9.0	2.9	6.1	1.0 – (-5.1)
G1	3	6	8.8	9.9	7.0	2.9	1.1 – (-1.8)
G2	3	4	11.7	14.5	9.7	4.8	2.8 – (-2.0)
G4	5	5	13.5	15.2	8.0	7.2	1.7 – (-6.8)
G5	5	5	14.3	15.9	7.5	8.4	1.6 – (-6.8)
G3	10	6	16.6	19.4	10.0	9.4	2.8 - (-6.6)
G7	10	6	15.4	18.3	6.4	11.9	2.9 – (-9.0)

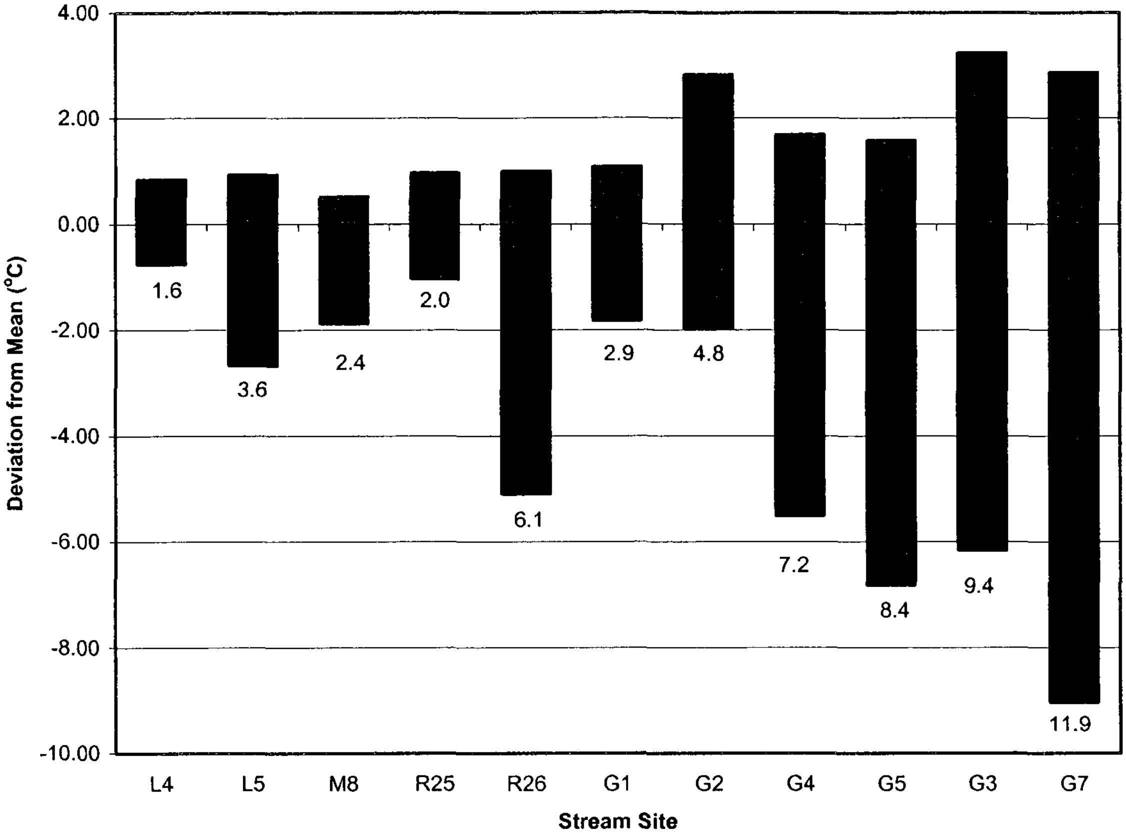


Figure 5. Range in streambed temperatures for all 11 study sites. Temperature distributions were standardized to mean = 0. Positive deviations from the mean are in red while negative deviations are in blue. The numbers below individual bars indicate the range (°C) between the maximum and minimum temperature deviation for the reach, or thermal variability.

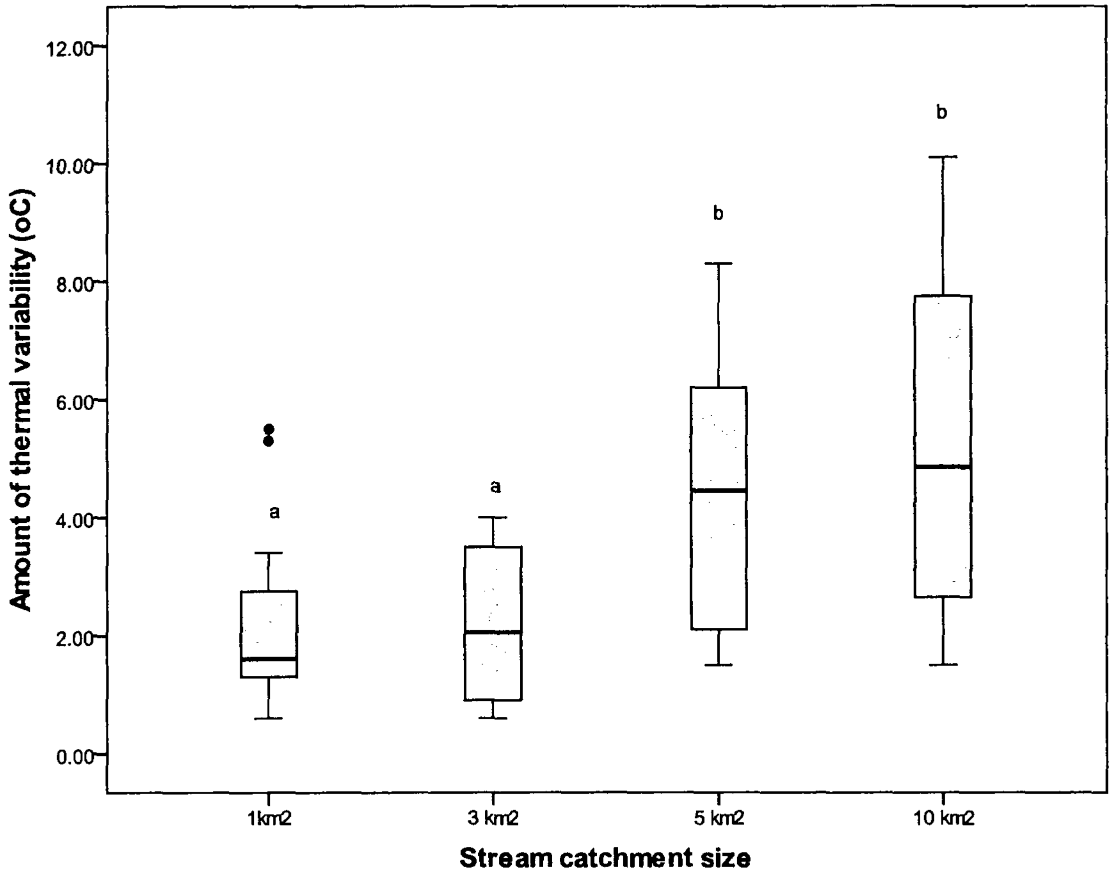


Figure 6. Distribution of thermal variability among stream reaches (n= 55) for each catchment size class. The median is represented by the solid lines, inter-quartile range by the boxes and range by the whiskers. Closed circles represent outliers. Different letters denote significant differences between means using a nested univariate ANOVA with least squares post-hoc analysis to revel differences between catchment size classes.

4.1.2 Small catchments – 1 km²

Thermal variability in 1 km^2 streams ranged from 1.6 °C to 6.1 °C (Table 5). The widest thermal variability was seen in R26, with a range of 6.1 °C throughout the total survey and 5.5 °C within one 50 m reach. The lowest thermal variability was measured in stream L4 with 1.6 °C range within entire survey. Within streams, the temperature range varied considerably with most of the thermal variability being below the mean streambed temperatures (Figure 7).

The thermal map for R26 (Figure 8) illustrates the spatial distribution of streambed temperatures throughout the 300 m of stream surveyed. The mean streambed temperature over the entire survey was 8.0 °C and a large proportion of the streambed temperatures fell on or near that temperature, indicated by the yellow shading. There were distinct regions where streambed temperatures were cooler than the stream mean, indicated by blue regions on the thermal map. The largest amount of variation within one transect had streambed temperatures ranging from 2.9 °C to 8.3 °C, a range of 5.4 °C. Although the majority of the streambed temperatures throughout the stream survey were close or equal to the stream mean, the regions with the largest deviation from the mean tended to be cooler, with deviations of up to 5.1 °C below the mean. In contrast, relatively few areas had temperatures deviating above the mean temperature and of those that did the maximum deviation was 1.0 °C above the mean (Figure 9). A more detailed examination of streambed temperatures across the entire stream survey shows several areas of relatively large negative deviations from the mean and a few areas of much smaller positive deviations (Figure 9). The remainder of the thermal maps for the 1 km^2 catchment streams are found in Appendix III.

Table 5. Summary of the thermal characteristics for all of the 50 m reaches surveyed in small, 1 km^2 stream catchments in 2008 (n= 23).

Site	Max deviation	Min deviation	Thermal variability	Mean deviation	% negative
L4					
0	0.7	-0.8	1.5	0.03	40
50	0.8	-0.8	1.6	-0.04	60
Stream survey			1.6		
L5					
0	0.9	-0.2	1.1	0.33	4
50	0.5	-0.9	1.4	-0.13	62
100	0.6	-2.7	3.3	-0.05	32
150	0.2	-1.7	1.9	-0.04	28
200	0.5	-1.7	2.2	-0.12	34
Stream survey			3.6		
M8					
0	0.5	-0.9	1.4	0.05	20
50	0.3	-0.4	0.7	0.03	28
100	0.3	-1.1	1.4	0.06	15
150	0.3	-1.3	1.6	-0.12	42
200	0.4	-0.9	1.3	0.02	22
250	0.4	-1.9	2.3	-0.04	25
Stream survey			2.4		
R25					
0	1.0	-0.7	1.7	0.04	35
50	0.7	-0.5	1.2	0.07	30
100	0.3	-1.0	1.3	-0.03	52
150	0.5	-0.7	1.2	-0.12	79
Stream survey			2.0		
R26					
0	0.5	-2.9	3.4	-0.02	33
50	1.0	-4.3	5.3	-0.06	35
100	0.4	-2.9	3.3	-0.02	30
150	0.7	-2.5	3.2	0.02	28
200	0.4	-5.1	5.5	-0.15	35
250	0.5	-0.1	0.6	0.23	6
Stream survey			6.1		

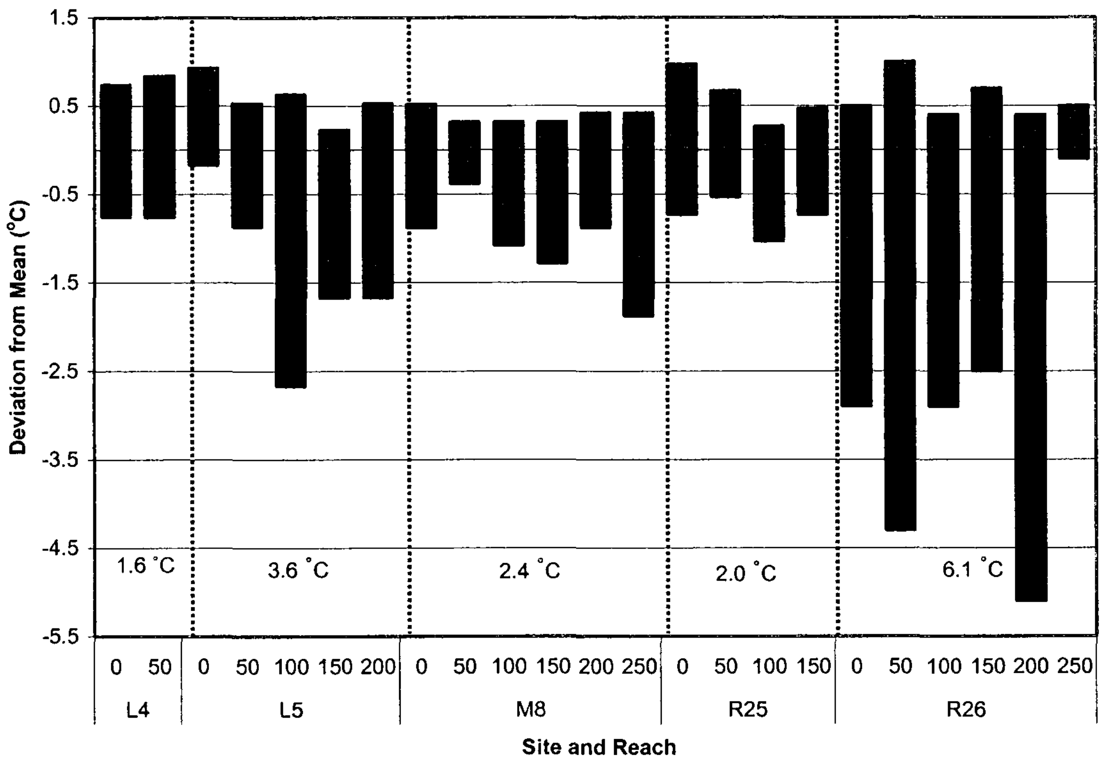


Figure 7. Streambed thermal variability for each 50 m reach sampled in the 1 km^2 catchments surveyed (n= 5). Temperature distributions were standardized to mean = 0. Positive deviations from the mean are in red while negative deviations are in blue. The numbers beneath the bars indicate the total amount of thermal variability (°C) for the stream.

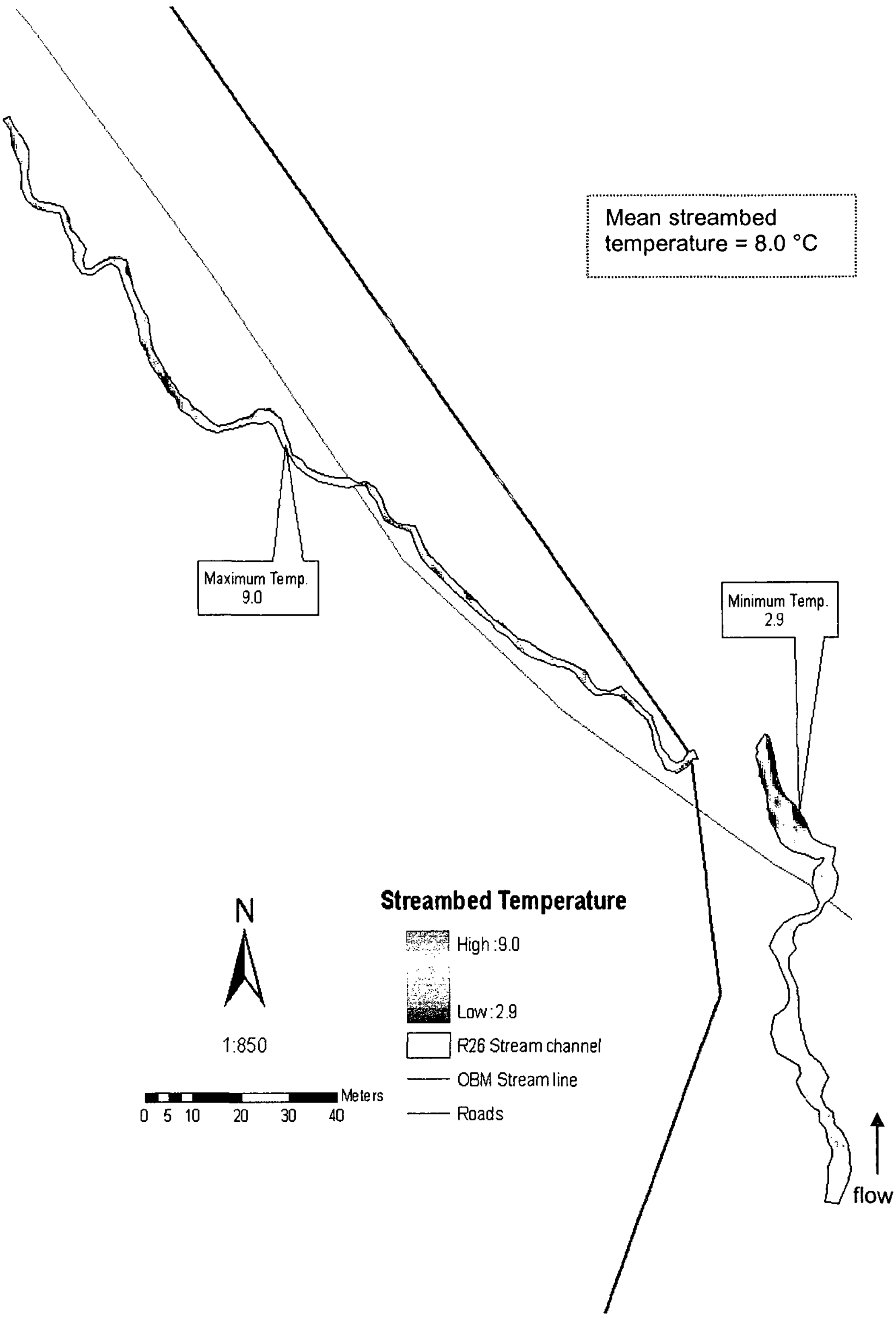


Figure 8. Streambed thermal map for stream survey, R26.The thermal map illustrates the pattern of thermal variation in streambed temperature. Differences in streambed temperatures are shown by a colour gradient with blue for the coldest temperature and red for the warmest.

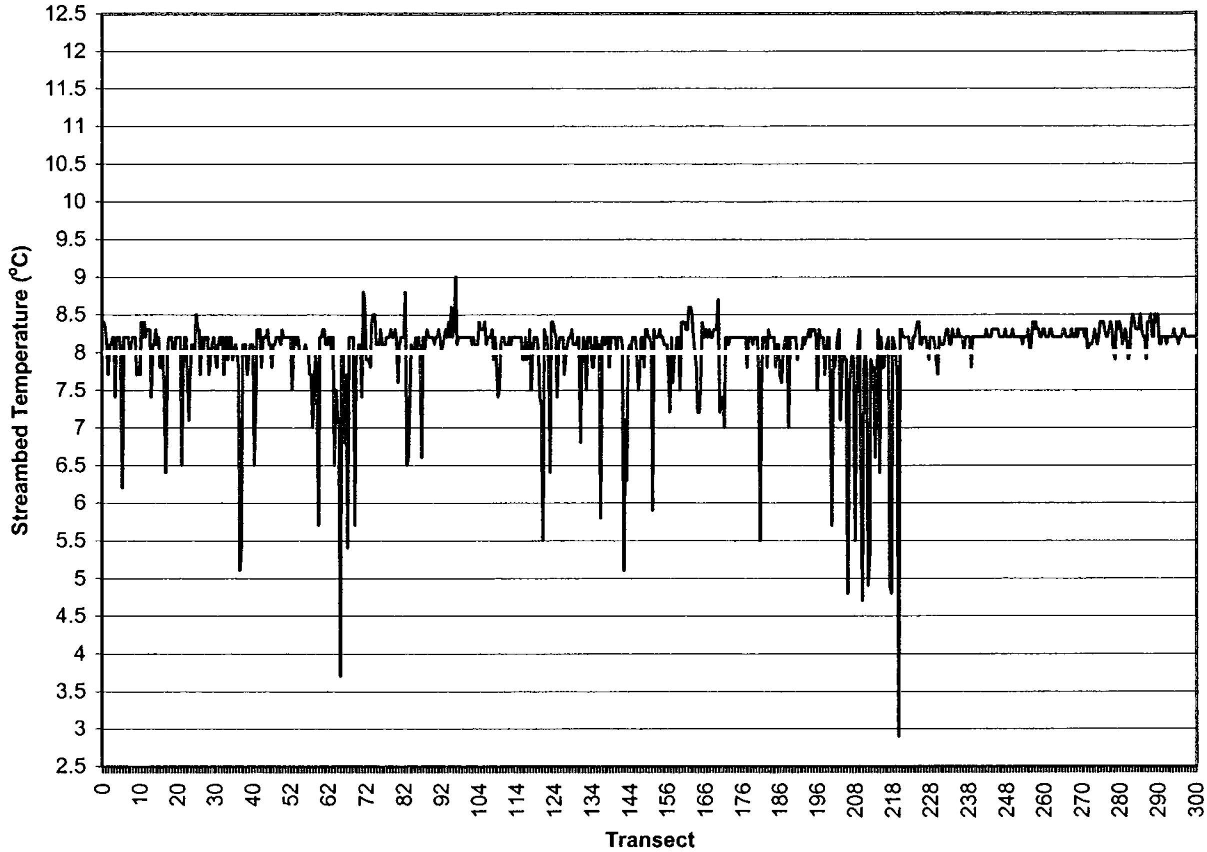


Figure 9. Illustration of the variation in streambed temperatures for each transect in the R26 stream survey. The mean temperature was 8.0 °C and is indicated by the horizontal yellow line. Temperatures that are below the mean are beneath the yellow indicator line.

4.1.3 Large catchments – 3, 5, 10 km^2

The larger catchment streams, 3, 5 and 10 km^2 had a wide range in streambed temperatures both between and within individual streams. The highest thermal variability was in G7 a stream in the 10 km^2 catchment class, with a range in temperatures of 11.9 °C over the 300 m survey and 10.1 °C within a 50 m reach (Table 6). The least thermal variation was seen in G1, a 3 km^2 stream with a temperature range of 2.9 °C throughout the entire stream. Although the thermal variability within stream surveys ranged widely, as in the 1 km^2 streams, the majority of the variability was below the mean temperature (Figure 10).

The streambed thermal map for site G4 illustrates the spatial pattern of thermal variability with streambed temperatures ranging from a maximum temperature of 15.2 °C to a minimum of 8.0 °C, a range of 7.2 °C (Figure 11). The majority of streambed temperatures were close to the mean of 13.5 °C (areas shaded in yellow; Figure 11) however several distinctly cooler regions occurred throughout the stream (areas in blue; Figure 11). The coolest streambed temperature throughout the survey was 8.0 °C, a 5.5 °C disparity from the mean streambed temperature. Within the transect with the coolest temperature, there was a range of 5.8 °C in streambed temperatures. In contrast, the warmest streambed temperature was 15.2 °C, deviating only 1.4 °C above the mean streambed temperature (Figure 11). The most apparent cooler regions were found between transects 78 and 96 and between 202 and 234 (Figure 12). Thermal maps for the G1, G2, G3, G5 and G7 are found in Appendix IV.

