Temporal variation of stream and intragravel water temperatures in an Atlantic salmon (Salmo salar) spawning area in Catamaran Brook (New Brunswick)

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2003

Canadian Technical Report of Fisheries and Aquatic Sciences 2464

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Fisheries and Aquatic Sciences 2464

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Cat. No. Fs. 97-6/2464E ISSN 0706-6457

Correct citation for this publication:

Caissie, D. and D.J. Giberson. 2003. Temporal variation of stream and intragravel water temperatures in an Atlantic salmon (Salmo salar) spawning area in Catamaran Brook (New Brunswick). Can. Tech. Rep. Fish. Aquat. Sci. 2464: 26p.

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ABSTRACT

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Surface and intragravel water temperatures were measured in a previously used spawning area of a New Brunswick salmon stream. Temporal variations (monthly, daily and hourly) were investigated in both surface and intragravel temperatures from 1995 to 1998. Hourly intragravel water temperatures were also modelled during a specific period in the summer of 1996, where both surface and intragravel temperatures showed significant diurnal variations.

Surface water temperature showed greater temporal variation than intragravel water temperature. Surface water temperatures were warmer in summer and cooler in winter than intragravel temperatures with cross-over periods in spring and fall. Mean monthly intragravel water temperatures were generally 1.0 to 1.1°C warmer in winter than surface water temperatures. In contrast, surface water temperatures in summer were warmer than intragravel temperature by as much as 2.0°C (August 1996). Further, when the surface water temperatures dropped below 1.5 °C in late autumn, intragravel temperature became stable at close to 1.0 °C and remained stable during the winter until surface water temperatures exceeded 2.0 °C in the spring. Although intragravel temperatures were stable throughout the winter, high flow events resulting from a mid-winter thaw depressed intragravel water temperatures for several days. The present study clearly demonstrated that temporal differences between surface water and the intragravel thermal regime are important to consider when studying aquatic biota that spend at least part of their life cycle within the substrate. This study also showed that a one-dimension diffusion model can effectively model intragravel water temperature for different depths within the substrate.

RÉSUMÉ

Caissie, D. and D.J. Giberson. 2003. Temporal variation of stream and intragavel water temperatures in an Atlantic salmon (Salmo salar) spawning area in Catamaran Brook (New Brunswick). Can. Tech. Rep. Fish. Aquat. Sci. 2464: 26p.

La température de l'eau en surface (rivière) et la température de l'eau dans le substrat ont été mesurées dans une zone de frai au Nouveau-Brunswick. Les variations temporelles (mensuel, journalier et horaire) de température ont été observées dans le substrat et dans l'eau de surface de 1995 à 1998. La température de l'eau horaire a également été modélisée durant une période de l'été 1996, période démontrant une variation diurne importante dans la température de l'eau en surface et dans le substrat.

La température de l'eau en surface démontra une plus grande variation temporelle que celle de la température dans le substrat. La température de l'eau en surface était plus chaude en été et plus froide en hiver que la température de l'eau dans le substrat avec une période de transition au printemps et en automne. La température moyenne mensuelle à l'intérieur du substrat était généralement 1.0 à 1.1°C plus chaude en hiver que la température de l'eau en surface. D'autre part, la température de l'eau en surface en été était plus chaude que la température de l'eau à l'intérieur du substrat jusqu'à 2.0 °C (août 1996). De plus, lorsque la température de l'eau en surface devint inférieur à 1.5 °C en automne, la température de l'eau dans le substrat devint très stable autour de 1.0 °C et demeure stable durant toute la période hivernale jusqu'au printemps suivant lorsque la température en surface dépasse 2.0 °C. Même que la température de l'eau dans le substrat est très stable en hiver, les débits de crues provenant de fonte hivernale peuvent réduire la température de l'eau dans le substrat de façon provisoire sur plusieurs jours. La présente étude démontre clairement que les variations temporelles de température de l'eau en surface et celle à l'intérieur du substrat démontrent un régime thermique différent qui doit être considéré dans les études de ressources halieutiques qui passent une partie de leur cycle de vie dans le substrat. Cette étude démontra qu'un modèle unidimensionnel de diffusion de la température peut être utilisé pour modéliser la température de l'eau dans le substrat à différentes profondeurs.