Table 6. Summary of the thermal characteristics for all of the 50 m reach surveyed in larger, 3, 5, 10 km^2, catchments in 2008 (n= 32).

Site	Max deviation	Min deviation	Thermal variability	Mean deviation	% negative
G1					
0	0.4	-0.4	0.8	0.06	45
50	0.5	-0.4	0.9	0.03	48
100	1.1	-1.8	2.9	0.02	60
150	0.7	-0.8	1.5	-0.07	70
200	0.3	-0.3	0.6	0.04	51
250	0.7	-0.4	1.1	0.04	56
Stream survey			2.9		
G2					
0	2.0	-2.0	4.0	-0.56	67
50	1.9	-1.9	3.8	0.18	29
100	2.8	-0.7	3.5	0.24	27
150	1.8	-0.8	2.6	0.2	27
Stream survey			4.8		
G4					
0	0.4	-1.1	1.5	0.1	22
50	1.3	-2.9	4.2	0.13	26
100	0.7	-1.0	1.7	0.16	16
150	1.7	-1.7	3.4	0.14	29
200	0.4	-5.5	5.9	-0.79	67
Stream survey			7.2		
G5					
0	1.6	-5.5	7.1	0.19	21.4
50	1.5	-3.2	4.7	-0.01	39.5
100	1.4	-4.8	6.2	-0.34	59.2
150	1.5	-6.8	8.3	-0.17	43.2
200	1.1	-1.0	2.1	0.31	16.9
Stream survey			8.4		
G3					
0	1.8	-1.5	3.3	0.39	5
50	0.6	-3.1	3.7	0.03	18
100	2.9	-5.3	8.2	-0.06	42
150	2.8	-6.6	9.4	-0.23	52
200	1.2	-6.1	7.3	-0.26	43
250	0.5	-2.7	3.2	0.12	12
Stream survey			9.4		
G7					
0	1.1	-9.0	10.1	-0.54	75
50	1.2	-5.3	6.5	-0.43	62
100	2.9	-3.1	6.0	0.2	24
150	1.1	-0.7	1.8	0.29	5
200	0.6	-0.9	1.5	0.23	9
250	0.8	-1.3	2.1	0.25	15
			11.9		

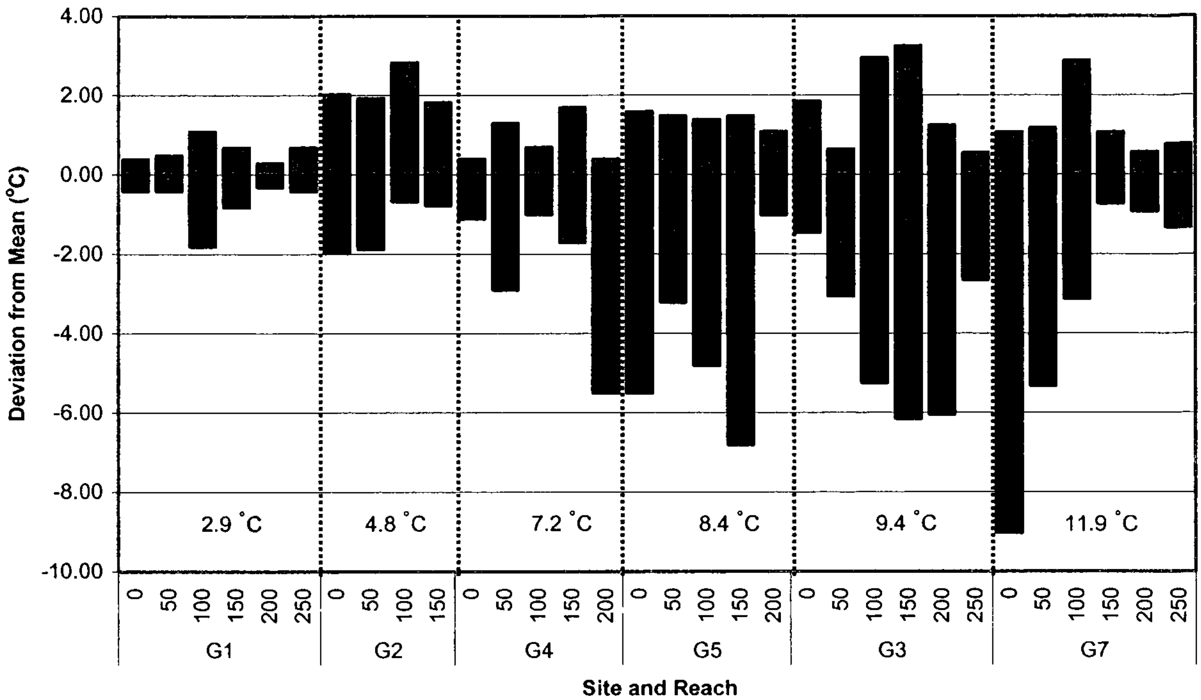


Figure 10. Streambed thermal variability for each 50 m reach sampled in the 3, 5, and 10 km^2 catchments surveyed (n= 6). Temperature distributions were standardized to mean = 0. Positive deviations from the mean are in red while negative deviations are in blue. The numbers beneath the bars indicate the total amount of thermal variability (°C) for the stream.

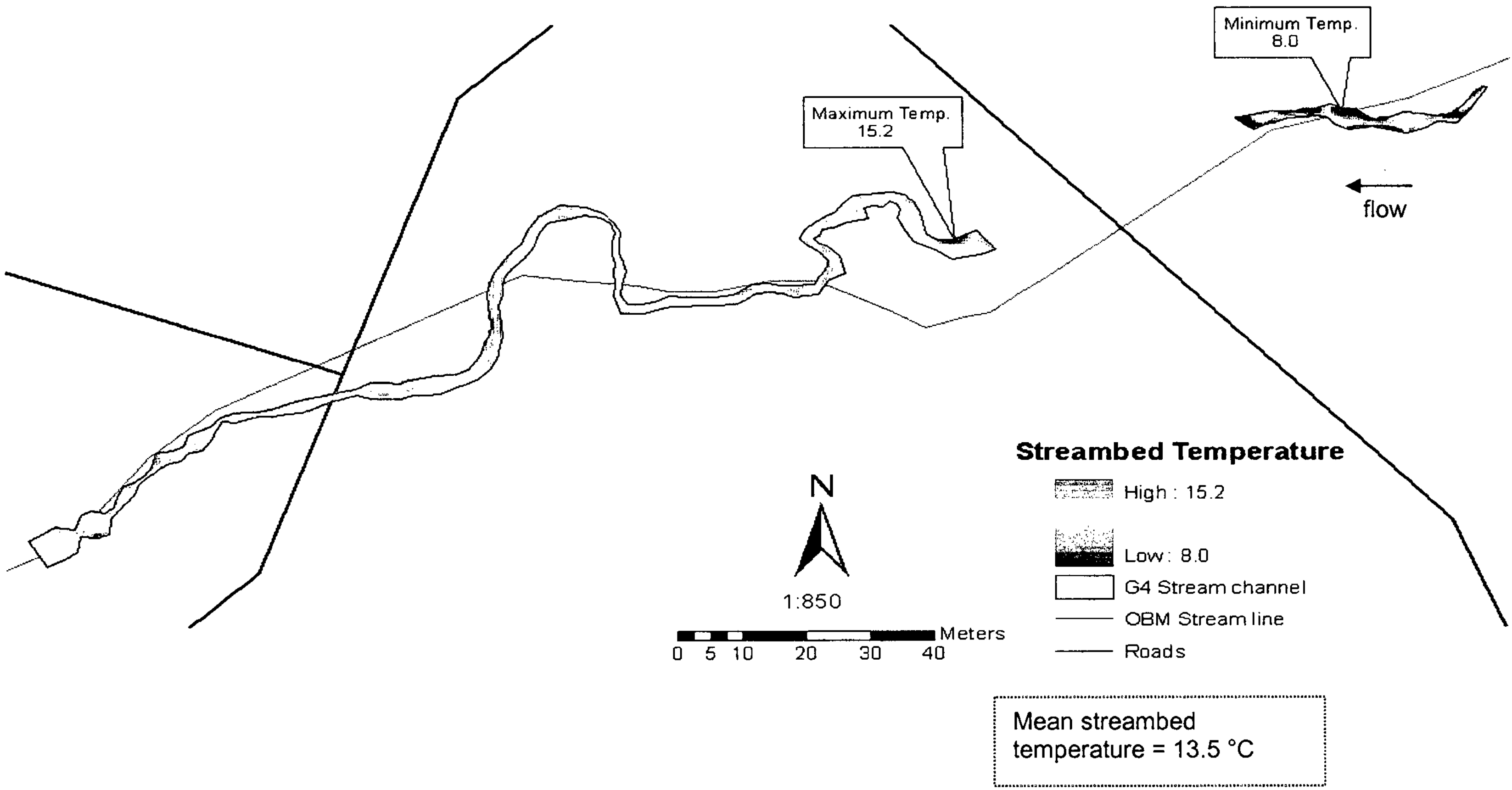


Figure 11. Streambed thermal map for stream survey, G4. The thermal map illustrates the pattern of thermal variation in streambed temperature. Differences in streambed temperatures are shown by a colour gradient with blue for the coolest temperatures and red for the warmest temperatures.

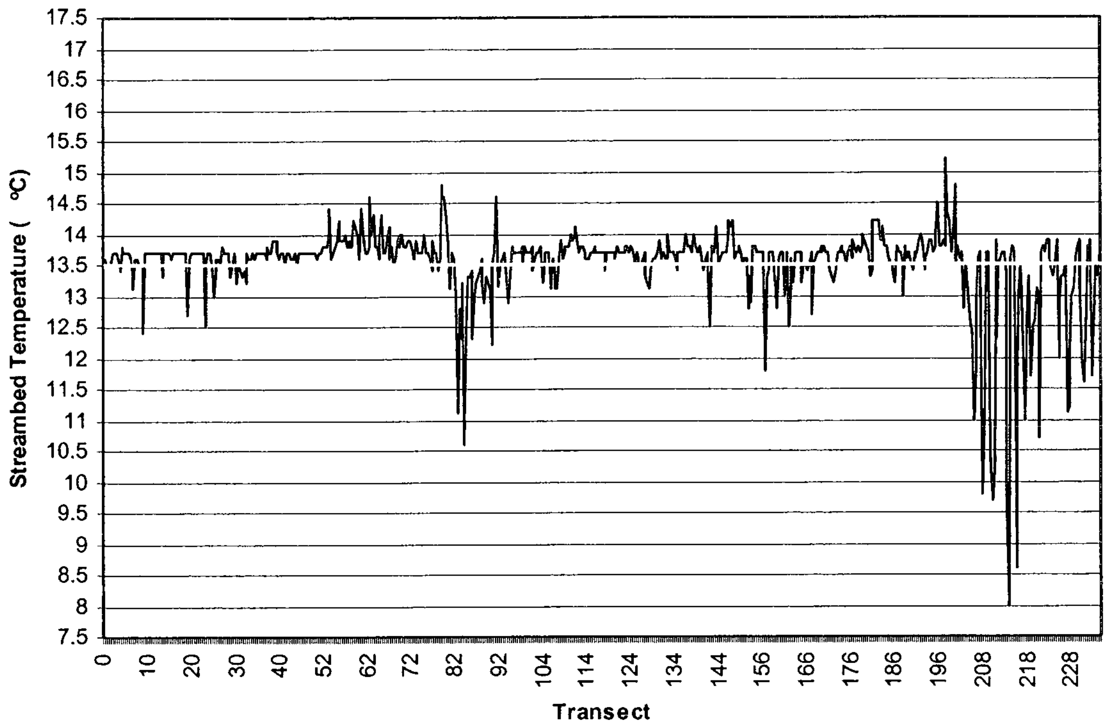


Figure 12. Illustration of the variation in streambed temperatures for each transect in the G4 stream survey. The mean temperature was 13.5 °C and is indicated by the horizontal yellow line. Temperatures that are below the mean are beneath the yellow indicator line.

4.2 Thermal and Fish Relationships

4.2.1 Stream fish data

A total of 636 fish from 14 species were captured in 4 of the 7 survey sites sampled by backpack electrofishing in the summer of 2008 (Table 7). The 3 streams without fish were, R25, a 1 km^2 catchment, G1, a 3 km^2 catchment and 1 of the 5 km^2 catchments, G5. Only the 2 downstream reaches in G2 had fish captured in them so the 2 most upstream reaches were omitted from the analyses. The absence of fish was expected due to low flow conditions which created a culvert barrier rather than a lack of suitable habitat. The total number of 50 m reaches surveyed with the fish present was 19.

The most common fish species were rainbow trout and brook trout constituting 36.7 % and 28.8 %, respectively, of all fish caught. Rainbow trout were found in 16 of the 19 reaches and brook trout were found in all of the 19 reaches sampled where fish were present (Table 7). The highest abundance of fish, 0.25 fish/m^2, was measured in G4, a 5 km^2 stream. G3 had the highest number of fish and highest species richness; 240 fish from 12 species. G7 had the highest total fish biomass of 2.209 g/m^2 (Table 7).

Species diversity was the only fish community variable which varied significantly among catchment size classes and not among sites within catchment sizes ($F_{(2,16)}$= 6.909, p = 0.23; Figure 13). The 10 km^2 catchment streams had species diversity approximately 1.4 times higher than the other catchment size classes. Brook trout abundance and relative abundance as well as rainbow trout abundance, relative abundance and biomass among reaches varied significantly by stream site within the catchment classes. The remaining fish variables did not differ significantly among in stream catchment size class.

Table 7. Summary of total fish catch at stream survey sites in 2008.

Species	Common name	Total catch	No. of sites	No. of reaches	Total weight (g)	Total Site G2	Total Site G3	Total site G4	Total Site G7	Reach range
Oncorhynchus mykiss	Rainbow trout	234	4	16	1092	21	5	101	107	0 - 37
Salvelinus fontinalis	Brook trout	184	4	19	2654	7	106	35	36	0 - 26
Rhinichthys cataractae	Longnose dace	84	3	12	249	2	61	0	21	0 - 13
Cottus sp.	Sculpin	41	4	12	99	2	16	14	9	0 - 8
Oncorhynchus tshawytscha	Chinook salmon	37	2	7	84	0	0	3	34	0 - 12
Phoxinus eos	N. redbelly dace	34	2	7	52	0	33	0	1	0 - 9
Catostomus commersoni	White sucker	6	1	1	27	0	6	0	0	0 - 6
Catostomus catostomus	Longnose sucker	5	1	3	11	0	5	0	0	0 - 2
Culaea inconstans	Brook stickleback	4	2	2	4	3	1	0	0	0 - 3
Luxilus cornutus	Common shiner	2	1	1	4	0	2	0	0	0 - 2
Margariscus margarita	Pearl dace	2	1	1	9	0	2	0	0	0 - 2
Phoxinus neogaeus	Finescale dace	2	1	1	4	0	0	0	2	0 - 2
Micropterus dolomieu	Smallmouth bass	2	1	2	21	0	2	0	0	0 - 1
Etheostoma nigrum	Johnny darter	1	1	1	4	0	1	0	0	0 - 1
Total		638	4	19	4314	35	240	153	210	
Total abundance (fish/m^2)						0.197	0.233	0.256	0.200	
Total Stream richness						5	12	4	8	
Total biomass (g/m^2)						1.138	1.209	1.221	2.209	

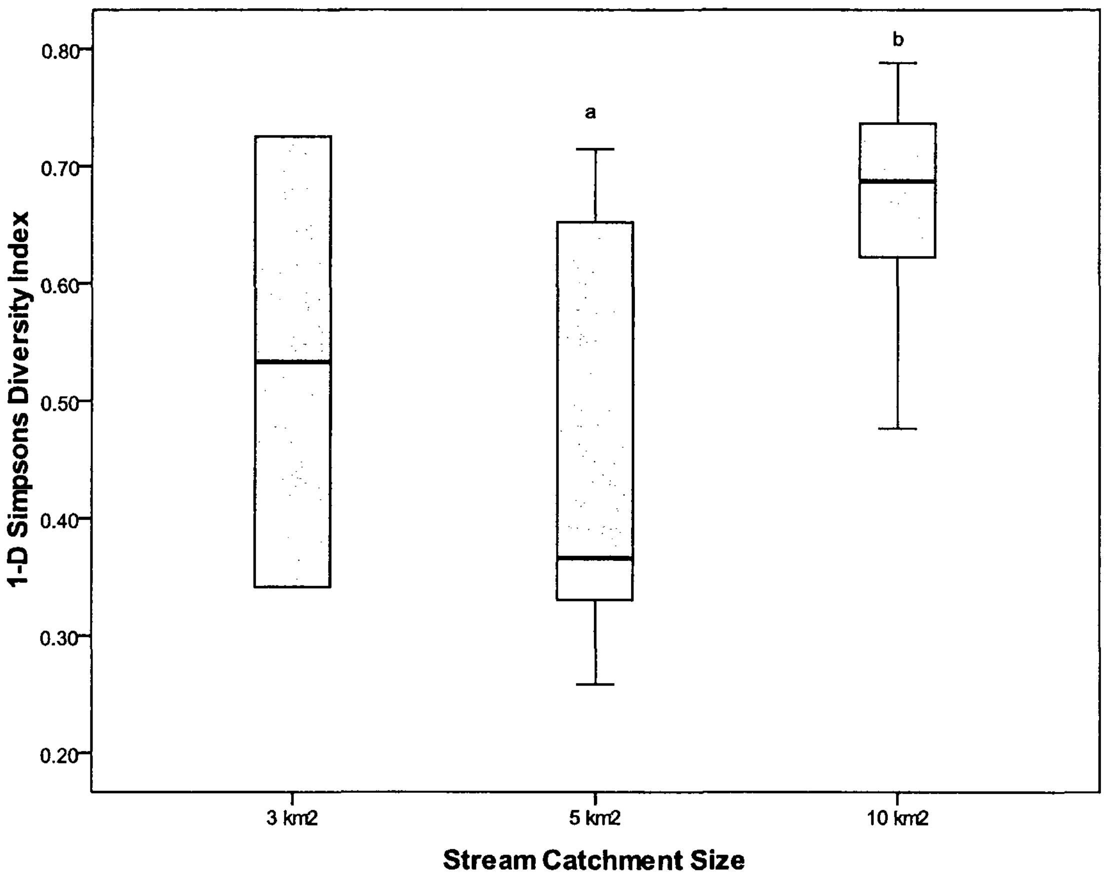


Figure 13. Distribution of fish species diversity using a Simpson Diversity Index (1-*D*) among reaches (n=19) with different stream catchment size classes. The solid lines represent the median, the boxes represent the inter-quartile and the whiskers are the range Different letters denote significant differences between means using a nested univariate ANOVA with least squares post-hoc analysis to reveal differences between catchment size classes.

Fish distribution was variable within and among surveyed streams. Total fish abundance in 19 reaches surveyed ranged from 0.09 fish/m^2 in G7, reach 0 (G7 0) to 0.49 fish/m^2 in G3 150 (Table 8). Reaches with high fish abundance did not have the most biomass. The reach with the largest biomass (G7 50) was 50 % less abundant than most abundant reach (G3 150). Species richness did not coincide with species diversity. The highest diversity was seen in G3 200 with only 6 species, 4 less species than the reach with the greatest richness, G3 0 with 11 species.

The distribution of the two salmonid species, brook and rainbow trout was variable among the stream reaches surveyed. Brook trout abundance ranged from 0.01 to 0.21 fish/m^2 while rainbow trout abundance ranged from 0 to 0.29 fish/m^2 (Table 8). Similar to total fish biomass, areas of high brook trout abundance tended to have smaller brook trout (Table 8). G3 100 had brook trout abundance values 7.4 times higher than the reach with the greatest biomass, G7 50. The relationship between size and abundance was not apparent for rainbow trout.

The relative abundance of the two salmonid species was higher in every reach surveyed compared to other fish species (Table 8). Brook and rainbow trout made up at least 50 % of the relative abundance for 16 of the 19 reach surveys; when the proportion of one species was higher the proportion of the other species was low. Brook trout had high relative abundance in G3, from 0.32 to 0.58 where as the relative abundance of rainbow trout was less than 0.10 in each reach within that stream (Figure 14). Conversely, the relative abundance of rainbow trout was 4 times higher than brook trout in the first two reaches of G4 (0, 50) (Figure 14).

Table 8. Summary of the fish community data for individual stream reaches (n= 19).

	Site G2		Site G3						Site G4					Site G7					
Fish	0	50	0	50	100	150	200	250	0	50	100	150	200	0	50	100	150	200	250
Abundance (fish/m^2)	0.18	0.22	0.23	0.2	0.4	0.49	0.18	0.14	0.25	0.36	0.2	0.2	0.27	0.09	0.2	0.17	0.39	0.19	0.2
Species richness	3	4	11	4	5	5	6	4	2	3	2	3	4	5	6	5	6	3	4
Species diversity	0.34	0.73	0.74	0.57	0.62	0.74	0.79	0.7	0.26	0.33	0.37	0.65	0.71	0.74	0.74	0.67	0.62	0.48	0.65
Biomass (g/m^2)	1.05	1.23	2.74	0.59	1.25	1.13	0.94	0.4	0.89	2.08	2.22	0.51	0.78	0.46	4.79	1.67	1.31	2.11	2.33
Brook Trout																			
Abundance	0.01	0.07	0.11	0.11	0.21	0.2	0.06	0.05	0.04	0.06	0.04	0.05	0.1	0.04	0.03	0.02	0.06	0.01	0.04
Relative abundance	0.06	0.32	0.48	0.58	0.51	0.41	0.32	0.33	0.15	0.17	0.22	0.25	0.36	0.46	0.14	0.13	0.16	0.04	0.19
Biomass	0.02	0.85	2.32	0.32	0.6	0.05	0.07	0.13	0.22	1.12	1.51	0.2	0.29	0.32	4.39	1.35	0.11	0.65	1.04
Mean weight (g)	2	13	21	3	3	3	9	3	6	18	35	4	3	8	37	65	2	87	26
Mean length (mm)	64	86	83	95	62	59	75	61	70	100	128	68	62	68	117	165	60	206	110
Rainbow trout																			
Abundance	0.15	0.09	0	0.01	0	0	0.02	0	0.22	0.29	0.15	0.1	0.1	0.02	0.1	0.07	0.23	0.13	0.11
Relative abundance	0.81	0.42	0.02	0.03	0	0	0.09	0	0.85	0.81	0.78	0.5	0.36	0.23	0.47	0.44	0.58	0.68	0.55
Biomass	0.94	0.27	0.06	0.08	0	0	0.11	0	0.68	0.95	0.71	0.25	0.26	0.02	0.26	0.19	1	1.33	1.17
Mean weight (g)	42	2	1	5	0	0	2	0	16	6	2	7	11	1	1	1	95	2	7
Mean length (mm)	76	70	108	103	0	0	81	0	85	82	79	70	73	36	60	78	89	95	108
Other species																			
Relative abundance	0.13	0.26	0.5	0.39	0.49	0.59	0.59	0.67	0	0.02	0	0.25	0.28	0.32	0.39	0.44	0.27	0.28	0.26

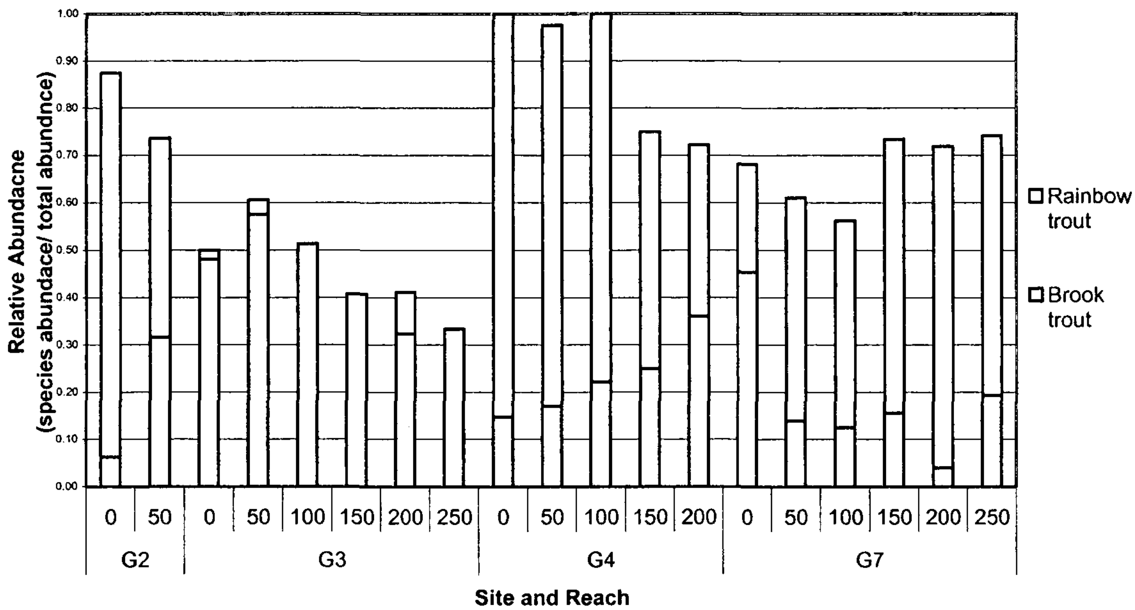


Figure 14. Relative abundance of brook trout and rainbow trout for each reach survey. Relative abundance is a measure of the proportion of a species in the total community with 0 as low and 1 as a high proportion (Krebs 1989). The height orange bars indicate the relative abundance of brook trout, the height of the yellow bars beyond the orange bars represent the relative abundance of rainbow trout.

4.2.2 Fish and thermal variability

Significant relationships were found between 8 of the 14 stream fish community variables and thermal variability for the 19 reaches surveyed (Table 9). A significant relationship was seen between the Simpson diversity index and stream reach thermal variability ($r^2 = 0.289$, $p = 0.018$). The Simpson diversity index ranged from a low of 0 to a high of 1; diversity values over 0.5 indicate high diversity while values below 0.50 are considered low diversity (Krebs 1989). Areas of greater thermal variability tended to be more diverse with Simpson diversity values over 0.5 (Figure 15). All of the diversity levels lower than 0.5 where found in reaches with less than 4.5 °C in thermal variability. However, the positive relationship may be an effect of catchment size because large catchments (5 and 10 km^2) had higher thermal variability values and were more diverse than smaller catchments (Figure 6 & 13). Total fish abundance, species richness and total biomass were not found to be significantly associated with thermal variability (Table 9).

The presence and abundance of brook trout was positively correlated with the thermal variability within stream reaches. Brook trout abundance was significantly associated with thermal variability ($r^2 = 0.232$, $p = 0.037$). Reaches with higher thermal variability also had a higher number of brook trout (Figure 16a). The reach with the most brook trout, 0.208 fish/m^2, had a thermal variability value of 8.2 °C compared to the reach with the lowest number of brook trout, 0.007 fish/m^2 which also had the lowest thermal variability, 1.5 °C in 50 m. The positive relationship between brook trout presence and thermal variability was further illustrated by the association between thermal variability and relative abundance of brook trout (r^2= 0.225, $p = 0.04$). In reaches with higher thermal variability the proportion of the fish community comprised of brook trout was also higher (Figure 16b). The reaches with the greatest thermal variability had 3 out of 5 of the highest brook trout proportions, although the greatest relative abundance of brook trout was recorded in a reach with low thermal variability (3.70 °C). However, the two measures of brook trout presence, abundance and relative abundance, were found to be collinear ($r = 0.749$) so their similar association with thermal variability should be expected. Other remaining measures of the brook trout populations: biomass, mean weight and mean length, were not found to be significantly correlated with thermal variability (Table 9).

In contrast to brook trout, measures of the rainbow trout population were all significantly negatively associated with reach thermal variability (Table 9). Stream reaches with higher variability in streambed temperatures tended to have lower rainbow trout abundance ($r^2 = 0.303$, $p = 0.015$; Figure 17a). The reach with the greatest thermal variability, 10.1 °C, had rainbow trout abundance 10 times (0.021 fish/m^2) lower than the reach with the lowest thermal variability of 1.5 °C (0.216 fish/m^2). The proportion of the fish community comprised of rainbow trout tended to be lowest in reaches with high thermal variability ($r^2 = 0.317$, $p = 0.012$; Figure 17b). Rainbow trout abundance and relative abundance were not independent of one another ($r = 0.899$) so a similar association to thermal variability is expected.

The presence of larger rainbow trout, measured as weight, biomass or length, was negatively associated with high thermal variability (Table 9). The larger rainbow trout tended to be found in regions of low thermal variability, less than 4.3 °C (Figure 18a & 18b). The mean weight (g) of rainbow trout was highest in stream reaches with thermal variability less than 3.0 °C (Figure 18c).

Table 9. Results from simple linear regressions performed on stream fish community variables using thermal variability as the independent variable.

Fish variable	r^2	p	F	β	df
Total Fish					
Total fish abundance (density)	0.030	0.477	0.528	0.174	18
Species richness	0.077	0.249	1.426	0.278	18
Simpson's Diversity Index (1-*D*) (diversity)	0.289	**0.018**	6.912	0.538	18
Total fish biomass (g/m^2)	0.013	0.643	0.223	-0.114	18
Brook Trout					
Brook trout abundance ($fish/m^2$)	0.232	**0.037**	5.131	0.481	18
Brook trout relative abundance	0.226	**0.040**	4.940	0.475	18
Brook trout biomass (g/m^2)	0.000	0.999	0.000	0.000	18
Brook trout mean weight (g)	0.002	0.867	0.223	0.041	18
Brook trout mean length (mm)	0.091	0.211	1.692	-0.301	18
Rainbow Trout					
Rainbow trout abundance ($fish/m^2$)	0.303	**0.015**	7.381	-0.550	18
Rainbow trout relative abundance	0.317	**0.012**	7.884	-0.563	18
Rainbow trout biomass (g/m^2)	0.430	**0.002**	12.829	-0.656	18
Rainbow trout mean weight (g)	0.401	**0.004**	11.374	-0.633	18
Rainbow trout mean length (mm)	0.386	**0.005**	10.666	-0.621	18

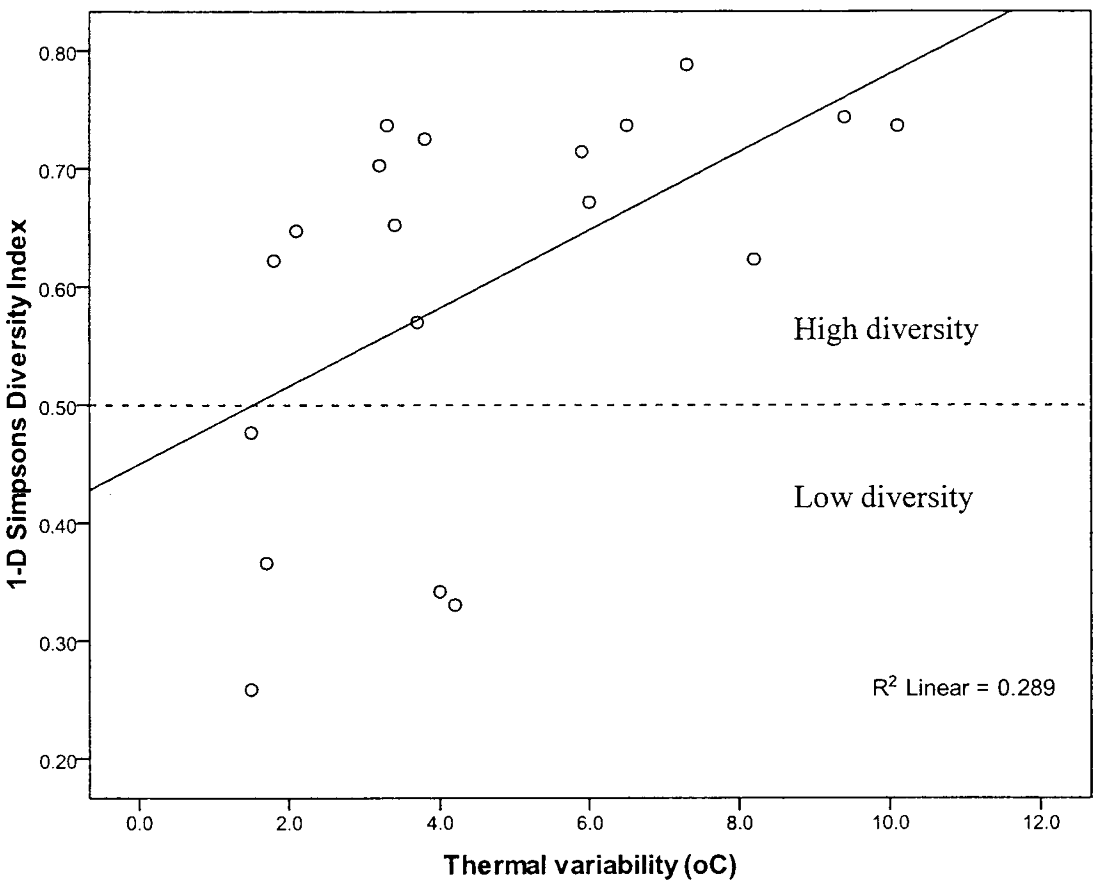
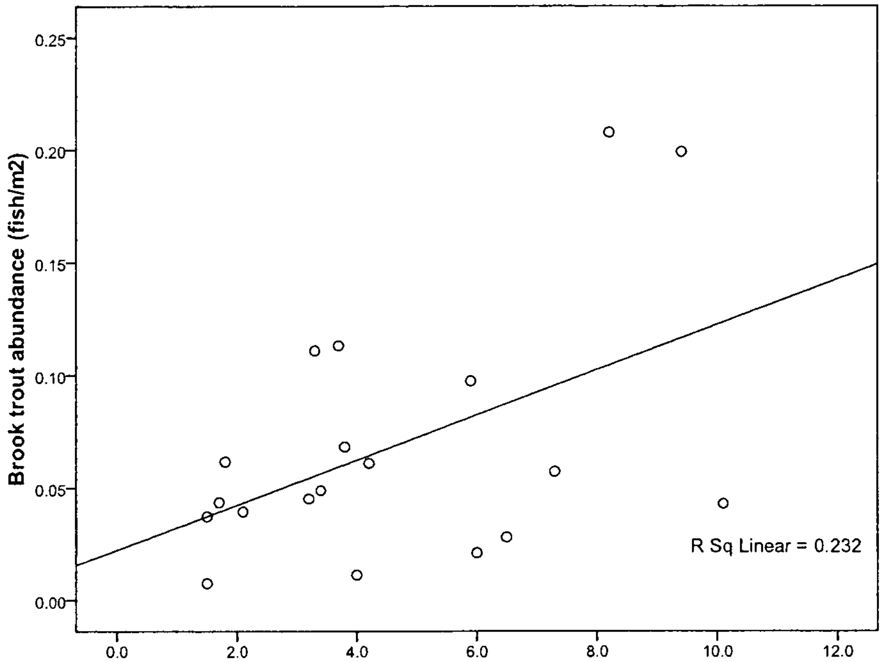
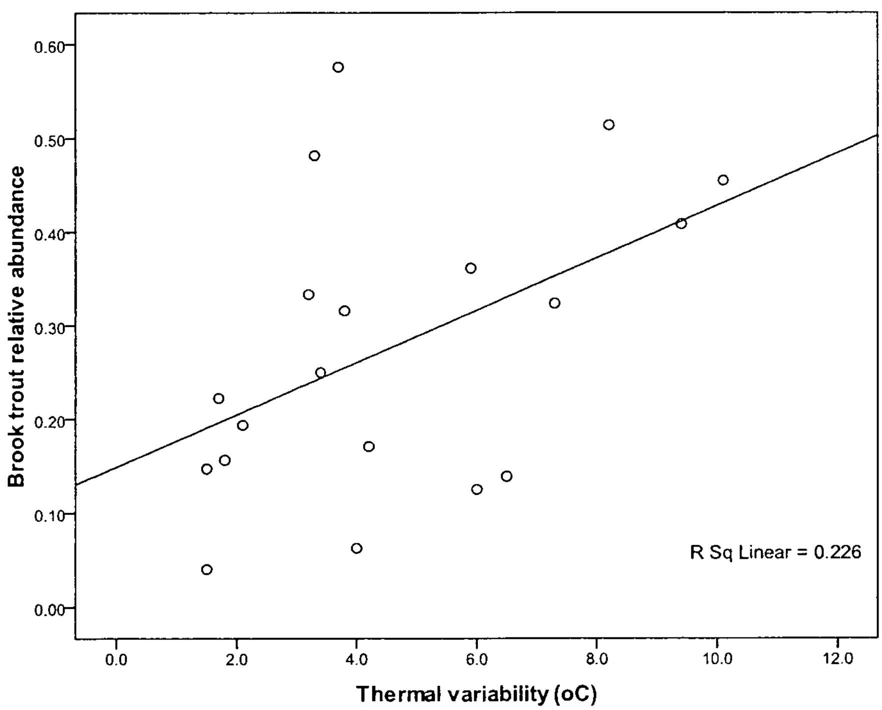


Figure 15. Relationship between thermal variability and fish community diversity indicated by the Simpson's Diversity Index (1-*D*). The horizontal dotted line represents the division between low and high diversity values (0.5). Points represent diversity index for the 19 stream reaches sampled.

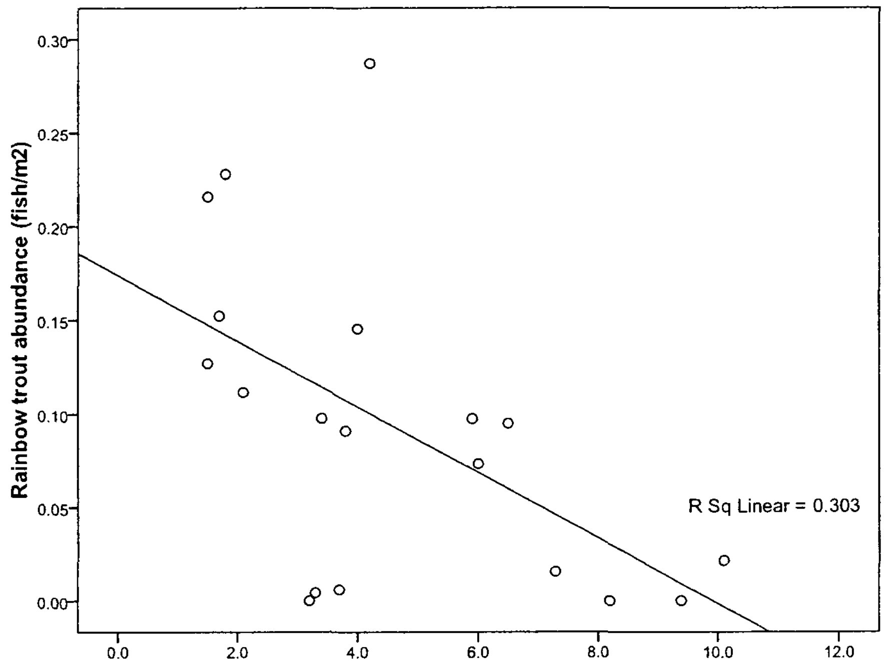


(a)

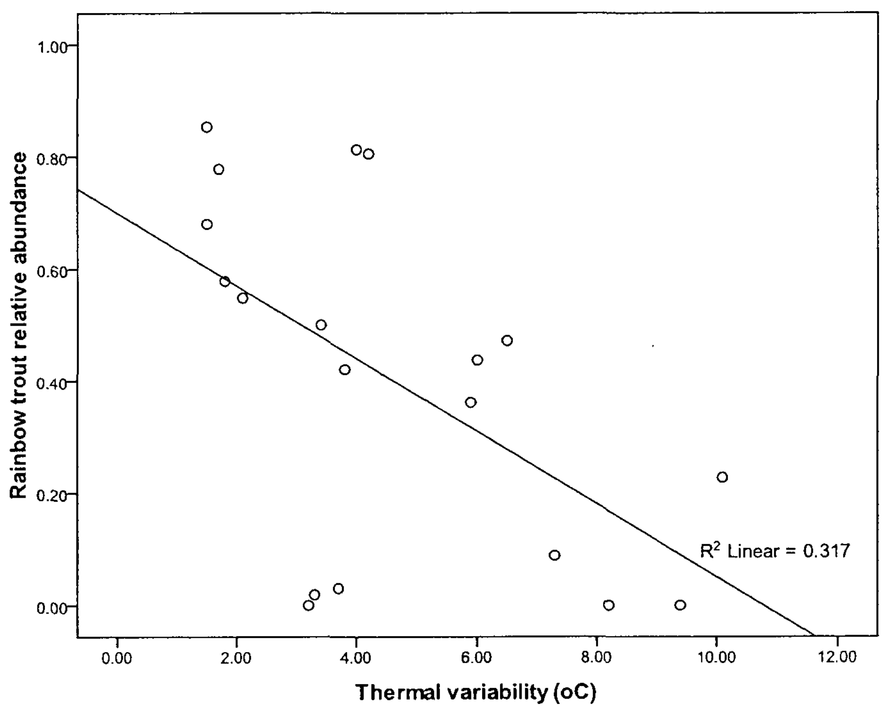


(b)

Figure 16. Relationship between thermal variability and brook trout (*a*) abundance (fish/m^2) and (*b*) relative abundance (brook trout abundance/total fish abundance). Points represent the abundance (*a*) and relative abundance (*b*) for brook trout in the 19 stream reaches sampled.

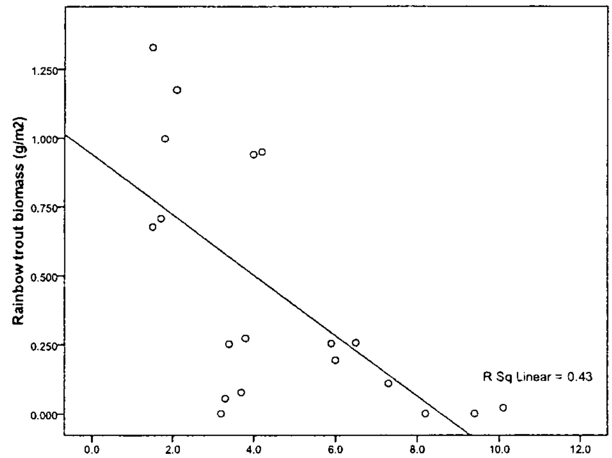


(a)

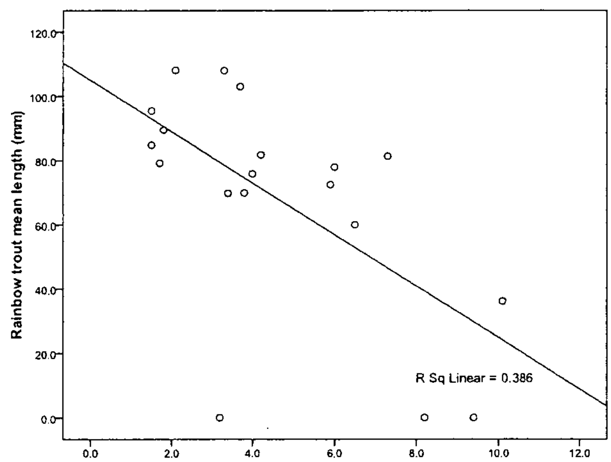


(b)

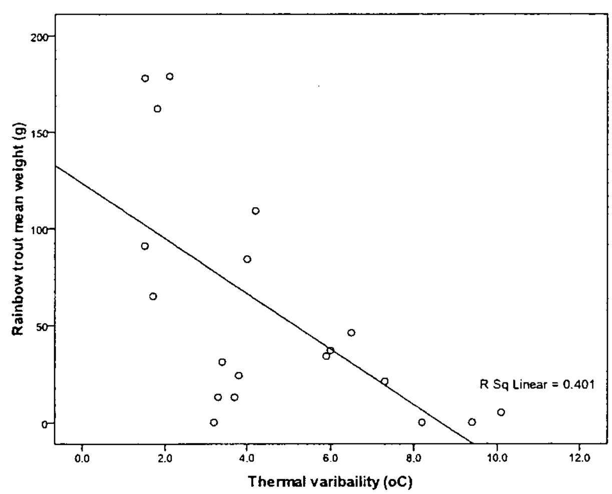
Figure 17. Relationship between thermal variability and rainbow trout (*a*) abundance (fish/m^2) and (*b*) relative abundance (rainbow trout abundance/total fish abundance). Points represent rainbow trout abundance (*a*) and relative abundance (*b*) for 19 stream reaches sampled.