1.0 Introduction

Stream and intragravel water temperatures are critical parameters in the ecology of streams and rivers. Temperature can influence both chemical and biological processes in streams. For instance, water temperatures can effect metabolic pathways of biota (Liu *et al*. 1995, Drake and Taylor 1996, Magoulick and Wilzbach 1997, Chauvet and Suberkropp 1998). Water temperature affects the developmental timing of stream biota through its effects on metabolic rates. The relationship between aquatic insect development and temperature is well documented, although food quality and photoperiod also play a role (Sweeney 1984). Water temperature is also directly related to the timing of hatching of salmonid eggs, and the emergence of larval fish (Alderdice and Velsen 1978, Bilby 1984, Johnston 1997). Further, stream invertebrates and fish may be found in a variety of habitats within a stream, including deep within the hyporheic zone, depending upon their life history stage and dispersal strategy (Giberson and Hall 1988, Garcia de Leaniz *et al*. 1993, Boulton *et al*. 1998). However, measured surface water temperature patterns in most studies may not accurately document the thermal environment experienced by biota in the substrate.

Although surface water temperatures are often monitored in streams, few studies have monitored and modelled temperature patterns within the stream bed, or hyporheic zone. The hyporheic zone represents a dynamic transition zone between surface water and groundwater, with the proportion of groundwater influence increasing with depth into the sediment and varying depending upon whether the zone is an upwelling or downwelling section of the stream (Boulton *et al*. 1998). Stream discharge is also important in the exchange between stream water and the hyporheic zone (Constantz 1998). Stream surface water temperatures reflect environmental conditions and vary diurnally and seasonally. In contrast, groundwaters are highly stable (Boulton *et al*. 1998, Constantz 1998). The interchange of surface water to groundwater within the hyporheic zone is dependant on many factors, including streambed elevation, substrate type and porosity (Vaux 1968, Thibodeaux and Boyle 1987). Devices that are used to study the interaction between stream water and hyporheic water conditions include mini-peizometers, seepage meters and dye injection techniques (Lee 1977, Lee and Cherry 1978, Boulton 1993).

Large differences may occur between surface and intragravel conditions, depending on season and locality (Hartman and Leahy 1983, Shepherd *et al*. 1986, Irons *et al*. 1989, Hendricks and White 1991). For example, Hartman and Leahy (1983) found that intragravel temperatures (30 cm depth) in Carnation Creek (B.C.) could reach 5.7 °C higher than surface waters in winter and 3.7 °C cooler in summer. Williams and Hynes (1974) found temperatures at 20 cm depth to be 0.5 - 1.0 °C warmer than surface waters in winter and 3.0-4.0°C cooler than surface waters in summer in the Speed River, Ontario. Hendricks and White (1991) showed that intragravel temperature patterns remained constant in a Michigan river from season to season and year to year, but that they may vary within a stream site. Temperatures at the downwell zone (e.g. the head of a riffle, where salmon redds would normally be present) showed conditions that were more similar to surface water, compared to an upwelling zone further downstream (White *et al*. 1987, Hendricks and White 1991), and intragravel temperatures were colder in mid-stream than near the stream edges (White *et al*. 1987). Temperature patterns may also be used to identify groundwater discharge zones and seasonal or diurnal sources of surface streamwater (Hartman and Leahy 1983, Shepherd *et al*. 1986, Constantz 1998). Lapham (1989) showed that intragravel water temperatures can be modelled using a diffusion model linking surface and intragravel temperatures.

Although many researchers have studied the biota and the physical and chemical conditions of intragravel waters in streams, little is known about temporal variations of intragravel temperature, or how they relate to surface temperatures over a number of seasons and years. Also, few studies have modelled intragravel water temperatures within the stream substrate using hourly data. The objective of the present study was to characterize the stream and intragravel water temperatures within an Atlantic salmon (Salmo salar) spawning area of Catamaran Brook, NB, over a 3-yr period (1996-98). Also a one-dimensional diffusion model was used to determine how well temporal patterns in intragravel water temperatures can be modelled.