(a)



(b)



(c)

Figure 18. Relationship between thermal variability regressed and rainbow trout (*a*) biomass (g/m^2), (*b*) mean length (mm) and (*c*) mean weight (g). Points represent the total biomass (*a*) mean length (*b*) and mean weight (*c*) of rainbow trout for 19 stream reaches sampled.

There was a clear separation between reaches with high and low species richness based on the thermal variability of the reach. In regions of high thermal variation, more species (>5) were found than in areas of low variability however, there were two exceptions in which the high richness category was predicted in areas of low thermal variability (Figure 19). Using thermal variability as a predictor increased the logistic model's accuracy 26.3 % relative to random with a correct classification percentage of 84.2 (Table 10).

Rainbow trout abundance was significantly associated with thermal variation (Table 10). The probability of high abundance of rainbow (>0.10 fish/m^2) decreased as thermal variability increased (Figure 20). Using thermal variability in the logistic model increased the correct classification of the rainbow trout categories by 21.0 % relative to random with a correct classification of 84.2 % (Table 10).

Thermal variability was not an effective predictor of total fish abundance, total fish biomass and brook trout abundance categories and did not significantly improve the predictive ability of the logistic models relative to random. The increase in the logistic model's correct classification of these variables using thermal variability was less than 10 % for each case (Table 10).

Table 10. Logistic regression results for the categorical fish variables.

Fish Community Variable	Units	Level: Few	Level: Many	Thermal Variability (covariate)				
		<	>	-2 log likelihood	Nagelkerke r^2	Correct classification (%)	Improvement (%)	p
Fish abundance	(fish/m^2)	0.20	0.20	26.25	0.03	57.9	5.3	0.846
Species richness	-	5	5	16.75	0.513	84.2	26.3	**0.025**
Species diversity	-	5	5	16.30	0.373	78.9	5.2	0.090
Fish biomass	(g/m^2)	1.5	1.5	23.92	0.131	57.9	0	0.197
Brook trout abundance	(fish/m^2)	0.10	0.10	17.87	0.133	73.7	5.2	0.207
Rainbow trout abundance	(fish/m^2)	0.10	0.10	12.68	0.652	84.2	21.0	**0.050**

Note: Bolded p values indicate a significant fit of the model ($p < 0.05$).

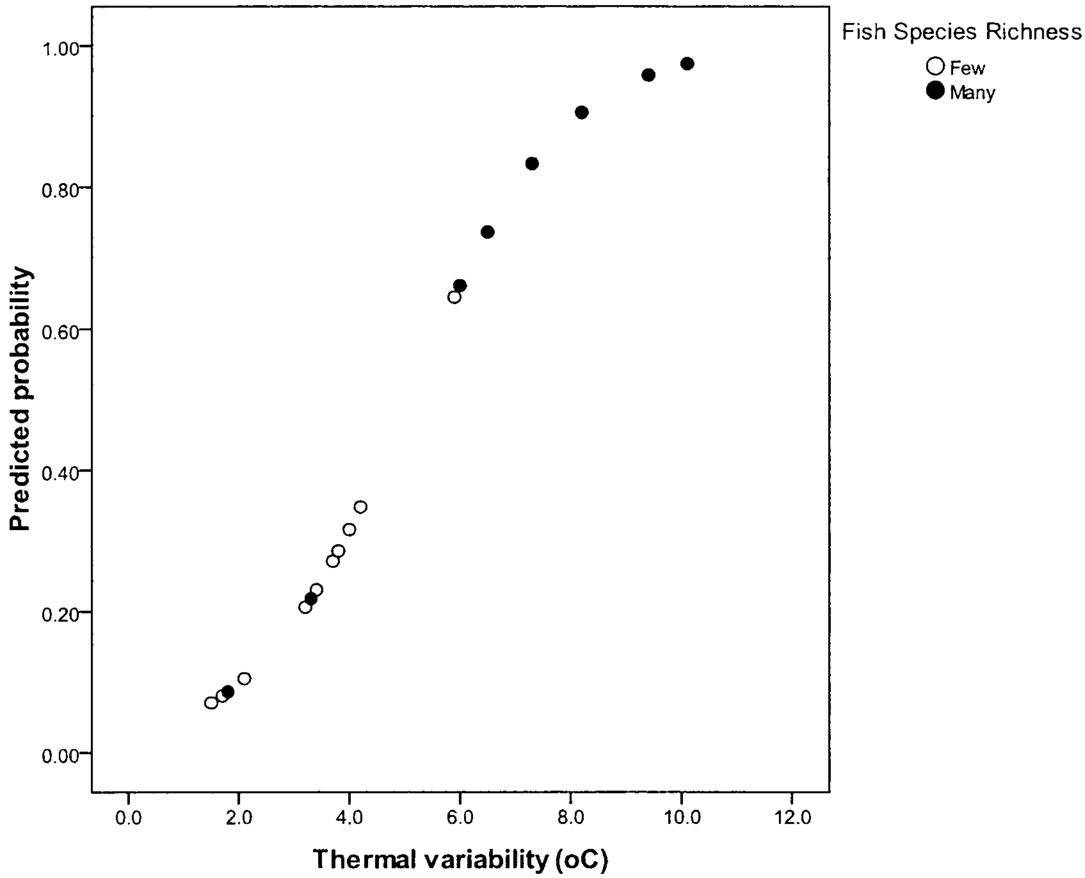


Figure 19. Predicted probability of low or high species richness using thermal variability as the predictor variable. Open circles represent reaches with low species richness, less than 5 species recorded (n= 11). Solid circles represent reaches with high species richness, more than 5 species recorded (n= 8).

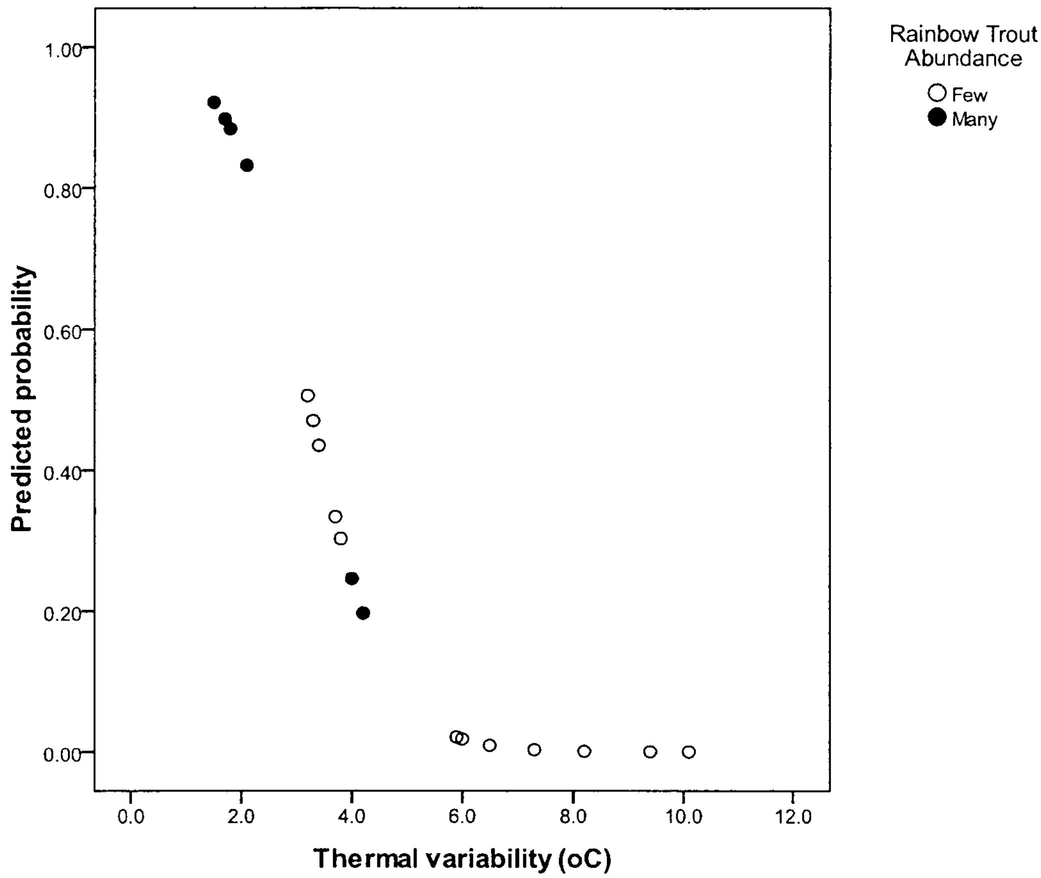


Figure 20. Predicted probability of few or many rainbow trout using thermal variability as the predictor variable. Open circles represent reaches with low rainbow trout abundance, less than 0.10 fish/m^2 (n= 12). Solid circles represent reaches with high rainbow trout abundance, more than 0.10 fish/m^2 (n= 7).

Brook trout and rainbow trout dependent variables were highly correlated so only abundance and length for each species was used in the multiple regression analyses (Table 11).

Associations were found between fish community structure and stream habitat variables as well as thermal variability. Species richness was higher in wider stream reaches (r^2= 0.325, p = 0.011; Table 12), species diversity was higher in reaches that were wider and more thermally variable (r^2= 0.456, p = 0.007; Table 12). Fish abundance and biomass was not significantly associated with any of the habitat or thermal variables measured in this study (p = >0.05). None of the habitat variables contributed to regression model between thermal variably and brook trout abundance. There were no apparent relationships between brook trout mean length and the habitat variables or thermal variability. The percentage of porous material in the streambed had the strongest relationship with rainbow trout abundance (r^2= 0.393, p = 0.04; Table 12). The abundance of rainbow trout tended to be lower in reaches with streambed comprised of porous material such as sand and gravel (β = -0.624). Thermal variability did not improve the fit of the model despite having a significant relationship with rainbow trout abundance (r^2= 0.303, p = 0.015; Table 9). The habitat variables did not improve the fit of the regression model between thermal variability and rainbow trout mean length and were not added to the model.

Table 11. Correlations between fish community variables.

Correlated Variables	r	p
Brook Trout		
Abundance x Relative abundance	0.749	< 0.01
Biomass x Mean weight	0.968	< 0.01
Rainbow Trout		
Abundance x Relative abundance	0.899	< 0.01
Abundance x Biomass	0.721	< 0.01
Abundance x Mean weight	0.777	< 0.01
Relative abundance x Biomass	0.812	< 0.01
Relative abundance x Mean weight	0.711	0.001
Biomass x Mean weight	0.964	< 0.01

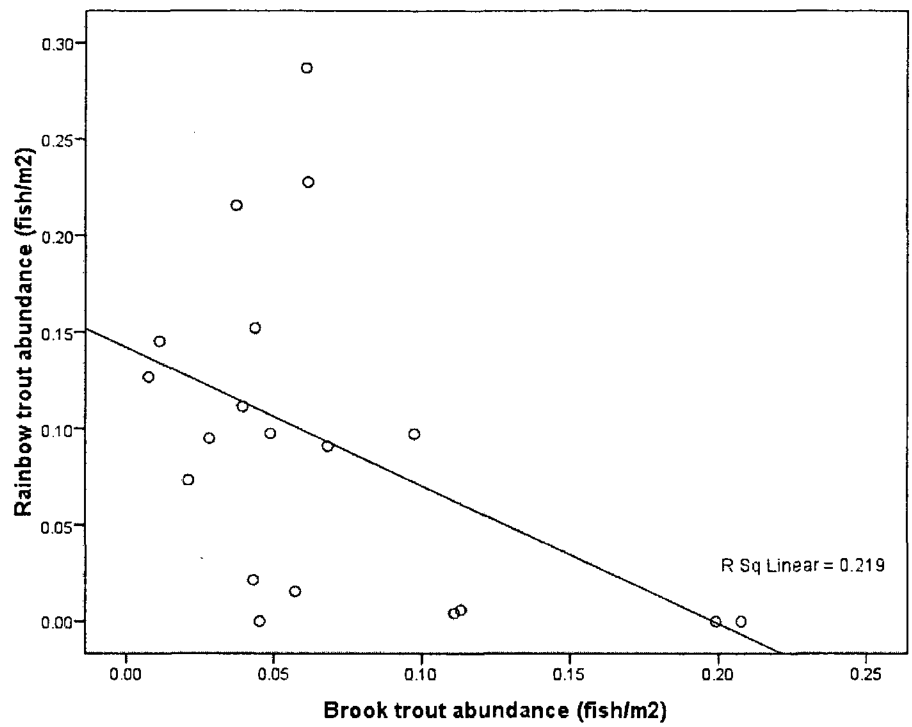
Table 12. Multiple regression results using thermal and habitat independent variables.

	r^2	F	p	Variables	β	p
Total abundance (density)	-	-	-	-	-	-
Total species richness	0.325	8.201	0.011	Width	8.201	0.011
Simpson's diversity (1 –*D*)	0.456	6.959	0.007	Thermal	0.484	0.018
				Width	0.423	0.036
Total biomass	-	-	-	-	-	-
Brook trout abundance	0.232	5.131	0.037	Thermal	0.481	0.037
Brook trout mean length	-	-	-	-	-	-
Rainbow trout abundance	0.393	11.014	0.004	% porous	-0.627	0.04
Rainbow trout mean length	0.386	10.666	0.05	Thermal	-0.621	0.05

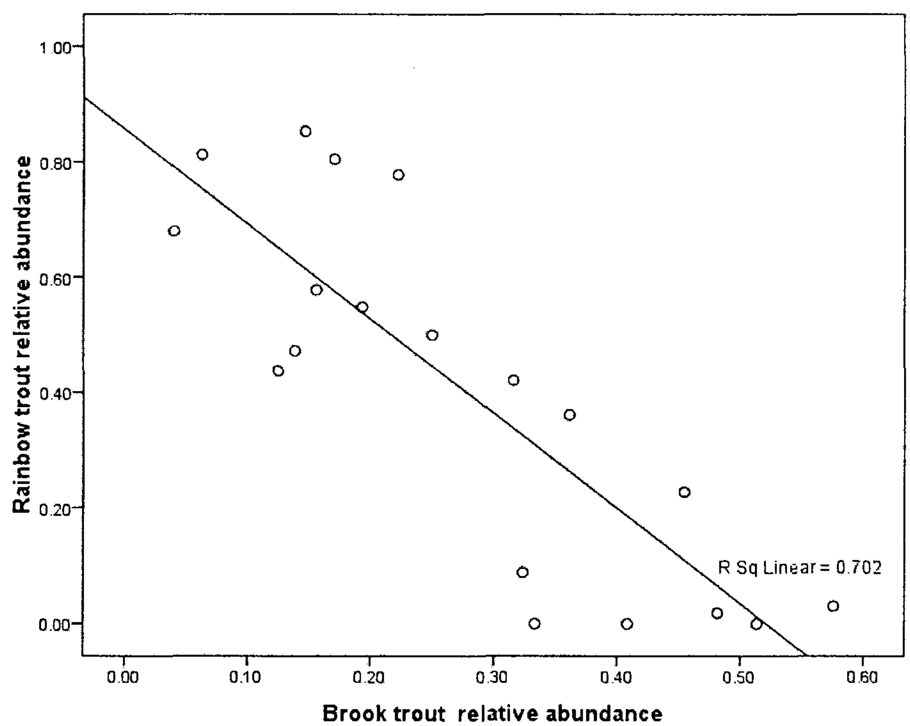
Note. Predictor variables; Width = wetted stream width (m), Thermal = thermal variability, % porous = percent of porous streambed sediment. Dashes (-) indicate the absence of significant correlations between dependent and independent variables.

4.2.3 Relationship between salmonid species

The abundance of brook trout had a negative relationship with the abundance of rainbow trout ($r^2 = 0.219$, $p = 0.043$; Figure 21a). The reach with the greatest abundance of brook trout, 0.208 fish/m^2, had no rainbow trout present, while the stream reach with the smallest brook trout abundance, 0.007 fish/m^2, had a rainbow trout abundance 18 times higher (0.127 fish/m^2). Similarly, the inverse relationship between the relative abundance of brook trout and the relative abundance of rainbow trout indicates that fish communities comprised mainly of brook trout will have few rainbow trout than a community with a small proportion of brook trout ($r^2 = 0.702$, $p < 0.01$; Figure 21b). The measurements of brook trout and rainbow trout productivity, biomass, mean weight and mean length, did not show any significant correlations ($p > 0.05$).



(a)



(b)

Figure 21. Relationship between brook trout and rainbow trout (*a*) abundance (fish/m^2) and (*b*) relative abundance. Points represent the abundance (*a*) and relative abundance (*b*) of the brook trout and rainbow trout caught in 19 stream reaches sampled.

4.3 Thermal and Environmental Variables

4.3.1 Environmental variability between streams

The majority of the habitat, riparian and catchment variables were highly variable both within and between watersheds and among the watershed size classes. When averaged over a reach scale, stream geomorphic structure and dominant W-type had very little to no variability and were determined not to be valuable variables for differentiating among streams and were omitted from any analyses.

The stream morphology of the 1 km^2 catchments was generally shallow water depths and narrow channels, with streambeds dominated by porous sediments comprised of coarse gravel and cobble (Table 13). The structure of the riparian zone for 1 km^2 streams was highly variable from narrow and steep to wide and flat. The variability in riparian zone structure was similar to the variation in RCA sizes, which ranged from <1 ha to almost 40 ha. The catchment landform geology for the 1 km^2 streams was comprised of bedrock with medium relief but the soil moisture and the coefficient of variation in elevation was too variable between sites to generalize.

The reaches with the 3, 5 and 10 km^2 catchment size classes had stream channels that were shallow and comprised of porous streambed sediments but were generally wider than the 1 km^2 streams (Table 14). The shallow depth of all stream sites was likely due to the low flow conditions when measurements were taken rather than the channel morphology. The riparian zone and catchment variables for the stream reaches in the 3, 5 and 10 km^2 categories were highly variable within and among streams.

The RCA classes for all the stream reaches varied from less than 1 ha to over 122 ha (Table 15).

Table 13. Minimum and maximum values for habitat, riparian and catchment environmental variables in 1 km^2 streams (n= 23).

		L4		L5		M8		R25		R26	
	Units	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Stream Habitat											
Depth	m	0.21	0.43	0.13	0.55	0.11	0.22	0.08	0.15	0.05	0.10
Wetted width	m	1.50	1.90	1.30	2.70	1.50	2.20	0.80	1.40	1.50	5.10
Bank height	m	0.35	0.51	0.08	0.58	0.20	0.37	0.17	0.28	0.15	0.61
Fine sediment	%	93.0	98.0	1.00	25.0	1.00	55.0	2.00	100	0.00	25.0
Porous sediment	%	0.00	7.00	5.00	91.0	45.0	100	0.00	98.0	75.0	93.0
Impervious sediment	%	0.00	23.0	2.00	79.0	0.00	7.00	0.00	1.00	0.00	1.00
Canopy closure	%	11.0	75.0	8.00	88.0	2.00	12.0	3.00	35.0	1.00	11.0
Riparian Zone											
RCA	ha	2.32	3.24	0.96	3.68	1.00	39.7	0.56	65.9	0.68	7.28
Riparian width	m	25.9	26.9	0.00	8.60	7.30	9.60	3.20	21.0	3.30	14.4
Riparian canopy	%	17.0	86.0	0.00	80.0	3.00	90.0	2.00	32.0	1.00	16.0
Riparian slope	°	2.0	3.0	3.0	20.0	1.0	6.0	2.0	11.0	2.0	9.0
Soil moisture		dry	damp	dry	wet	dry	damp	damp	wet	dry	wet
Soil type		O	O	O	B	O	O	S	S	S	C
Soil depth	m	0.81	0.85	0.00	0.81	0.19	0.36	0.26	0.51	0.27	0.49
Wetland type	W-type	16, 32		16, 30		34, 35		30, 33, 35		30, 33	
Catchment											
Coefficient of variation		0.80	0.90	0.40	1.20	1.50	3.40	0.00	1.20	2.40	11.1
Catchment slope	°	2.43	2.46	2.27	5.95	5.81	10.53	1.17	2.13	9.92	24.96
Bedrock	%	100	100	100	100	100	100	100	100	6.10	38.7
Topographic relief		M	M	M	M	M	M	M	M	L	L
Soil moisture		damp	damp	damp	damp	wet	wet	dry	dry	wet	wet

Note: Riparian soil type codes; O= organic, B= bedrock, S= silt/sand, C= clay. Wetland type codes; 16= tall shrub conifer, 30= intermediate conifer swamp, 32= rich conifer swamp, 33= hardwood swamp, 34= hardwood swamp (black ash), 35= thicket swamp. Landscape relief codes; H= high, M= moderate, L= low.

Table 14. Minimum and maximum values for habitat, riparian and landscape environmental variables in 3, 5, 10 km^2 streams (n= 32).

		G1		G2		G3		G4		G5		G7	
	Units	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Stream Habitat													
Depth	m	0.02	0.07	0.06	0.13	0.07	0.20	0.07	0.15	0.09	0.16	0.11	0.33
Wetted width	m	0.49	4.16	1.01	1.79	1.83	4.88	1.84	2.69	2.23	2.99	2.68	4.67
Bank height	m	0.79	2.63	0.40	2.27	0.23	1.55	0.28	1.24	0.38	0.65	0.27	0.61
Fine sediment	%	0.00	2.00	8.00	58.0	0.00	25.0	1.00	13.0	0.00	38.0	0.00	18.0
Porous sediment	%	13.0	100	42.0	79.0	67.0	100	15.0	91.0	62.0	100	5.00	83.0
Impervious sediment	%	0.00	87.0	0.00	13.0	0.00	8.00	0.00	83.0	0.00	28.0	17.0	95.0
Canopy closure	%	67.0	95.0	51.0	93.0	59.0	88.0	26.0	56.0	74.0	97.0	35.0	99.0
Riparian Zone													
Slope	°	3.3	9.0	1.0	2.0	1.0	4.0	1.0	7.0	1.0	2.0	1.0	3.0
RCA	ha	0.32	36.72	0.52	122.2	0.72	67.12	0.36	2.96	1.20	4.00	0.32	70.1
Riparian width	m	1.00	16.7	1.50	10.0	1.25	13.5	1.00	17.5	5.00	10.0	2.50	16.0
Riparian canopy	%	45.5	94.5	0.00	87.5	0.20	81.0	4.80	94.0	58.0	100	30.0	96.0
Riparian slope	°	2.0	49.0	1.0	62.0	3.0	13.0	3.0	7.0	3.0	6.0	3.0	10.0
Soil moisture		dry	damp	dry	damp	dry	damp	dry	damp	dry	wet	dry	dry
Soil type		S	C, B	C	B	S	C	S	C	S	S	S	C
Soil depth	m	0.09	0.39	0.00	0.85	0.13	0.69	0.20	0.85	0.44	0.85	0.13	0.85
Wetland type	W-type	0, 32, 33		34		34		0, 30, 32, 35		34		34, 35	
Catchment													
Coefficient of variation		0.40	3.6	0.10	8.50	0.60	2.20	0.20	1.00	0.10	2.10	0.20	3.20
Landscape slope	°	4.69	15.29	0.96	7.33	3.30	5.42	2.92	3.57	2.58	4.32	1.69	4.02
Bedrock	%	0.00	73.4	0.00	7.10	0.00	19.8	0.00	0.00	100	100	0.00	15.3
Topographic relief		M	H	L	L	L	M	H	H	M	M	L	L
Soil moisture		damp	wet	dry	dry	wet	wet	wet	wet	wet	wet	wet	wet

Note: Riparian soil type codes; O= organic, B= bedrock, S= silt/sand, C= clay. Wetland type codes; 0= no riparian, 16= tall shrub conifer, 30= intermediate conifer swamp, 32= rich conifer swamp, 33= hardwood swamp, 34= hardwood swamp (black ash), 35= thicket swamp. Landscape relief codes; H= high, M= moderate, L= low.

Table 15. Summary of RCA size (ha) within individual stream reaches (n= 55).

	1 km^2 streams					3, 5, 10 km^2 streams					
Reach	L4	L5	M8	R25	R26	G1	G2	G3	G4	G5	G7
0	3.24	0.96	39.72	0.56	0.92	2.24	0.52	1.08	1.92	0.72	70.08
50	2.32	3.68	1.76	41.88	0.68	0.80	4.36	0.88	2.20	1.20	65.88
100		2.92	1.04	56.48	1.60	36.72	122.20	0.36	1.20	1.64	0.32
150		0.96	1.00	65.92	7.28	0.32	0.52	2.12	2.20	1.24	0.92
200		0.96	23.12		4.12	2.20		2.96	4.00	67.12	1.60
250			21.12		0.80	0.72				1.20	0.92
Mean	2.78	1.90	14.63	41.21	2.57	7.17	31.90	1.48	2.30	12.19	23.29

4.3.2 Environmental variables and thermal variability

Stream bank height, % impervious sediment, % fine sediment, stream slope, riparian canopy closure, riparian soil depth, landscape slope were highly collinear with the other environmental variables and were omitted from the analyses ($r > 0.5$, $p \leq 0.01$; Appendix V). The number of environmental variables was reduced from 20 to 13. RCA size classes were $\log_{(10)}$ transformed to improve normality.

Thermal variability was not significantly associated with RCA($\log_{(10)}$) when tested with all of the catchment size reaches pooled together in the regression analysis ($r^2 = 0.017$, $p = 0.336$, $n=55$). The lack of a relationship between thermal variability and RCA($\log_{(10)}$) may be an effect of catchment size due to the significant difference in thermal variability amongst the 1 and 3 km^2 and the 5 and 10 km^2 catchments (Figure 6).

The distribution of thermal variability measurements within stream reaches was highly positively skewed. Thirty-two percent of the reach thermal variability measures were greater than one standard deviation (SD) above the mean. For further analyses, reach were categorized as normal (within one SD of the mean, 0 – 5.5 °C) or extreme (above SD from the mean, Figure 22).

Reaches within the 5 and 10 km^2 catchment size classes had both normal and extreme thermal variability; reaches within the 1 and 3 km^2 catchments had only normal thermal variability values (Figure 23). The difference in thermal variability by catchment size grouped the stream reaches in size classes as, 1 and 3 km^2 catchments (n= 33 reaches) and 5 and 10 km^2 catchments (n= 22 reaches). The remaining analyses were conducted on the groups separately.

The relationship between RCA($\log_{(10)}$) and thermal variability differed among catchment sizes. There was a positive relationship between thermal variability and RCA($\log_{(10)}$) for the reaches within the 5 and 10 km^2 catchment sizes (r^2= 0.237, p = 0.022). Stream reaches with larger contributing areas tended to have more variability in streambed temperatures than reaches with small contributing areas (Figure 24). There was no significant relationship between thermal variability and RCA($\log_{(10)}$) for the 1 and 3 km^2 catchment size category (Figure 24). There was a distinct grouping of the reaches in the 1 and 3 km^2 catchments in lower surface water temperatures and low thermal variability and no relationship was seen between thermal variability and mean surface water temperature (r^2= 0.056, p = 0.185; Figure 25). The reaches in catchments of 5 and 10 km^2 were spread between low and high thermal variability with a positive relationship between thermal variability and mean surface water temperature (r^2= 0.429, p = 0.001; Figure 25).

Thermal variability for stream reaches within the 1 and 3 km^2 catchment size was higher in reaches with catchments that had large CV values (r^2= 0.274, p = 0.002, β = 0.523) and a low percentage of bedrock (r^2= 0.183, p = 0.013, β = -0.428). None of the habitat or riparian variables had a significant relationship with thermal variability for the 32 reaches.

Thermal variability for stream reaches within the 5 and 10 km^2 catchment size category was higher in reaches a larger percent of porous streambed material (r^2= 0.233, p = 0.023; Figure 26) and larger RCAs. None of the catchment variables had a significant relationship with thermal variability in the 5 and 10 km^2 catchments (r^2 <0.15, p >0.05, n = 22).

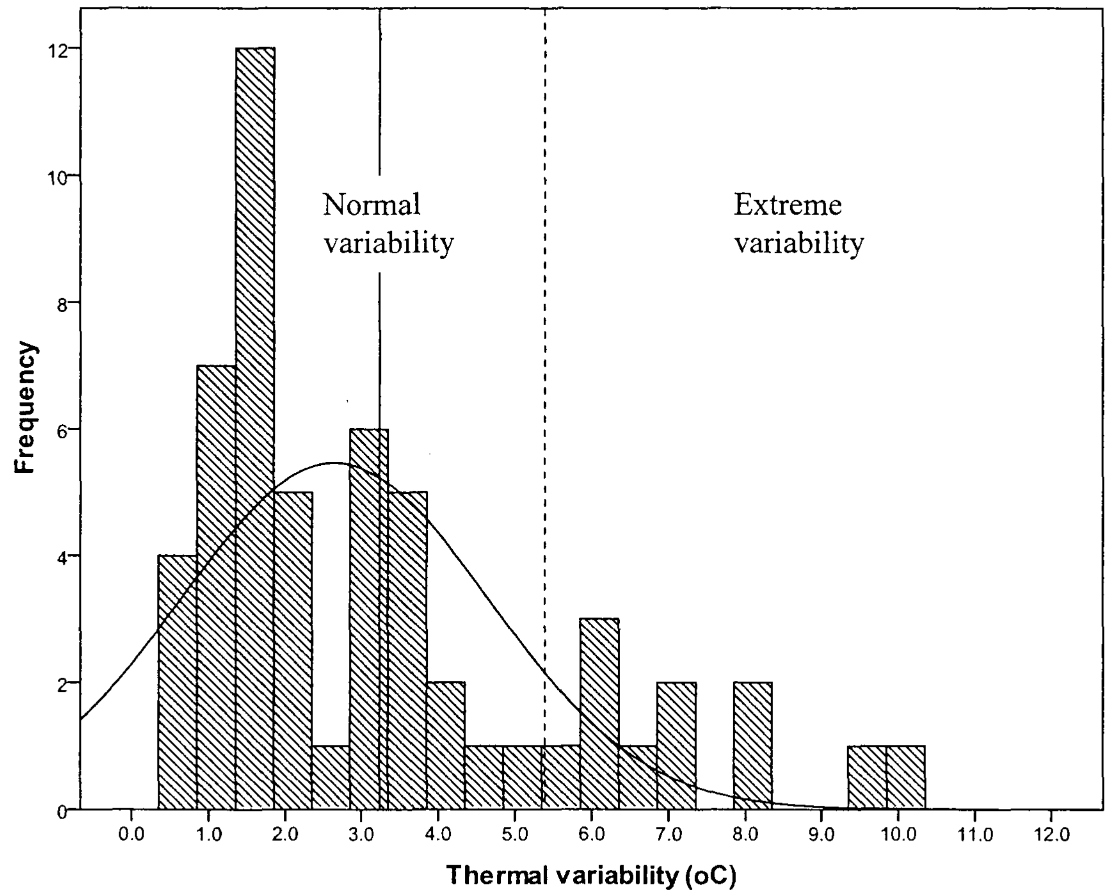


Figure 22. Frequency distribution curve of the thermal variability in stream reaches. Bars represent the frequency of occurrence and the solid black line indicates the frequency distribution. The vertical solid line indicates the mean (3.24 °C) and the dashed line indicates 1 standard deviation from the mean (2.30 °C). Reaches below 1 standard deviation (5.5 °C) were classified as normal and above (> 5.5 °C) were classified as extreme thermal variability.

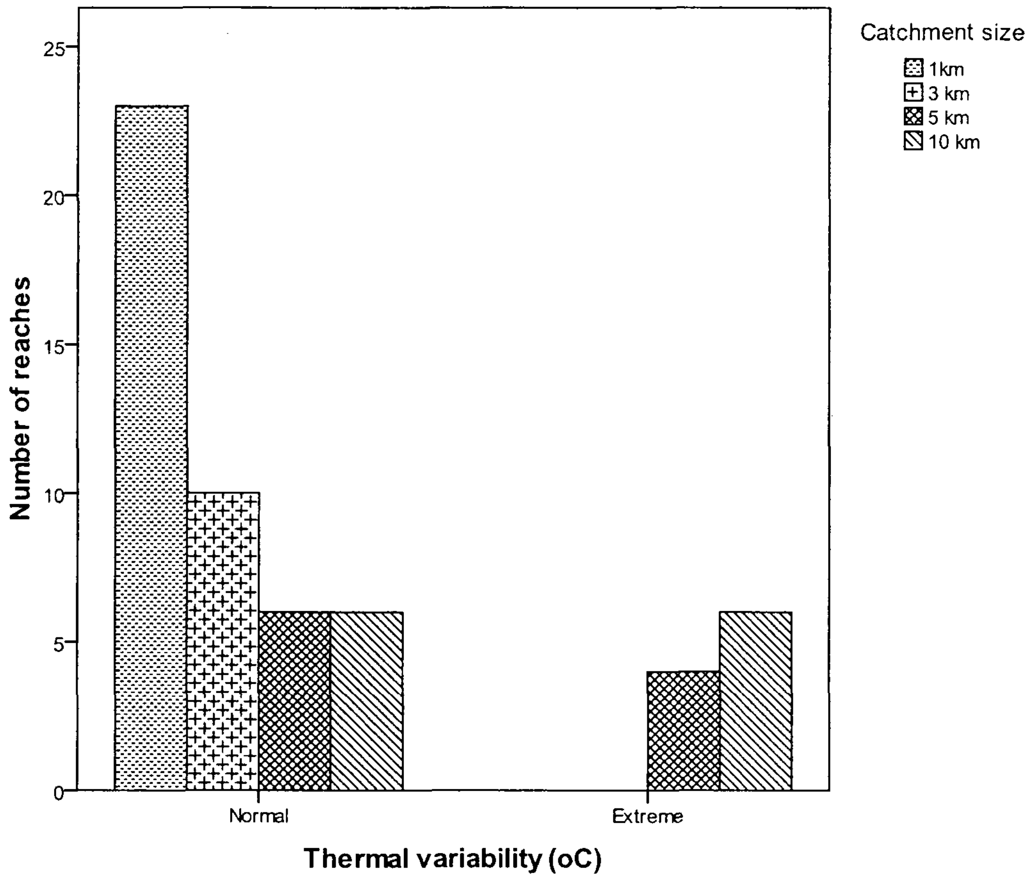


Figure 23. Distribution of stream reaches based on catchment size classes within the thermal variability categories, normal (0 - 5.5 °C) and extreme (>5.5 °C). The height of the bars represents the number of reaches within 1, 3, 5 and 10 km^2 catchment sizes that had normal or extreme thermal variability.

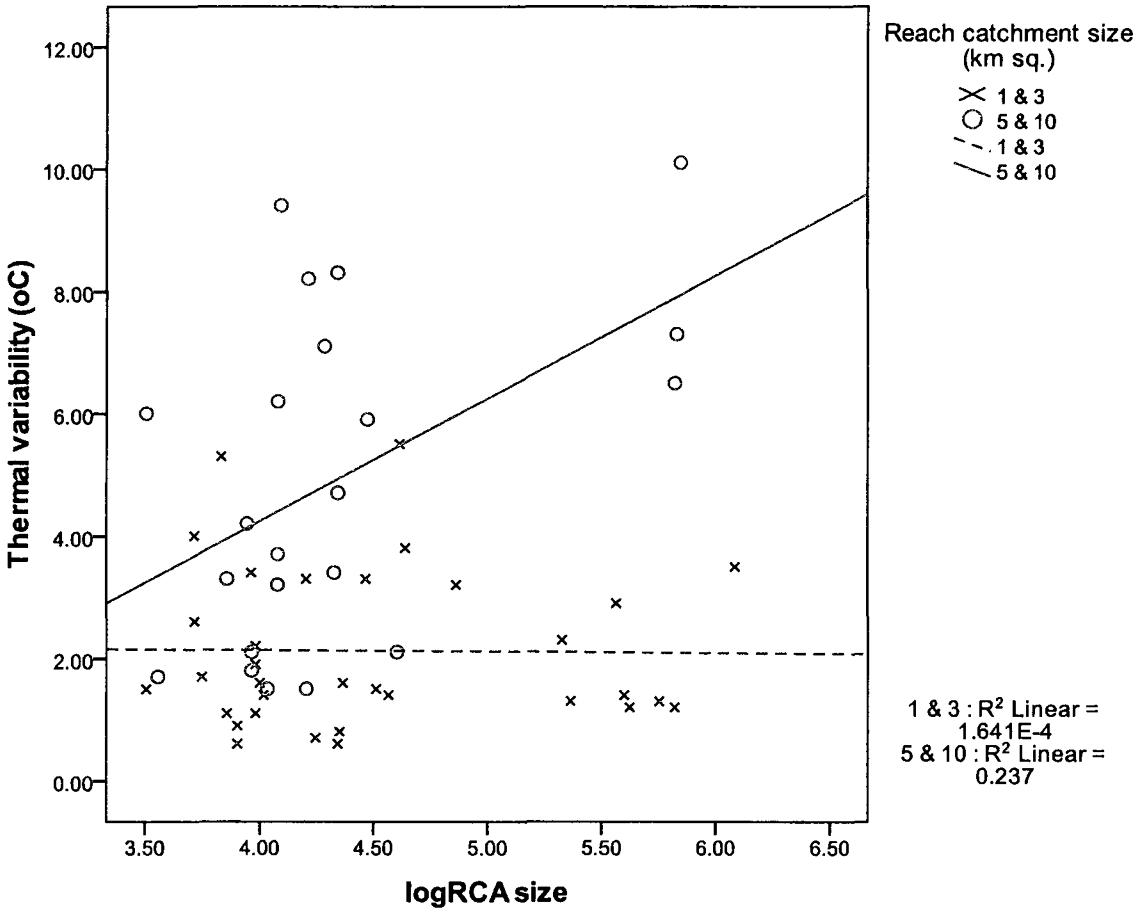


Figure 24. Relationship between thermal variability and RCA($\log_{(10)}$) for reaches in streams with 1 & 3 km^2 catchments and reaches within 5 & 10 km^2 catchment size streams. The x symbols represent the 33 reaches in the 1 & 3 km^2 catchment category and the open circles represent the 22 reaches in the 5 & 10 km^2 category. The dashed line is the regression line for the 1 & 3 km^2 and the solid line is the regression line for the 5 & 10 km^2.

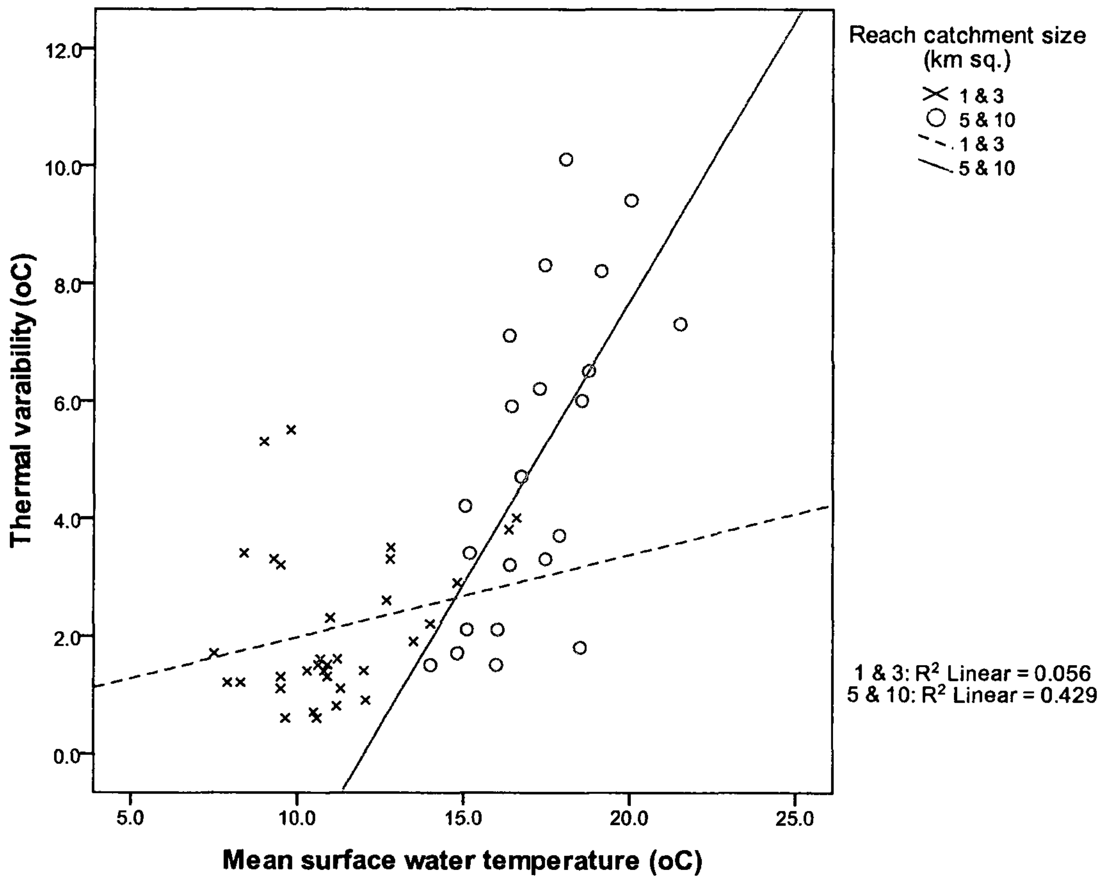


Figure 25. Relationship between thermal variability and mean surface water temperature for reaches in streams with 1 & 3 km^2 catchments and reaches within 5 & 10 km^2 catchments size streams. The x symbols represent the 33 reaches in the 1 & 3 km^2 catchment category and the open circles represent the 22 reaches in the 5 & 10 km^2 category. The dashed line is the regression line for the 1 & 3 km^2 and the solid line is the regression line for the 5 & 10 km^2.

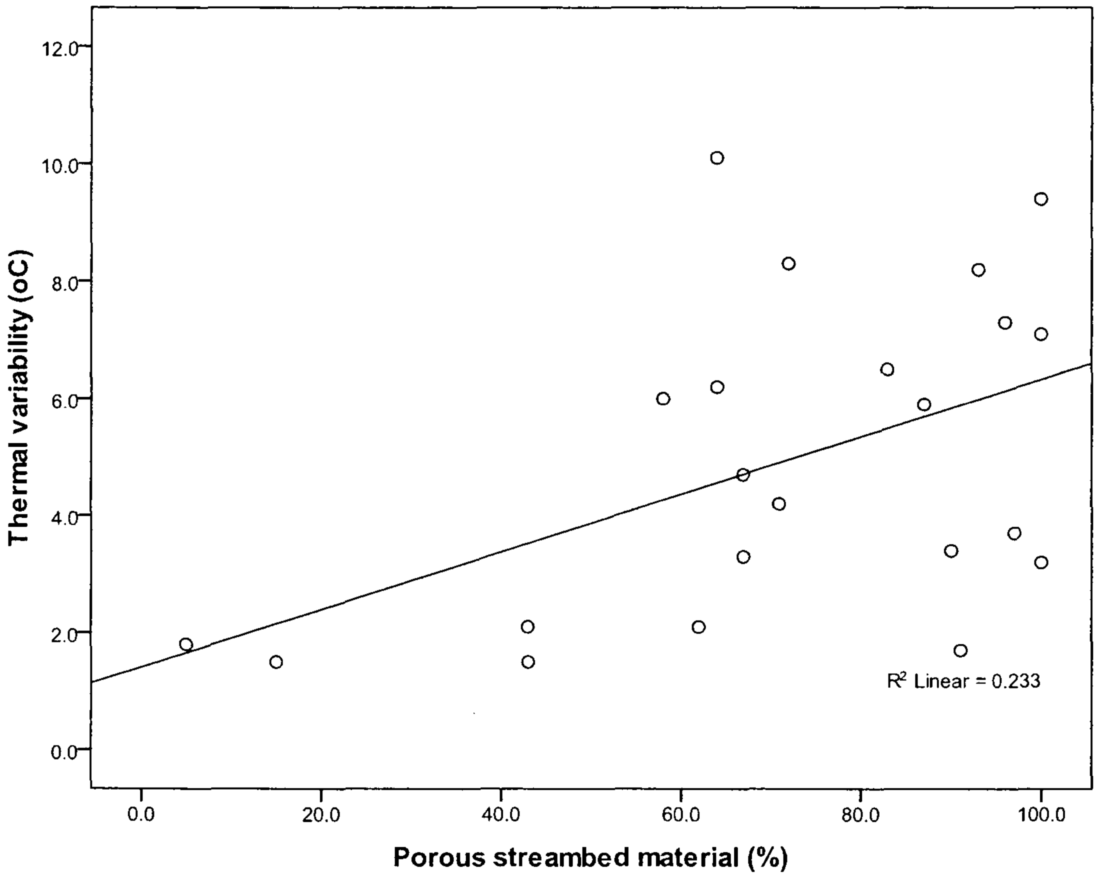


Figure 26. Relationship between thermal variability in the 5 & 10 km^2 catchments size streams and porous streambed material. The open circle points represent the 22 stream reaches sampled with the 5 &10 km^2 catchment category.