2.0 Materials and Methods

2.1 Study area

This study was conducted in Catamaran Brook (46° 52.7' N, 66° 06.0' W), a small stream catchment (51 km^2) in the Miramichi River system of New Brunswick (Fig. 1). Catamaran Brook is the site of a 15-yr multidisciplinary hydrobiological research study aimed at quantifying stream ecosystem processes and the impact of timber harvest (Cunjak *et al*. 1990). The present forest cover is mainly second-growth forest, consisting of mostly mature species estimated as 65% coniferous and 35% deciduous (Cunjak *et al*. 1990; St. Hilaire *et al*. 1996). Atlantic salmon (Salmo salar) is the most common fish species in Catamaran Brook, and anadromous adults enter the brook to spawn in late October and early November. Brook trout (Salvelinus fontinalis) are common in the headwater portions of the basin and in Catamaran Lake (Cunjak *et al*. 1993).

Stream water chemistry for the Catamaran Brook basin has been monitored since 1990, and is summarized in Komadina-Douthwright *et al*. (1999). Catamaran Brook is approximately circumneutral in pH, with values ranging between 6.6 to 7.8 during the period of record. Specific conductance typically varies between 28 - 80 μS/cm, with a mean value of 53 μS/cm.

Climate data (air temperature, precipitation) have been collected at a meteorological station located at mid-basin (Fig. 1) since 1990. In addition, historical data on air temperatures and precipitation have been collected from the nearby McGraw Brook Department of Natural Resources and Energy (DNRE) meteorological station since 1970, and have been used to determine long-term climatic conditions. The McGraw Brook meteorological station is less than 7 km from Catamaran Brook. Annual precipitation ranges from 860 - 1365 mm, with a long-term average of 1142 mm (Cunjak *et al*. 1993; Caissie and El-Jabi 1995). January has the coldest mean monthly air temperature, with a long-term mean of -11.8°C. July is the warmest month, with a mean monthly air temperature of 18.8°C.

Stream discharge has been monitored continuously at a hydrometric gauging station located at mid-basin (Fig. 1) since October 1989. The mean annual flow for Catamaran Brook has been calculated at 0.69 m^3/s or 754 mm of runoff (Cunjak *et al*. 1993). The highest measured discharge in the period of record was recorded during the spring flood period from late April to early May, 1991, with a peak value of 13 m^3/s on May 3, 1991. The lowest recorded discharge was 0.016 m^3/s, recorded September 3, 1994.

2.2 Monitoring of surface and intragravel water temperatures

Surface temperatures have been recorded since 1990 at a site located approximately 20 m below the hydrometric station at mid-basin (Fig. 1). The stream water temperature sensor was installed at approximately 1 m from the bank near the stream bottom, and records surface water temperatures on an hourly basis. The sensor (Model 107B, from Campbell Scientific Canada

Corp., 1992) incorporates a Fenwal Electronic thermister probe, and has an error less than 0.2°C for the range of -30 to +40 °C. The sensor accuracy was verified against a standard mercury thermometer (1/10 °C), and recorded values within 0.1 °C of actual stream water temperatures. Localised variations in stream water temperatures were monitored by taking measurements with a mercury thermometer at 0.5 m intervals from bank to bank. No variations were observed due to the well mixed nature of Catamaran Brook. The highest stream water temperature on record between 1990 and 1998 was 20.3 °C, measured on July 24, 1994.

The intragravel water temperature sensor was the same type as that used for surface waters. Special attention was required to verify the zero value for the intragravel sensor, since winter temperatures are critical for invertebrates and salmonid eggs, and winter temperatures may approach 0°C. The sensor was submerged into an ice bath prior to installation to determine the near 0°C accuracy, and only a small offset of 0.05°C was required to set the data logger to the zero reading. The sensor was installed in October 1995 at a depth of 20 cm into the substrate and approximately mid-stream in a spawning area (Fig. 1), where Atlantic salmon have been observed spawning in the past. Intragravel water temperatures were monitored through to the end of 1998.