5.0 DISCUSSION

Stream temperature is one the most critical abiotic factors in the maintenance and health of stream ecosystems. It influences other abiotic conditions such as the dissolved oxygen and pH as well as biotic processes such as organism health (Caissie 2006). Spatial variability in surface water temperature has typically been used as the prime indicator of stream thermal conditions (Clarke et al. 1999; Arscott et al. 2001; Mellina et al. 2002; Picard et al. 2003; Storey 2003) however the variability in streambed temperatures may be equally important to the thermal conditions of a stream system as seen by the results of this study.

There was a great deal of thermal variability within and among streams, potentially associated with differences in groundwater input as predicted by my first hypothesis. Thermal variability was primarily associated with temperatures colder than the reach average; reaches tended to have larger negative deviations from the mean than positive deviations which supports my assumption that variability is an indicator of groundwater input. Other studies have also concluded that, during the summer, regions receiving groundwater are cooler than streambed regions with only surface water mixing (Moore et al. 2005; Schmidt et al. 2006; Tague et al. 2007). Due to the heterogeneous nature of groundwater inputs into a stream, one stream section may be receiving groundwater while a few metres up or down stream may be downwelling (surface water) into the streambed (Chen 2009). The upwelling (groundwater input) areas of a streambed would be cooler than downwelling areas creating microthermal variation in streambed temperatures (Webb et al. 2008). In a 600 m streambed thermal survey, Westhoff et al.

(2007) found a 4.5 °C difference in streambed temperatures with the highest variability measured directly downstream of a known groundwater source.

The level of thermal variability was unequal among reaches of different catchment sizes. Reaches in streams that had a catchment size of 5 or 10 km^2 had on average double the level of thermal variability than stream reaches within 1 or 3 km^2 catchments. The reduced level of thermal variability in the 1 and 3 km^2 catchments may be explained by the stream flow conditions and time of year in which the thermal mapping was completed. During base flow conditions, the surface water in small streams has had relatively little time to warm from the groundwater source so it is likely not sufficiently thermally discrete from groundwater upwellings to be easily detected (Brunke and Gosner 1997; Malcolm et al. 2004; Schmidt et al. 2007).

The structure of a fish community in a stream environment may be highly influenced by thermal conditions of a stream (Baltz et al. 1987). My results partially support my second hypothesis that thermal variability would be positively associated with fish abundance, species diversity and total biomass, specifically for brook trout and rainbow trout populations. Species diversity, richness and brook trout abundance was higher in stream reaches with more thermal variability, however there was no difference in brook trout size in these areas. In contrast to brook trout, rainbow trout size and abundance was lower in reaches with high thermal variability, which was opposite to my prediction. Additionally, contrary to my hypothesis, there was no correlation between thermal variability and the abundance or size of fish. This observation may be related in part, to the observed pattern of brook trout and rainbow trout abundance. Brook trout and rainbow trout were the most abundant species encountered in all the stream surveys and comprised more than 65 % of all fish sampled. However, the abundance of brook and rainbow trout were negatively correlated and had opposite relationships with thermal variability so a high abundance of one species was contrasted low abundance of the other. This pattern masked any relationship between total fish abundance and thermal variability.

Fish species richness and diversity were positively associated with thermal variability. Regions with variable thermal habitats had a greater number of fish species and were more homogenous in abundance within species. High species richness was predicted in reaches with high thermal variability and low richness in reaches with low thermal variability. Species diversity had a positive correlation with thermal variability and was nearly 1.5 times greater in the 10 km^2 catchments with the highest thermal variability levels than in the less variable 3 km^2 catchments. These results may be explained by the River Continuum Concept which suggests that low diversity in headwater streams was due to the small differences in the spatial and temporal thermal regimes, where as streams directly receiving contributions from the headwaters had more temperature variation and more biotic diversity (Vannote et al. 1980). The River Continuum Concept is one example of, and support for, the hypothesis that a positive species-area relationship existed because larger areas had more habitat heterogeneity and available resources, and thus may support more species (Williams 1964). An alternative hypothesis is that increasing sampling area increased the chance of finding more individual organisms as well as more species; because larger areas can contain more individuals (Connor and McCoy 1979). The results from this study seem to support the habitat heterogeneity hypothesis because there was no significant relationship between abundance and stream size, while diversity was higher in larger catchments because of the potential for more available resources and preferred habitat niches (Angermeier and Schlosser 1989).

Areas with greater thermal heterogeneity may support a diverse community structure by incorporating the preferences and optimal temperatures of multiple fish species (Vannote and Sweeny 1980; Brown et al. 2005; Chu et al. 2006). The importance of thermal variability in maintaining species diversity is illustrated by 3 coldwater fish species found in Northwestern Ontario, slimy sculpin, Chinook salmon and brook trout, whose optimal temperature range differs by almost 7 °C. Slimly sculpin have a preference for temperatures around 10 °C while Chinook salmon prefer 14 °C and brook trout in the region of 17 °C (OMNR 2008a). Yet, during the electrofishing surveys, slimy sculpin, Chinook salmon and brook trout were found in streams with surface water temperatures beyond their thermal preference. Slimy sculpin and brook trout were found in areas with stream water temperatures of 22 °C, while Chinook salmon was found in temperatures of 19 °C. These coldwater species may have tolerated surface water temperatures exceeding their preferred temperatures by as much 12 °C by using cooler streambed areas as temporary habitats with temperatures nearer their thermal preference (Matthews and Berg 1997). The distribution of slimy sculpin within a stream has been strongly correlated to temperature. During the summer months the highest densities may be found in groundwater input areas, which coincide with the lowest summer temperatures in a stream (Edwards and Cunjak 2007). Similarly, Chinook salmon inhabit stream reaches with temperatures that exceeded their lethal limit of 25 °C due to cooler groundwater patches distributed throughout the stream (Torgersen et al. 1999).

The positive influence of thermal variability in streambed temperatures on fish abundance was most evident in brook trout. Brook trout abundance was probably higher in reaches with greater thermal variability because of the thermal refugia that cooler areas provide during warm summer water temperatures (Curry et al. 1997). The majority of the brook trout caught in the stream surveys were small, young individuals that use upwelling groundwater to maintain body temperature. Unlike the larger adults, young brook trout are unable to migrate long distances into deeper lake habitats and rely on groundwater inputs throughout they warm summer months (Power et al. 1999). The cold patches in streams are critical to the growth of young brook trout. High water temperature can raise basal metabolic costs, leaving less energy for growth and activity (Drake and Taylor 1996).

Length and biomass was not correlated with thermal variability in brook trout populations possibly because larger adults can migrate into larger water bodies (Lake Superior) maintaining body temperature according to the, "bigger fish – deeper habitat", relationship (Faush and Bramblett 1991; Bell 2006). For example, a study on brook trout movement patterns in Nipigon Bay found that brook trout often used deeper areas during the warmest part of the daylight hours and moved to shallow near shore areas during cooler periods (Mucha and Mackereth 2008).

In contrast to brook trout the abundance, relative abundance, length and biomass of rainbow trout were lower in areas of high thermal variability than in areas with low thermal variability. The negative relationship observed between thermal variability and rainbow trout was unexpected because brook trout and rainbow trout have generally been grouped in the same coldwater species category (Wang et al. 2003). Thermally sensitive cold water fish species, such as brook and rainbow trout tend to be found in deep, narrow, high gradient coldwater streams with high inputs of groundwater (Wang et al. 2003). In this study, both brook trout and rainbow trout were found in these types of coldwater streams, however, at a smaller reach scale the abundance of the two species differed within this stream type.

One possible explanation for the observed pattern of rainbow trout distribution may be that they are more strongly influenced by habitat characteristics other than thermal variability. Thermal variability was generally greatest in stream sections with low gradients, slower discharge and porous streambed materials (Chang 2003), while rainbow trout prefer swifter moving water and are often found at the bottom of a riffle entering a pool (Scott and Crossman 1973). Ebersole et al. (2001) examined the association between coldwater refugia provided by groundwater inputs and the density of rainbow trout in a stream. The authors found no significant correlation between the number of coldwater patches and the density of rainbow trout in a stream. They suggested that this may be due to the refugia not meeting important physiological requirements such as dissolved oxygen concentration, food availability and predation avoidance.

Differences between brook trout and rainbow trout methods of behavioural thermoregulation may also explain their different relationships with thermal variability. Coldwater stream fish typically thermoregulate by actively migrating into an area that is within their thermal preference, for instance, a groundwater seep or deep lake habitat (Reynolds and Casterlin 1979). However, it has been noted that in water near lethal thermal conditions juvenile rainbow trout may not always thermoregulate by moving into cooler temperatures but compensate for the conditions by continuously foraging (Spina

2007). Maintaining body temperature below lethal limits may be more critical to young brook trout than rainbow trout, which may choose to trade optimal body temperature for larger foraging territory. For instance, a study on behavioural thermoregulation in brook trout and rainbow trout found that brook trout consistently had cooler body temperatures than the stream surface water during the summer months as well as having significantly cooler body temperatures than rainbow trout (Baird and Krueger 2003).

Competition and displacement may also contribute to the negative relationship in abundance of rainbow trout and the presence of brook trout. According to Yodzis (1986) community structure may be niche controlled where, in order for species to coexist without competition they must differ in their trophic niches. Although the specific habitat niches between brook trout and rainbow trout differ, there may have been certain overlapping preferences, such as food, which may have lead to completion between the two species. The competitive ability of species within an aquatic habitat aquatic can be easily altered by abiotic changes of the habitat (Taniguchi et al. 1998; Wotton 1998; Blanchet et al. 2008). The abiotic influence of the outcome of the competition may explain the differences in the dominance of brook trout and rainbow trout under different thermal variability conditions. A review of the literature however, provides conflicting results on the outcomes from competition between brook trout and rainbow trout over differing habitat types. In slow velocity habitats brook trout have been observed to have dominance over rainbow trout (Cunjak and Green 1984), however, they have also been found to dominant in faster velocities as well (Magoulick and Wilzbach 1998). In contrast, Isley and Kempton (2000) found that in laboratory trials with mixed communities of juvenile brook trout and rainbow trout, rainbow trout were dominant and had significantly higher growth rates over brook trout. Sympatry has also been observed between the two species with no displacement, so brook trout and rainbow trout effectively overlap each other in habitat locations (Strange and Habera 1998). The negative association between brook trout and rainbow trout was beyond the scope of my project; however, the ability of rainbow trout to tolerate near lethal conditions to secure optimal foraging opportunities (Spina 2007) and reduce competition with brook trout for optimal thermal habitats may be a reasonable hypothesis.

Considering that streambed thermal variability was associated with increasing species diversity and had an effect on population distribution of coldwater species, it is essential to develop hypotheses related to the consequences of landscapes changes on thermal variability. Proper planning must be applied during landscape alterations such as forest harvesting operations, road construction and development to maintain thermal variability in coldwater stream systems (Schlosser 1991). Indicators of thermal variability that are easily identifiable may assist in predicting the locations of groundwater movements for the purpose of planning which may mitigate disturbances within these areas.

Thermal variability was associated with RCA size and environmental characteristics related to groundwater flow; however these associations were dependent on catchment size. My results partially support the third hypothesis of this study that reaches with high thermal variability have larger contributing areas and different environmental variables than reaches with low variability. While no relationship existed between RCA and thermal variability in a reach when all reaches were analyzed, thermal variability was significantly greater in reaches with large RCAs in the 5 and 10 km^2

catchments. Thermal variability in the 1 and 3 km^2 catchments was significantly lower than the 5 and 10 km^2 classes, and this may explain why there was no relationship with RCA for the 1 and 3 km^2 classes. Thermal variability was less than 5.5 °C and 74 % of thermal variability levels fell below 3.0°C within all of the 1 and 3 km^2 catchments. The narrow range of temperature may make any difference in groundwater movement associated with larger RCAs difficult to detect in these small streams.

Greater differences between surface and streambed temperatures were found in the 5 and 10 km^2 reach classes. Within these larger streams, reaches with large RCAs had greater variability in streambed temperatures in comparison to the small RCAs. Larger RCAs have more surface area to accumulate and retain groundwater, while small RCA have less storage capacity and will contribute more surface water during precipitation events than groundwater (Thompson and Moore 1996). Although large RCAs may accumulate more groundwater the pattern of thermal variability is also influenced by the streambed which must be comprised of permeable sediment to allow for the movement of groundwater from the RCA into the aquatic environment.

The results of this study indicated that reaches with greater thermal variability (5 and 10 km^2 catchments) had streambeds comprised of porous materials such as gravel and sand. Differences in the permeability of streambed substrate contribute to the heterogeneous distribution of groundwater inputs (Chang 2003; Kalbus et al 2009). Areas with gravel and coarse sand may enhance upwellings resulting in cooler temperatures than areas of less permeable substrate such as clay or fine silt (Lapointe et al. 2004). The differences in streambed substrate may result in the distribution of groundwater into specific areas and contribute to the thermal variability within a reach.

Although no relationship was found between thermal variability and RCA size in 1 and 3 km^2 catchments, there were correlations between thermal variability and topographic and hydrogeological features associated with groundwater accumulation, retention and discharge. Thermal variability for the 1 and 3 km^2 catchments was highest in reaches that had a high coefficient of variation in elevation values within the RCA contributing to the reach. This may be because rougher terrain within a RCA is associated with higher levels of groundwater movement and higher thermal variability. At a spatial scale of a few metres, landscape roughness is a combination of ridges, mounds and depressions in the terrain (Candela et al. 2005). Within a RCA, the landscape may have numerous micro-topographical changes including concave areas that trap water and recharge soil moisture (Bronstert et al. 1998). An increase in terrain roughness creates more storage "pockets" for groundwater accumulation and retention, which may hold and store groundwater long after a rainfall event, cooling the temperature of the groundwater before it moves into a stream system (Freeze and Witherspoon 1968; Berry 2007).

The geologic characteristics of RCAs were also correlated with thermal variability in the 1 and 3 km^2 catchments. RCAs with relatively little bedrock had higher thermal variability. Landscapes dominated by bedrock outcrops have low infiltration capacity because of the shallow overlaying till depth where the pore spaces in the soil quickly fill with water from precipitation events and move quickly into a stream channel as surface runoff and shallow subsurface flow (Freeze and Cherry 1979; Wels et al. 1991). Because of the smaller infiltration rates and shorter retention time, bedrock dominated RCAs may contribute relatively little groundwater to a stream and therefore streambed temperatures of the receiving reach would be closer to surface water temperature and less thermally variable.

According to the Process Domains Concept (Montgomery 1999), spatial variability in the topological and geological features within a stream catchment may be used to estimate stream conditions and community structure at specific points within the watershed as well as potential response to disturbances. Within my study, I found that the use of topographical features, such as RCA, could effectively estimate the thermal conditions of a stream reach which, were associated with differences in the fish community structure.

The results of my study provide only a single snapshot of the distribution of thermal variability in streambed temperatures. To better understand how thermal variability is affecting stream habitat conditions a long term monitoring of stream temperature would be necessary. Future studies may include sampling a larger set of stream reaches with known fish populations, such as brook trout, along with long-term streambed temperature monitoring to provide a better representation of the relationship between stream fish and streambed temperatures. However, it is difficult to estimate fish presence in the region of this study because there is very little information on fish inventory for the small streams in Northwestern Ontario. GIS provided a good tool to quantify the local topographic features of stream catchments but the inaccuracies in the DEM and the disparity in spatial scales, from a 20 m^2 RCA grid cell to a narrow 50 m stream reach, make precise modeling of RCAs difficult. Increased accuracy in field testing of RCA generation with a GIS would improve the reliability of this tool for future use in the determination of stream thermal conditions.

6.0 CONCLUSIONS

My results demonstrated the heterogeneous spatial distribution of cool groundwater inputs in streams systems using streambed thermal maps. The thermal maps illustrated that variability in streambed temperatures can be measured at stream reach and transect scales as well as between streams within different catchment sizes. Catchment size was an important factor related to thermal variability, the level of thermal variability increased incrementally between the 1, 3, 5, and 10 km^2 stream catchment sizes.

Thermal variability was linked to the structure of the stream fish community; areas of high variability had a more diverse community with more brook trout compared to areas with little variability in temperature during the warm summer months. Rainbow trout were less abundant in regions with high thermal variability which was unexpected because they are considered to be cold water species. However, rainbow trout presence was also negatively related to brook trout presence possibly due to factors such as: thermal preferences, foraging opportunities, habitat preference, behavioural tradeoffs or competition. Thermal variability can provide optimal thermal conditions for a diversity of fish species as well as refuge for species with low thermal tolerance. Stream reaches with high thermal variability tended to have a large amount of adjacent reach contributing area (RCA) as well as a channel structure that permits groundwater flow through the streambed.

Contrary to my hypothesis, the relationship between thermal variability and RCA was present in 5 and 10 km^2 catchment size stream reaches but was absent in the 1 and 3 km^2 catchment size stream reaches. Stream reaches within the 1 and 3 km^2 catchment size had only small variations in streambed temperatures because base flow was sustained by groundwater inputs which maintained cooler surface water temperatures. The cool surface water made areas of lateral inputs difficult to identify using temperatures so there was little thermal variability despite the size of the RCA. Although the thermal variability was small in the 1 and 3 km^2 catchment size classes, it was higher in reaches that had rougher surface terrain and less bedrock geology in the contributing catchment areas compared to reaches with smoother bedrock dominated catchments.

The results from this study are a preliminary indication that RCAs can be used to estimate thermally sensitive areas in stream systems. RCAs may be an important feature to consider during land use practices to protect the groundwater pathways contributing to thermally important areas from disturbances such as road construction and forest harvesting. Further research is needed to examine the accuracy of RCA as a predictive tool for locating groundwater discharge flowing into streams. Sampling a larger set of stream reaches of varying catchment sizes would assist in increasing the predictability power of RCAs. Furthermore, more research needs to be considered looking at the effect of landscape disturbance on the quality and quantity of cool lateral inputs into a stream and how this may influence the structure of the stream fish community.

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APPENDICES

Appendix I - Detailed information on thermal map construction

1. GPS points were collected with a Trimble ProXRS and ArcPad every 2 m along the centreline of the channel for the entire length of the reach. All points were post-processed for differential correction. These points marked the locations where five stream bed temperatures would be collected across the wetted width of the channel.
2. UTM coordinates were calculated for the GPS point shapefile in ArcMap.
3. A line layer was generated from the GPS coordinates to produce a series of connected arcs, each approximately 2 m long, along the centreline of the channel
4. The upstream azimuth of each 2 m line segment was determined with an extension for ArcGIS called "Tools for Graphics and Shapes" (J. Jenness, version 1.185, downloaded directly from Jenness Enterprises at: http://www.jennessent.com/arcgis/shapes_graphics.htm.
5. Using Microsoft Excel, the bisecting angle between two adjacent 2 m centerline segments was calculated to determine the azimuth of the cross-channel transect located at each node (GPS point) along the centreline.
6. Microsoft Excel was used to calculate the coordinates for the from- and to-nodes, representing the left and right banks respectively, for each transect using the cross-channel transect azimuths determined in step 6, the centreline node UTM coordinates, and channel widths measured in the field. These coordinates were then used to generate a point layer representing the left and right bank for each cross-channel transect.
7. Using ArcGIS an empty polygon layer was created. The empty polygon was digitized on-screen along the left and right bank points for each cross-channel transect to define the two-dimensional extent of the surveyed channel. The lower and upper most cross-channel transects closed the polygon. If a road crossed the surveyed reach the polygon was broken, and a multi-part polygon was created.
8. Microsoft Excel was used to calculate point coordinates for the five locations along each cross-channel transect where streambed temperatures were collected in the field. During the field survey the temperature survey points were located along each cross-channel transect at 12.5, 25.0, 50.0, 75.0, and 87.5 % of the channel width, with the 50 % points coincident with the GPS-located channel centreline points. Temperature point locations were calculated from the UTM coordinates of the 50 % points, the field measured wetted widths, and the cross-channel azimuths determined with the GIS. A point layer was generated in the GIS to represent the locations where streambed temperatures were measured and recorded in the field.
9. Using a common join-field preset the streambed temperature data (contained in a *.dbf file) and the streambed temperature point layer were joined.
10. A raster, with a resolution of 0.2 m, representing the distribution of streambed temperatures within the two-dimensional extent of the surveyed reach was interpolated using the spline algorithm available through the Spatial Analyst extension for ArcGIS. The polygon representing the extent of the surveyed stream

reach was used as an analysis mask to limit the interpolation to the boundary of the surveyed portion of the stream.

11. The streambed temperature raster data was symbolized stretched blue to red colour ramp representing colder to warmer temperatures, respectively.

Appendix II - Detailed information on RCA delineation

1. GIS data contained within Ontario's Natural Resources Values Information System (NRVIS) dataset (Ontario Ministry of Natural Resources (OMNR) 2008) were used as inputs to generate Reach Contributing Areas (RCAs). Specific datasets used included: Provincial Digital Elevation Model (version 2, 20 m resolution) (DEM), stream lines (NRVIS Waterline shapefile), lake and wetland polygons (NRVIS Waterpoly shapefile), and road lines (NRVIS Roadseg shapefile).
2. Model builder for ArcGIS 9.2 and Python 2.4 were used to develop a processing model for generating the RCAs (ESRI, version 9.2) and PythonWin (version 2.4).
3. The NRVIS Waterline and Roadseg data are generalized representations of the on-the-ground features they represent. A Trimble ProXRS sub-metre GPS unit was used to capture a more precise level of detail on the pathways of stream reaches surveyed for this study. GPS point data were collected approximately every 2 m along the centreline of the wetted stream channel for the length of each study reach. GPS data were post-processed for differential correction using the Ontario Ministry of Natural Resources' community base station, located at Lakehead University in Thunder Bay, Ontario. These data were used to generate a directionally correct stream line shapefile for each study reach. Newer roads not present in the Roadseg shapefile were GPS located and added to the base NRVIS dataset.
4. The new detailed stream lines and Waterpoly shapefiles and DEM were used as inputs to generate an enhanced flow direction grid (called efdir1), as per the method described by Kenny & Matthews (2005).
5. To account for the influence that roads have on surface runoff, DEM grid cells coincident with these features were raised by 5 m, except at locations where culverts were known to exist. Doing this effectively forced surface runoff intercepted along the uphill sides of roads to be directed downhill, alongside the roads, as flow in roadside ditches would be directed. The surface runoff could then effectively flow to the other side of the road through the culverts where the 5 m was not added to the DEM. This new DEM was called DEM_rd.
6. The fill tool available through the Spatial Analyst extension for ArcGIS was used to fill sinks in the DEM_rd grid and generate a sink-free DEM called Fill1_rd.
7. The flow direction tool available through the Spatial Analyst extension for ArcGIS was used to generate a new flow direction grid from the Fill1_rd grid. This new grid was called Fdir1_rd.
8. The road centreline was buffered on both sides and ends by a distance of 20 m (equal to the width of one grid cell) to create a poly shapefile called Roadbuff_20.shp.
9. Culverts points were buffered by 30 m to create a poly shapefile called Culvbuff_30.shp.
10. The Roadbuff_20.shp poly was erased with the Culvbuff_30.shp poly to create a new poly shapefile called Rd_msk.shp.
11. The Rd_msk.shp polygon was set as a mask for the Spatial Analyst extension, then the Fdir1_rd raster was merged over the enhanced flow direction grid (efdir1) to derive the final flow direction grid, called efdir1_rd.