Both sensors were connected to a CR10 Data Logger (Campbell Scientific Canada Corp. 1992) and water temperatures were monitored every second during the last minute of the hour (i.e. from minute 59 to 60) to establish a mean value corresponding to the hourly reading. Due to a malfunction in the data logger, no temperature data were obtained from late November to early December, 1995 and also in January 1997.

2.3 Intragravel water temperature model

The heat exchange between the surface water and intragravel temperatures has been described in the literature by Stallman (1965). The one-dimensional diffusion equation takes the following form:

$$k \frac{\partial^2 T}{\partial z^2} = c\rho \frac{\partial T}{\partial t} \qquad [1]$$

where k = thermal conduction of the rock-fluid matrix (kcal/ hr m^3 °C);

T = temperature in °C at depth with time (hr);

c = heat capacity of the rock-fluid matrix (kcal/m^3 °C);

ρ = density of the rock-fluid matrix (kg/m^3);

z = depth within the substrate (m);

terms in equation [1] can be expressed with the following explicit finite difference approximation:

$$\frac{\partial T}{\partial t} \cong \frac{T_z^{t+1} - T_z^t}{\Delta t} \qquad [2]$$

and

$$\frac{\partial^2 T}{\partial z^2} \cong \frac{T_{z+1}^t - 2T_z^t + T_{z-1}^t}{\Delta z^2} \qquad [3]$$

When equation [2] and [3] are substituted in equation [1], a finite difference model was obtained, which is represented by the following equation:

$$k\left[\frac{T_{z+1}^t - 2\,T_z^t + T_{z-1}^t}{\Delta z^2}\right] = \rho c\left[\frac{T_z^{t+1} - T_z^t}{\Delta t}\right] \qquad [4]$$

after rearranging the above equation by assembling the temperature terms (T) together, the following equation can be obtained to express the temperature (T) with depth (z) at time step $t+1$:

$$T_z^{t+1} = T_z^t + \frac{k\Delta t}{\rho c \Delta z^2}\left[T_{z+1}^t - 2\,T_z^t + T_{z-1}^t\right] \qquad [5]$$

where all parameters were defined previously. Past studies have shown (Stallman 1965) that such explicit scheme is numerically stable (i.e. convergence to a solution) when the coefficient in front of the second term on the right hand side of equation [5] is less than 0.5, i.e.:

$$r = \frac{k\ \Delta t}{\rho c \Delta z^2} \qquad [6]$$

Therefore to assure stability of equation [5], the value of r should be less than 0.5. A computer program was written in BASIC to solve equation [5] for specific substrate conditions and groundwater temperatures. Intragravel temperatures were simulated on an hourly basis for different depths within the stream substrate during the summer of 1996 from day 212 (July 31) to day 245 (September 2). This period was chosen because it covered a wide range of surface water and intragravel temperatures. Simulated data were compared to actual measurements of intragravel water temperatures at a depth of 0.2 m.

3.0 Results

3.1 Daily patterns in water temperature

Both stream and intragravel water temperatures showed little variation during the winter months, but did show some among-year differences (Fig. 2). Surface water temperatures remained near 0°C for most of the winter of 1996 (day 1-91), but were slightly higher in subsequent winters, particularly in 1998. Winter intragravel temperatures were usually higher than recorded at the surface, and were quite stable throughout the study period, although a decline in intragravel temperature occurred during late-January 1996, due to a thaw period (Fig. 2 and Fig. 3a). Following the thaw, intragravel temperatures recovered to pre-event conditions in approximately 10 days.

Spring and summer temperatures in both the stream and the substrate showed greater fluctuations than were observed during the winter. The period of greater fluctuation generally began in April (after day 91) except for 1998, when it occurred earlier. By early May of each year, surface and substrate temperatures were almost identical (Fig. 2), and remained similar until the end of May (day 151). By June, the mean daily stream water temperatures were higher than daily intragravel temperatures, and this lasted to mid-September (day 260). Daily mean water temperatures were similar in the two zones until late November, when intragravel temperatures again became higher than stream water temperatures.

In Catamaran Brook, mean daily surface water temperatures exceeding 15°C were recorded between early July to late August, with most of these high temperature events occurring in 1996 (Fig. 2). Alternatively, mean daily intragravel temperatures reached 15°C on only a few occasions between 1996 and 1998. One such event occurred in 1996 on August 08 (day 221), while two such events were observed in 1998 (Jul. 17, day 199; Aug. 10, day 223; Fig. 2).