12. Pour points were created from the detailed stream centreline by first using the "Polyline to Raster" tool to convert the stream centreline to a grid called Str_ctrl (Spatial Analyst cell size and analysis window set to match those of the Fill1_rd grid, with no mask). Next, the "Raster to Point" tool was used to convert the Str_ctrl grid to a point shapefile called RCA_pours. An extra point was created upstream of the stream centreline to stop longitudinal flow from entering the stream centreline where only lateral inputs were of interest.
13. The watershed tool available from Spatial Analyst extension for ArcGIS was used to delineate RCAs for each point in the RCA_pours shapefile using the flow direction grid, efdir1_rd.
14. RCA area (m^2) was calculated in a new attribute field using the field calculator. Using a common join-field preset the RCA data (contained in a *.dbf file) was joined to the RCA_pours shapefile to allow for zonal statistics to be completed on stream reaches.

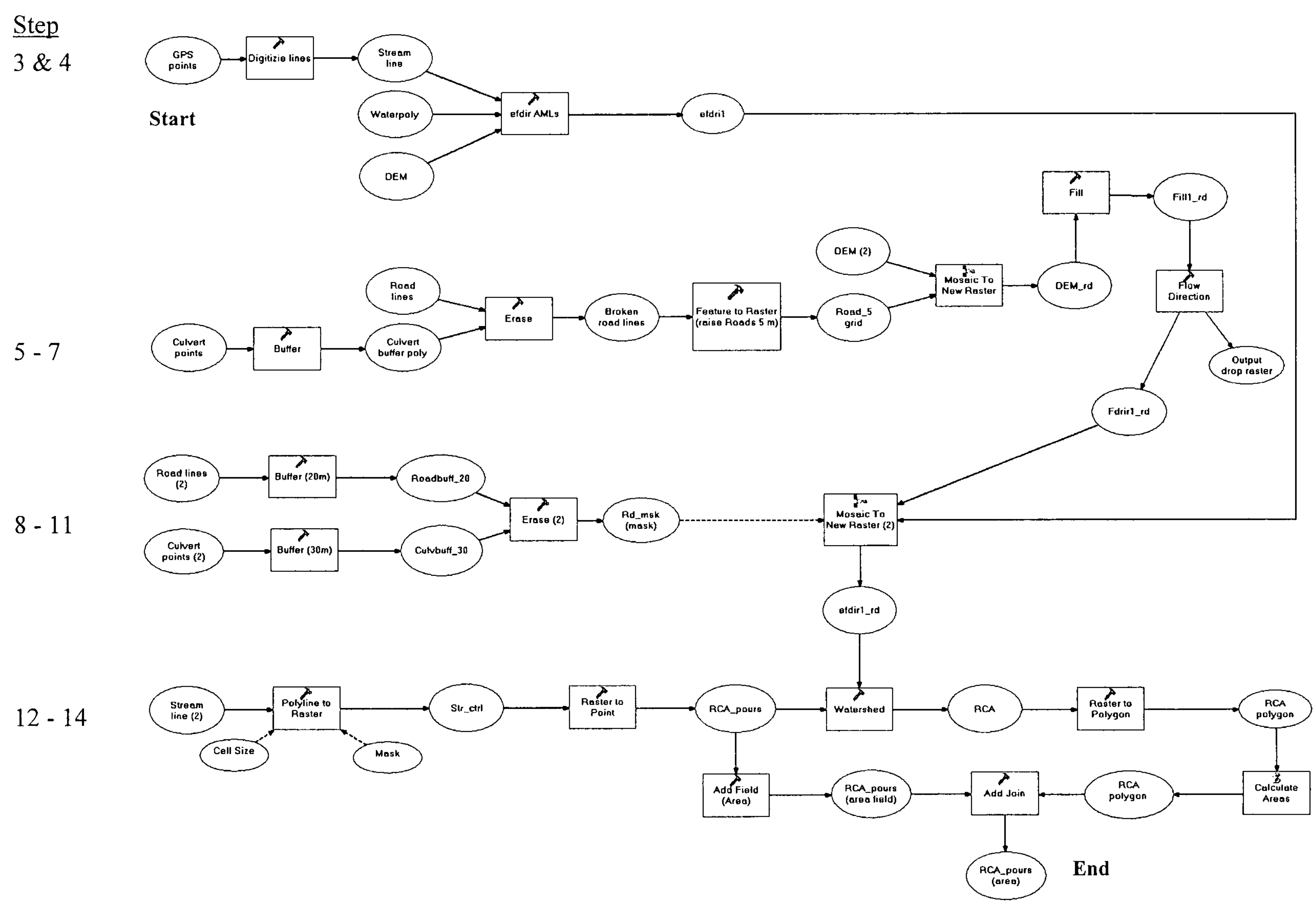

Figure. Model schematic for the delineation of RCA. The numbers in the left column indicate the steps evolved from the summary.

Appendix III – Streambed thermal maps for 1 km^2 catchment streams.

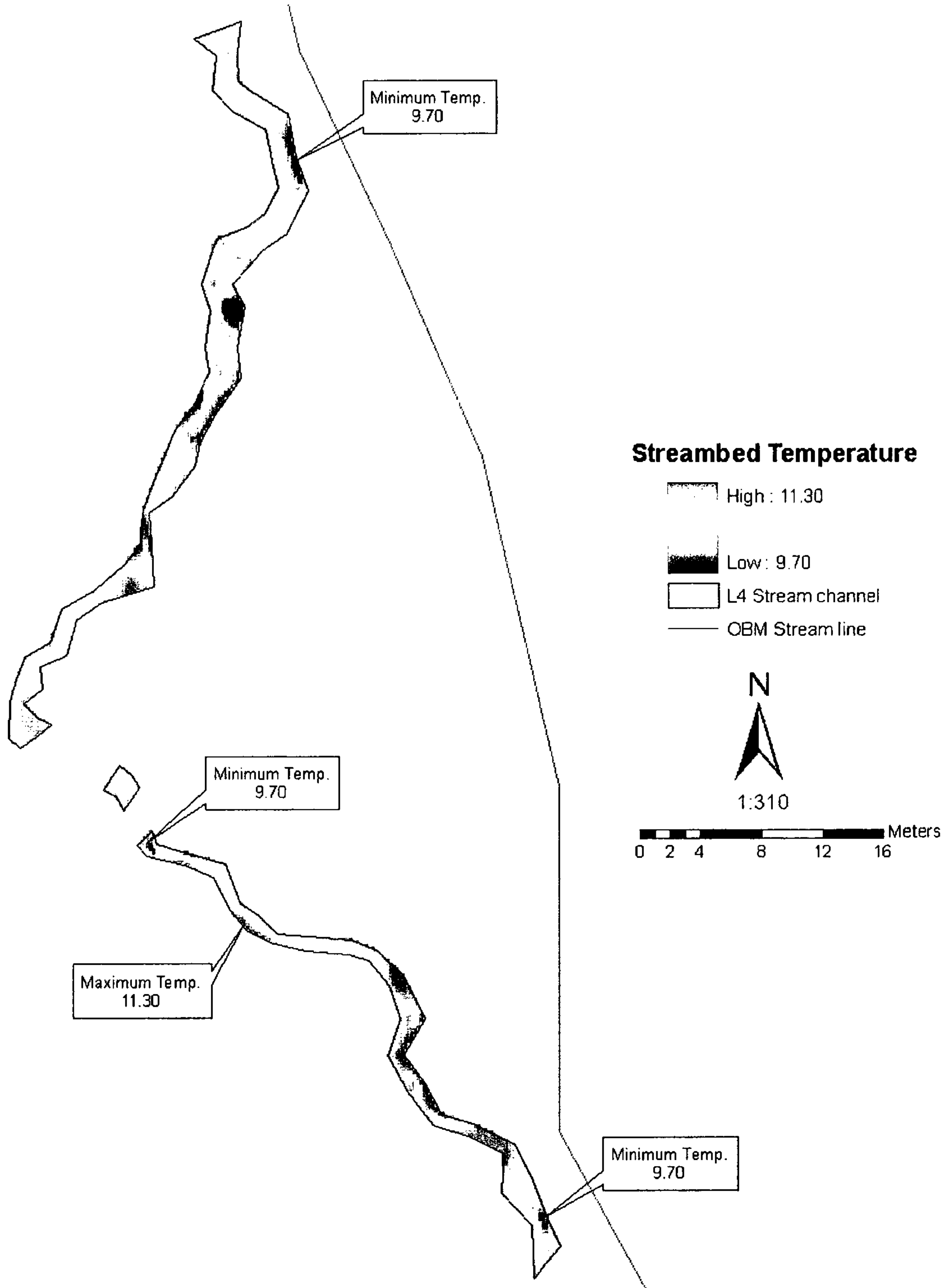

Figure 1. Thermal map for site L4 demonstrating the spatial distribution in streambed temperatures. The minimum and maximum streambed temperatures recorded are noted.

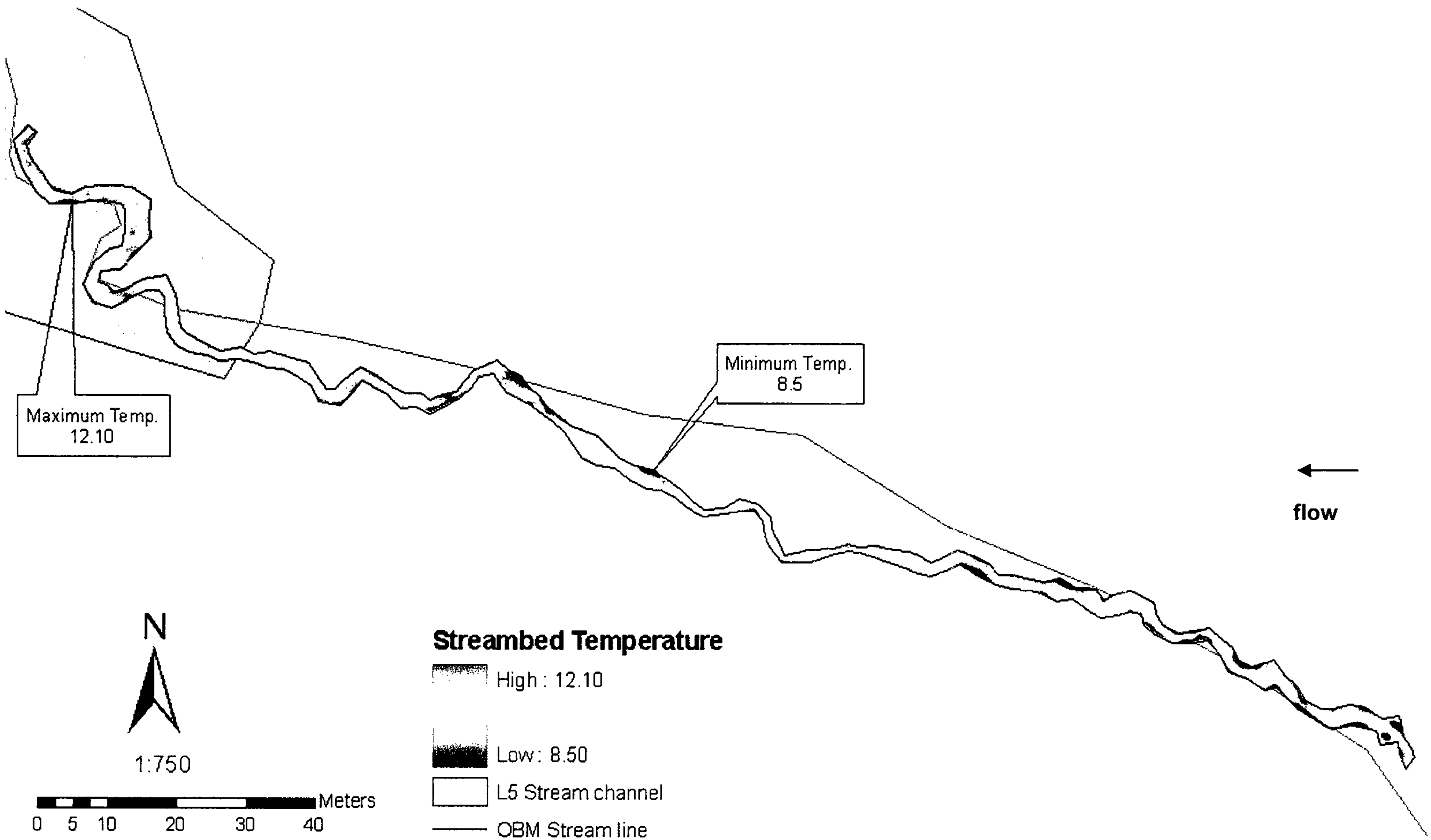

Figure 2. Thermal map for site L5 demonstrating the spatial distribution in streambed temperatures. The minimum and maximum streambed temperatures recorded are noted.

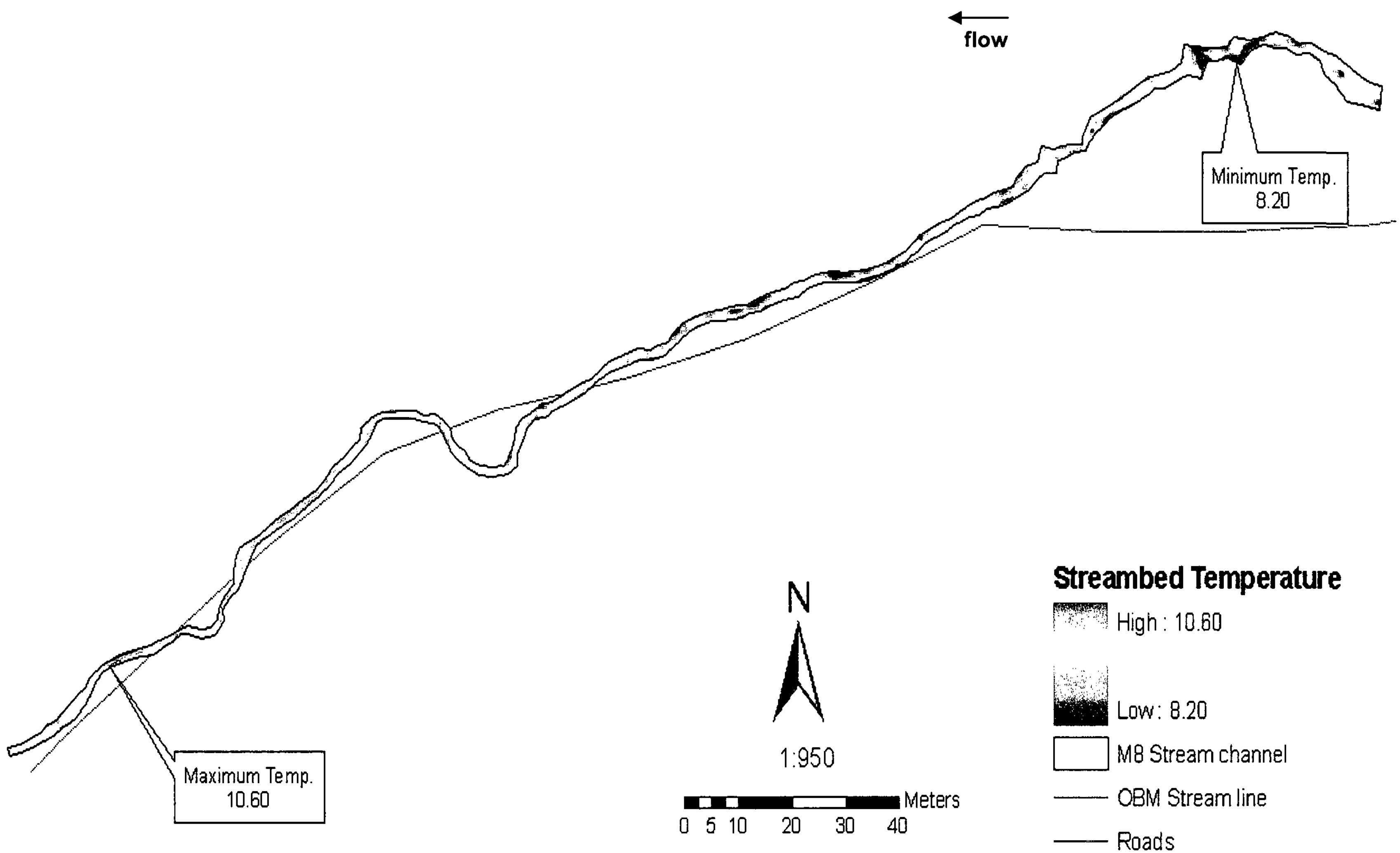

Figure 3. Thermal map for site M8 demonstrating the spatial distribution in streambed temperatures. The minimum and maximum streambed temperatures recorded are noted.

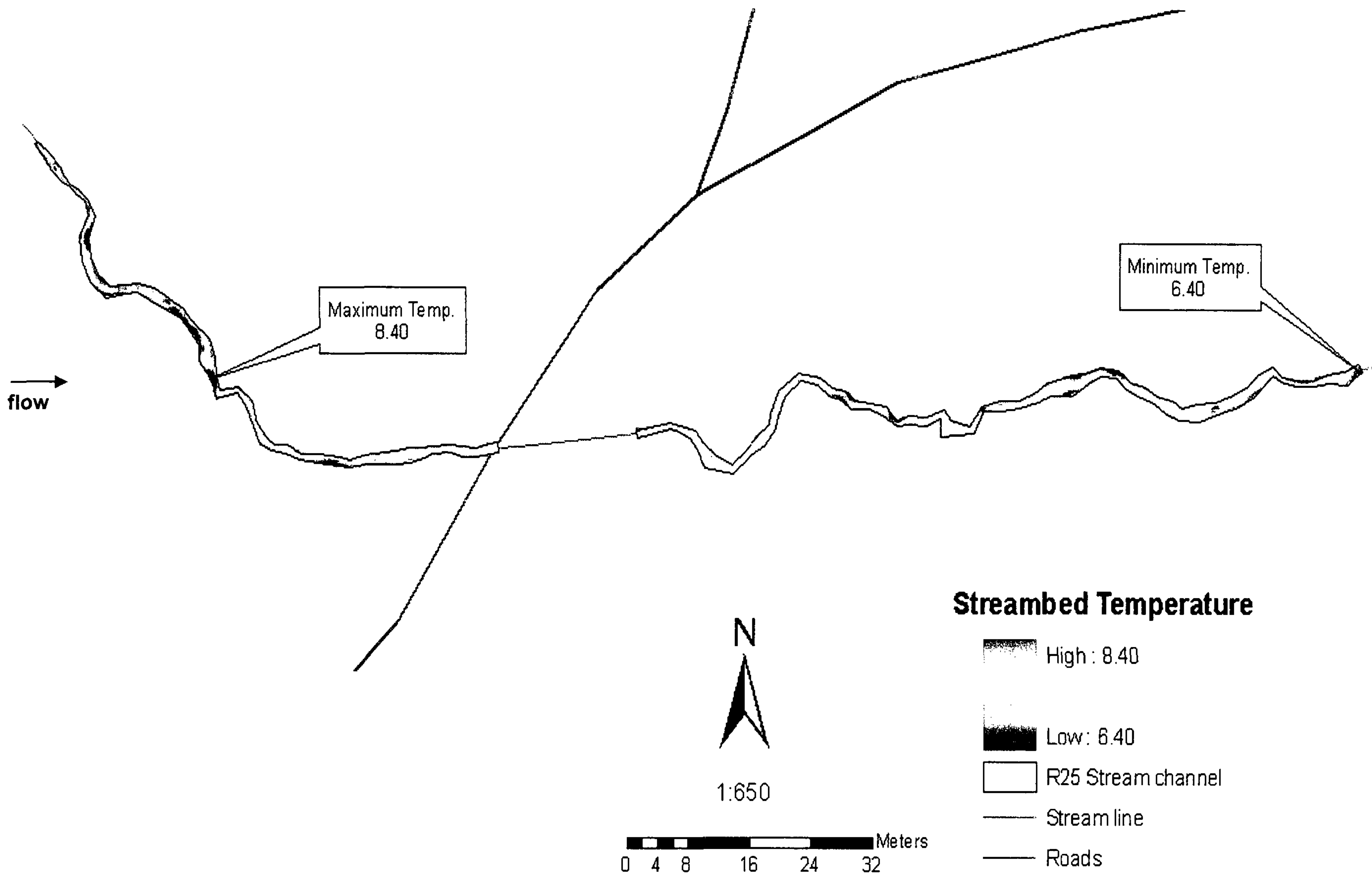

Figure 4. Thermal map for site R25 demonstrating the spatial distribution in streambed temperatures. The minimum and maximum streambed temperatures recorded are noted.

Appendix IV – Streambed thermal maps for 3, 5, 10 km^2 catchment streams.