3.2 Diurnal variations in water temperature

Diurnal patterns were evaluated to assess the importance of high and low flow events on water temperature and also to determine whether sampling at different times of the day could affect interpretation of water temperature data. Hourly variations in both surface and substrate water temperatures were recorded throughout the year, but were most pronounced in summer.

In winter, diurnal and daily fluctuations in intragravel water temperature were minor, except following particular hydrological events, for example, the observed thaw in January 1996. During that period, intragravel temperatures decreased more than 0.4°C (from 1.0°C to 0.6°C), responding to influx of cold water into the stream and gradually increased to pre-event conditions after a few days (Fig. 3a). Diurnal fluctuations became dramatically more obvious in late winter (April 2: day 93, Fig. 3b), as peak surface water temperatures approached those in the substrate. The influence of stream surface temperature on the intragravel temperature at this time resulted in increased fluctuation in intragravel temperatures, with a time lag of approximately 4 hours (i.e. maximum surface water temperature occurred at approximately 1700h [5:00 p.m.] whereas the maximum substrate water temperature occurred at 2100h [9:00 p.m.]). In contrast, the minimum temperatures showed a time lag of about 2 hours during this time, with surface temperature minima occurring at 0800h [8:00 a.m.] and those in the substrate occurring at 1000h [10:00 a.m.].

By early May (day 121, Fig 3b) surface and substrate temperatures followed each other more closely with 2 and 1 hr time lags for maximum and minimum respectively, values in the two zones. Maximum water temperatures occurred at 1800 h [6:00 p.m.] in surface waters and at 2000h [8:00 p.m.] in the gravel, and minimum temperatures were recorded at 0900 [9:00 a.m.] in surface waters and 1000h [10:00 a.m.] in the gravel. Hourly fluctuations were greater than were observed in April in both zones, but more pronounced in the surface waters; the maximum fluctuation noted in surface waters in May was 4°C, compared to only about 2°C in the gravel.

During the summer months, intragravel temperatures were markedly cooler than those of surface waters, although the diurnal fluctuations followed each other closely in the two zones

(Fig. 3c). The maximum daily range in surface water temperatures was 5.0°C, recorded in mid-summer, whereas fluctuations in the substrate water temperatures were still low, with a range of only 1.7°C. The maximum recorded water temperature during the three years of study occurred on August 8 (day 221, Fig. 3c): 20.6°C at 1700h [5:00 p.m.] in surface waters and 16.0°C at 2100h [9:00 p.m.] in the substrate.

By mid-September (Fig. 3d, day 259), mean temperatures of the surface and intragravel water were similar to each other again, but fluctuations were greater in the surface waters, and time lags between the surface and substrate waters ranged from 3 - 4 hours. Later in the autumn, intragravel temperatures again exceeded the surface water temperatures, and this pattern persisted through the winter.

3.3 Monthly temperature patterns

Monthly intragravel temperatures ranged from 0.72°C in February 1998 to a high of 14.1°C in July of the same year (Table 1). Annually, mean monthly intragravel temperatures remained near 1.0 °C (range 0.7°C - 1.6°C; Table 1) between December and March in all years, then increased gradually to 13.0 °C – 14.0 °C by mid-summer, and declined again in autumn. Stream surface water temperatures followed a similar annual cycle, but were colder in winter (close to 0.1°C in January) and warmer in summer than intragravel temperatures (Table 1). Differences in mean monthly values between the two zones were low throughout the year (highest difference was 1.9°C; Aug. 1996), but there were some variations between years, particularly in the relatively warm spring (March) in 1998.

3.4 Intragravel water temperature model

In order to run the model, physical parameters needed to be estimated. The density of the rock-fluid matrix (ρ) was assumed at 1700 kg/m^3 while the heat capacity of the rock-fluid (c) matrix was assumed at 600 kcal/m^3 °C based on data and graphs from Lapham (1989). The mean groundwater temperature at Catamaran Brook was 6.5 °C and was observed to be relatively constant throughout the year (6.4 - 6.6 °C). A constant groundwater temperature of 6.5 °C was assumed at a depth of over 1m into the substrate.