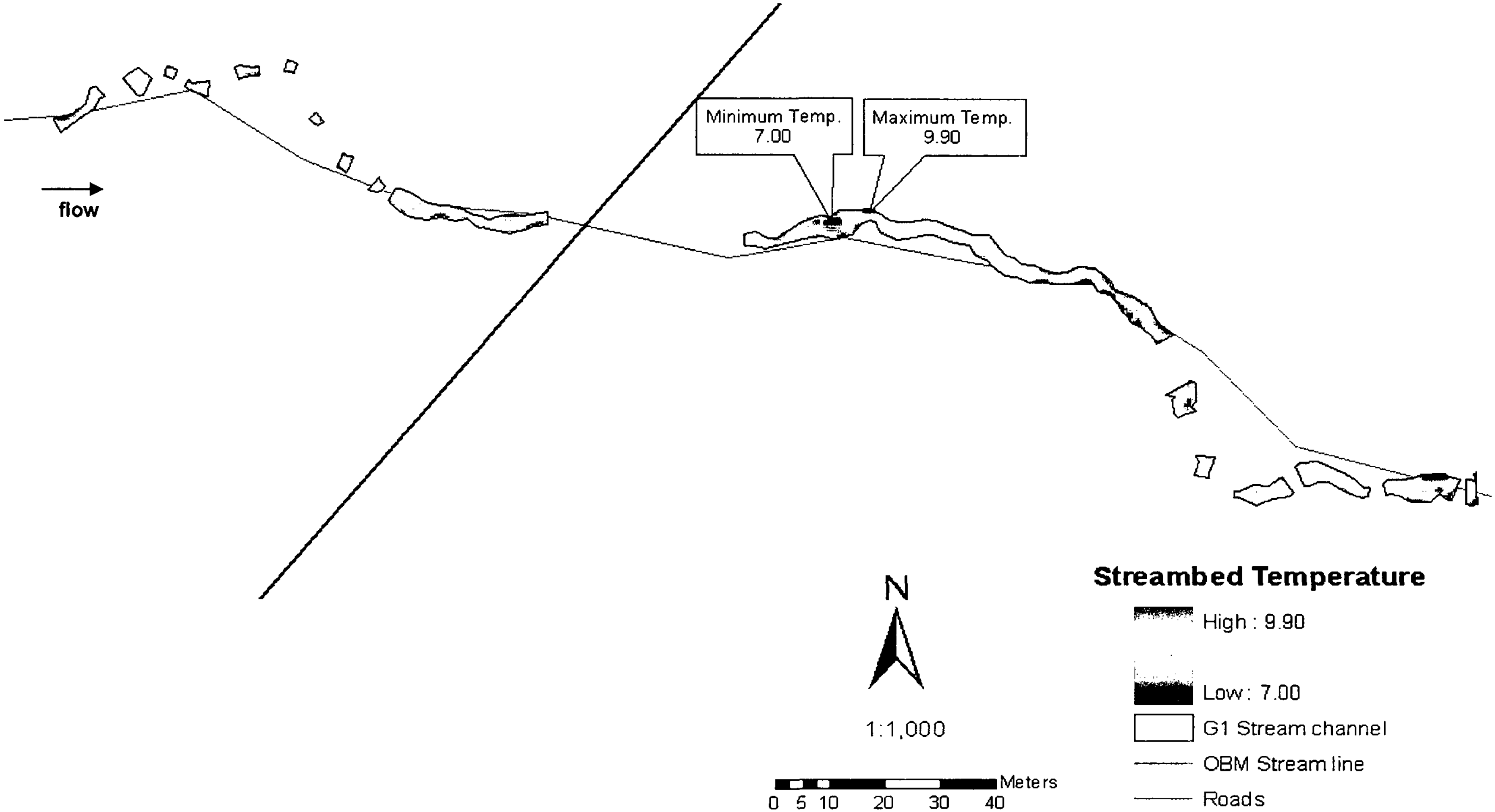

Figure 1. Thermal map for site G1 demonstrating the spatial distribution in streambed temperatures. The minimum and maximum streambed temperatures recorded are noted. The small gaps between the stream polygons indicate dry regions of the stream where there was no stream flow or subsurface flow only.

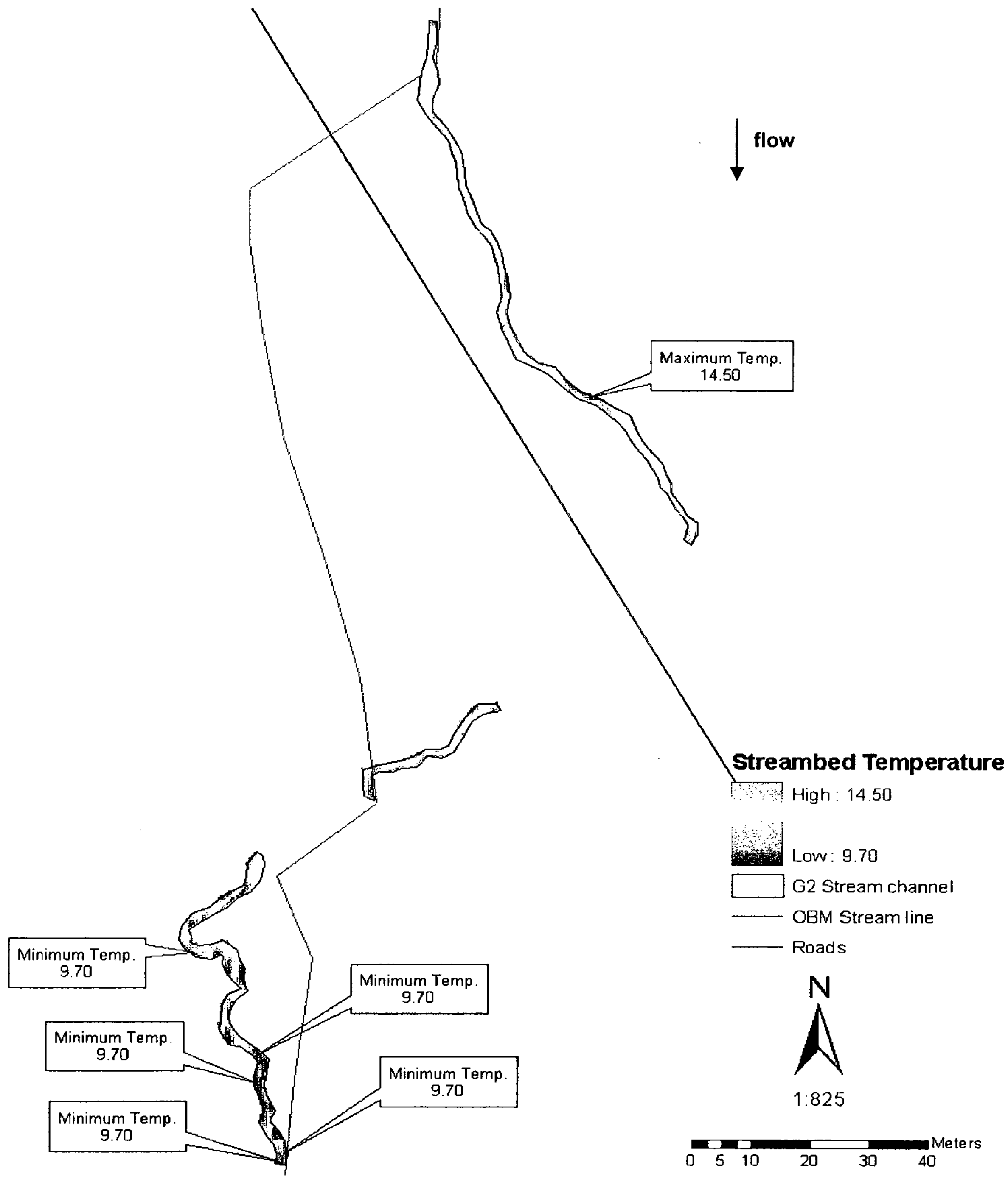

Figure 2. Thermal map for site G2 demonstrating the spatial distribution in streambed temperatures. The minimum and maximum streambed temperatures recorded are noted

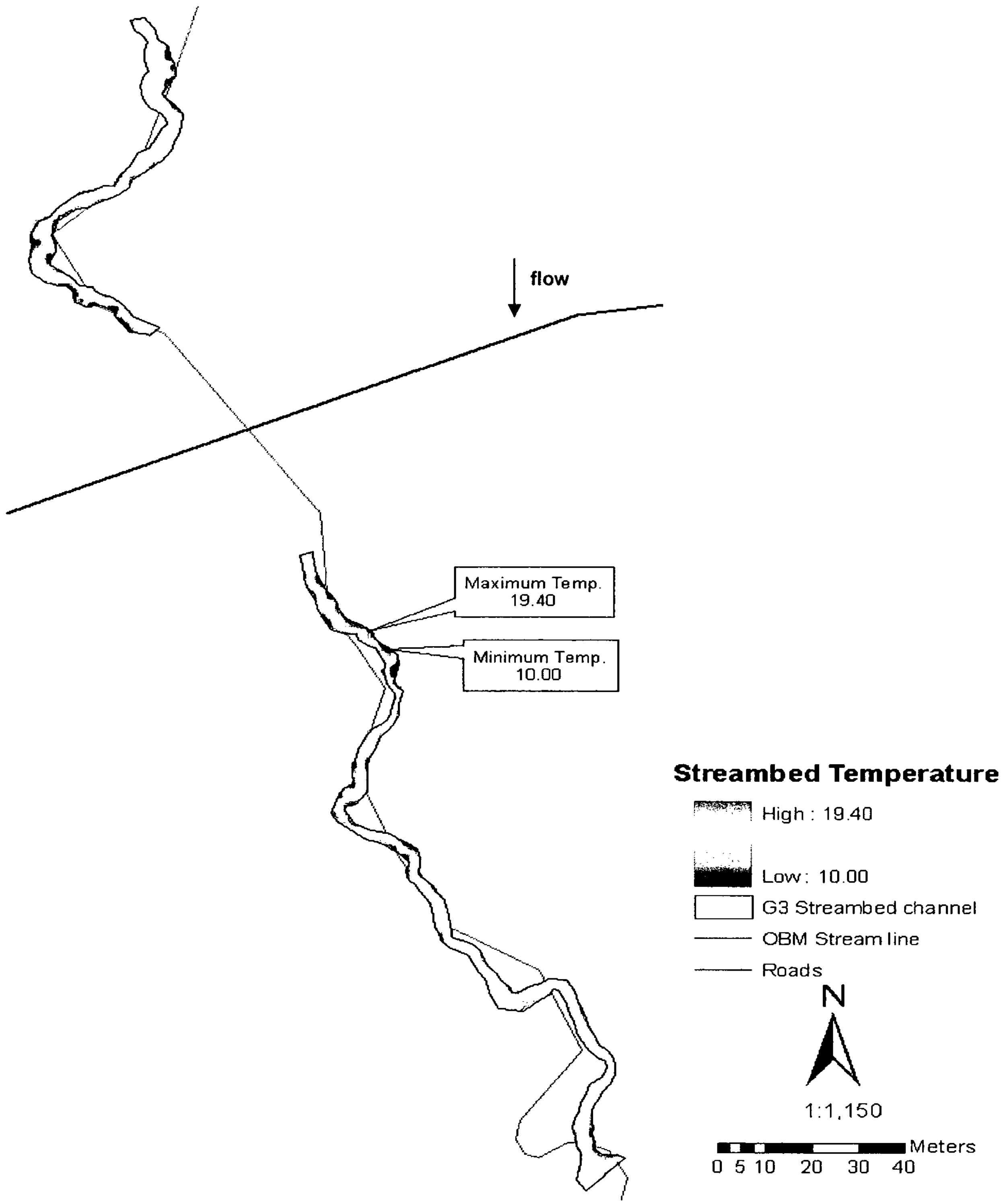

Figure 3. Thermal map for site G3 demonstrating the spatial distribution in streambed temperatures. The minimum and maximum streambed temperatures recorded are noted.

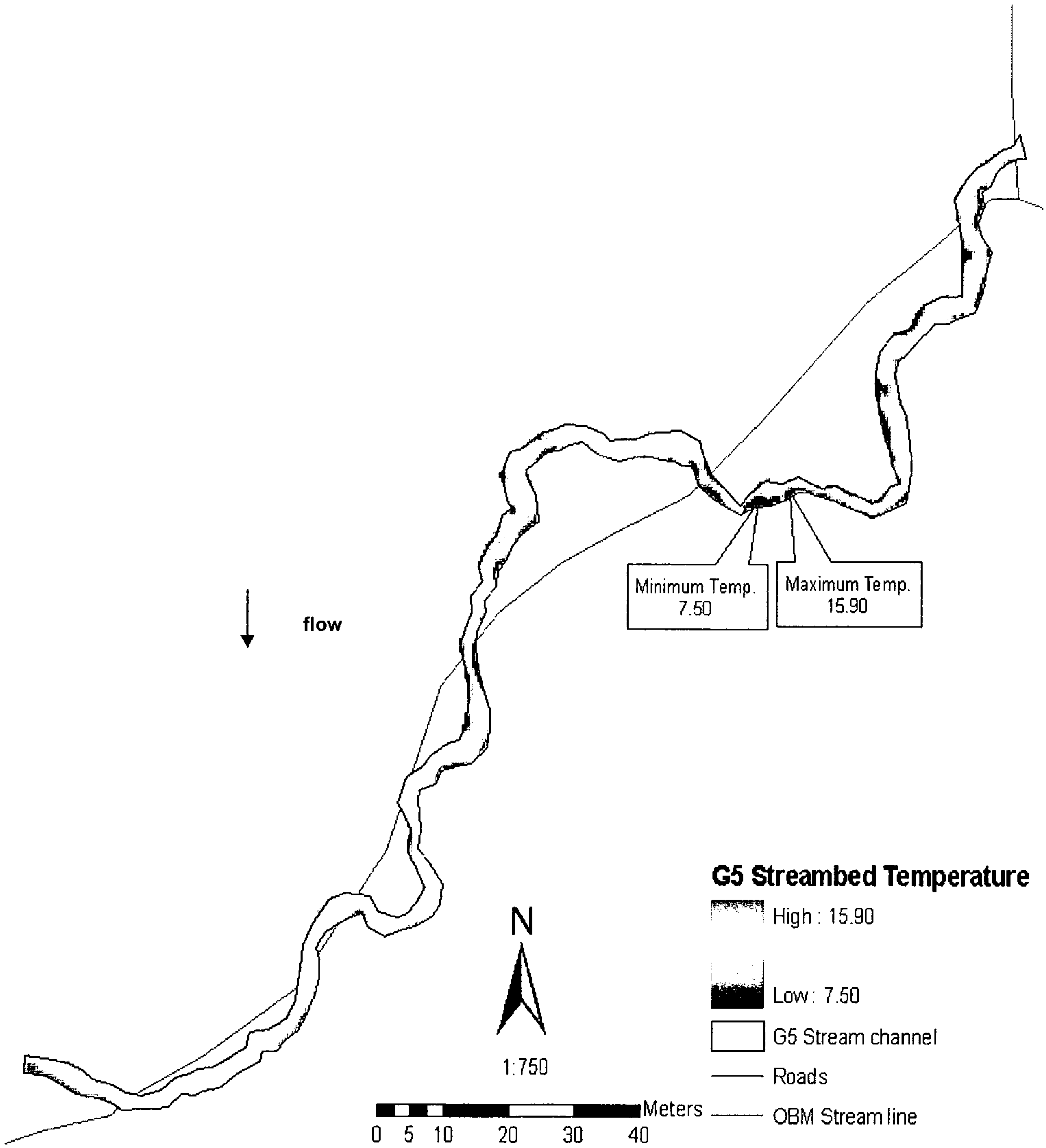

Figure 4. Thermal map for site G5 demonstrating the spatial distribution in streambed temperatures. The minimum and maximum streambed temperatures recorded are noted.

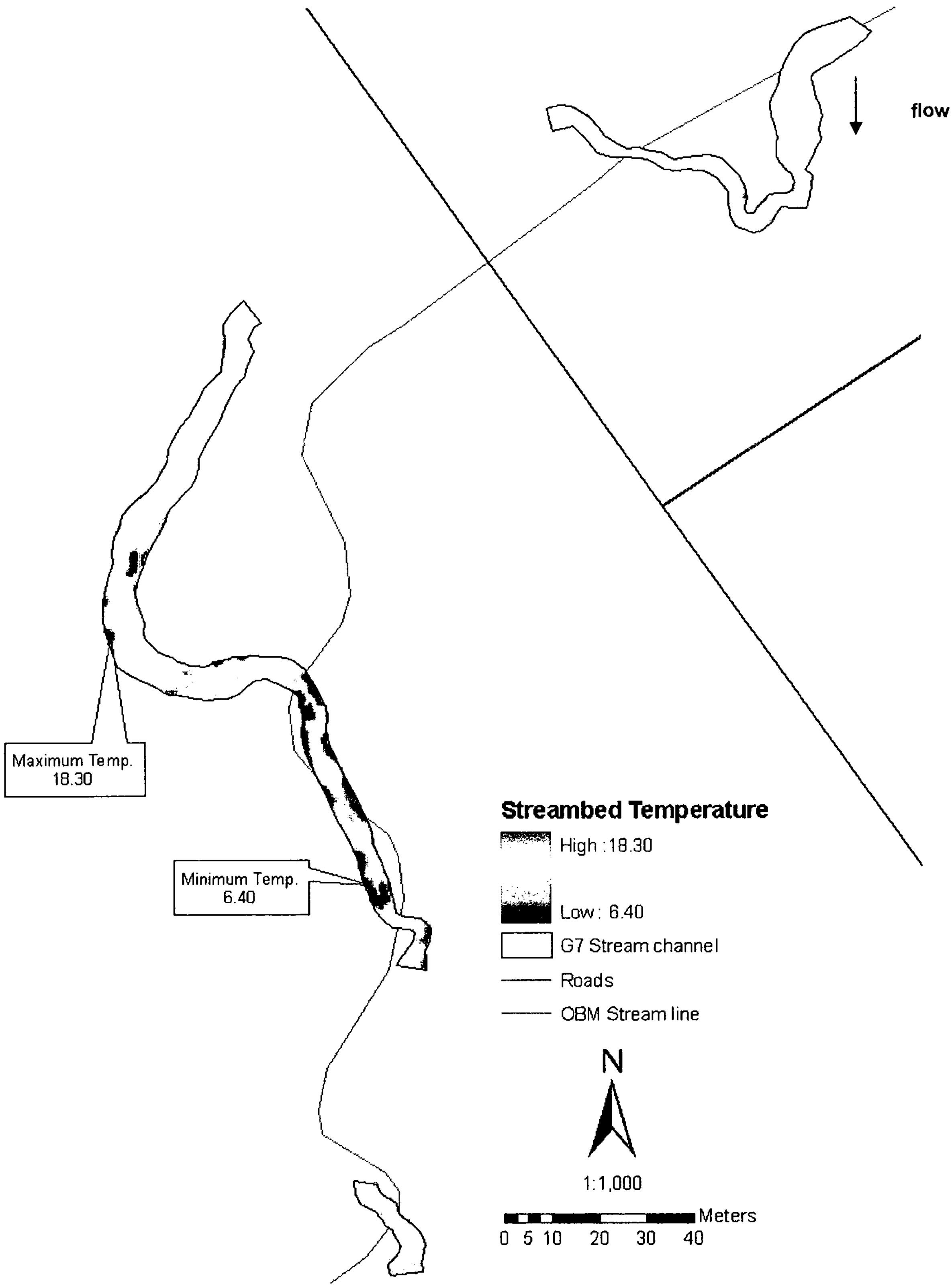

Figure 5. Thermal map for site G7 demonstrating the spatial distribution in streambed temperatures. The minimum and maximum streambed temperatures recorded are noted.

Appendix V – Correlation matrix for environmental variables.

		Stream depth	Stream wetted width	Average bank height	Impervious streambed (%)	Fine streambed (%)	Porous streambed (%)	Stream canopy closure	Stream slope	Riparain width	Riparian canopy closure	Riparain slope	Riparain soil depth	RCA($log_{(10)}$)	CV	Landscape slope
Stream wetted width	r	.047														
	p	.735														
Average bank height	r	-.384**	-.104													
	p	.004	.452													
Impervious streambed (%)	r	.051	.172	.205												
	p	.714	.210	.133												
Fine streambed (%)	r	.359**	-.252	-.066	-.312*											
	p	.007	.064	.631	.021											
Porous streambed (%)	r	-.331*	.047	-.133	-.657**	-.511**										
	p	.014	.733	.333	.000	.000										
Stream canopy closure	r	.053	.139	.366**	.182	-.089	-.093									
	p	.703	.311	.006	.184	.517	.499									
Stream slope	r	-.503**	-.251	.651**	.382*	-.408*	-.174	.284								
	p	.003	.165	.000	.031	.020	.341	.115								
Riparain width	r	.313*	-.189	-.310*	-.132	.532**	-.303*	-.046	-.243							
	p	.020	.167	.021	.337	.000	.024	.738	.181							
Riparian canopy closure	r	.053	.129	.102	.261	-.072	-.180	.695**	-.131	.216						
	p	.699	.346	.457	.055	.604	.188	.000	.474	.114						
Riparian slope	r	-.231	-.134	.655**	.075	-.020	-.051	.144	.451**	-.408**	-.160					
	p	.089	.330	.000	.589	.886	.709	.293	.010	.002	.243					
Riparain soil depth	r	.293*	-.164	-.228	-.281*	.347**	-.023	.280*	-.457**	.572**	.404**	-.391**				
	p	.030	.233	.095	.038	.009	.870	.038	.009	.000	.002	.003				
RCA($log_{(10)}$)	r	.113	-.029	-.046	-.276*	.231	.066	-.117	-.035	.009	-.038	-.137	.041			
	p	.412	.835	.737	.041	.090	.632	.393	.848	.948	.785	.319	.767			
CV	r	-.164	.053	.091	-.216	.044	.160	-.273*	.109	-.104	-.221	-.077	.135	.393**		
	p	.231	.702	.511	.113	.749	.244	.044	.553	.451	.106	.577	.325	.003		
Landscape slope	r	-.289*	.097	.187	-.094	-.175	.223	-.357**	.838**	-.153	-.425**	.163	-.175	-.084	.688**	
	p	.033	.479	.171	.495	.202	.101	.007	.000	.264	.001	.235	.200	.544	.000	
RCA bedrock (%)	r	.415**	-.314*	-.396**	-.139	.317*	-.127	-.303*	-.222	.177	-.176	-.201	.044	.235	-.101	-.175
	p	.002	.020	.003	.312	.018	.356	.024	.222	.196	.198	.142	.752	.084	.465	.200

Note: r = Pearson correlation product; p = significance level, ** = correlation is significant at 0.01 level, * = correlation is significant at 0.05