Using the above parameters, the model was calibrated using a thermal conduction of the rock-fluid matrix (*k*) of 4000 kcal/ hr m^3 °C, which is within values reported in the literature (Lapham 1989). Results of the modelled and measured intragravel temperatures at a depth of 0.2 m are presented in Figure 4 as well as modelled (predicted) values at depths of 0.4 m and 0.6 m, which were not measured in this study. The modelled intragravel temperatures were closely related to the observed values at 0.2 m depth in both magnitude and timing. The diurnal variations were predicted to be more stable as depth increased (e.g. 0.4 m vs. 0.6 m). The mean surface water temperature during the study period was calculated at 14.7 °C. Modelled intragravel water temperatures were calculated at 13.2 °C, 11.3 °C and 9.4 °C for depths of 0.2 m, 0.4 m, and 0.6 m respectively. Although some differences were observed between modelled and observed intragravel water temperatures, the mean values were the same at 13.2 °C.

4.0 Discussion

Two dominant patterns have emerged from the literature regarding surface-flowing and intragravel water temperatures in streams. Stream (surface) water responds more rapidly to environmental conditions and shows greater annual fluctuations than intragravel temperatures which are predominantly controlled by groundwater (e.g. Constantz 1998). In addition, surface-flowing waters tend to be warmer in summer and cooler in winter than intragravel waters, with cross-over transition periods in spring and fall (e.g. White *et al*. 1987). These patterns were confirmed in the present study, but the actual magnitude of the differences varied from previous studies, presumably due to local climate conditions. For example, average intragravel temperatures during the winter in Catamaran Brook were generally 1.0 - 1.1 °C warmer than stream water temperatures, resulting in differences that were greater than those reported by Shepherd *et al*. (1986) in a British Columbia river where stream water temperature rarely dropped below 3 °C in winter. Figure 5 presents some of the magnitude patterns reported in the literature.

The nature and the magnitude of the temperature pattern is also dependent on depth and location within a riffle. The upstream portion of the riffle is usually a downwell zone, characterized by surface waters infiltrating the substrate, carrying oxygen and nutrients into the hyporheic zone, and having temperatures that are closer to those of the stream water (White *et al*.

1987). The downstream portion of a riffle tends to be dominated by upwelling from groundwater, and both the water chemistry and temperature patterns in the substrate in this zone will be closer to groundwater conditions (White *et al*. 1987). Growth and survivorship of organisms within the substrate will therefore depend on their longitudinal location within the riffle. In this study, only one substrate location was monitored, so it was not possible to compare the temperatures at different locales within the site. However, the sensor was deliberately located in an area of the stream where Atlantic salmon have spawned over several years (R.A. Cunjak, University of New Brunswick, Personal Communication), to provide information on the temperature variations experienced by salmon eggs and emerging fry. The present study showed that mean daily intragravel temperatures in both the autumn and spring were close to mean daily surface water temperatures. Daily intragravel temperatures in late autumn and during the spring season was also closely related to the surface stream temperatures at the depth of incubating salmon eggs. In addition, when the surface water temperature dropped below 1.5°C, the intragravel temperature was very stable at close to 1.0 °C. Such information can be valuable in the calculation of accumulated degree days to estimate the timing of fry emergence.

In this study, we were able to monitor not only the overall patterns in intragravel temperatures, as indicated above, but also the degree of variation on both an hourly and a daily basis. Hourly (i.e. within-day) intragravel temperatures were extremely stable during the winter, with only minor fluctuations, suggesting a thermally stable environment for organisms within the substrate at that time. However, temperature fluctuations can occur among-days following specific environmental events, and these fluctuations can have serious implications for winter conditions for biota. For example, a thaw in January 1996 resulted in a high flow event and depressed intragravel temperatures for several days. Later in the season, within-day variations increased in both the surface and intragravel temperatures, but conditions within the gravel were always more stable than those at the surface. Summer temperature differences between the substrate and the surface waters should not be as important for salmon since the fry emerge from the gravel in Catamaran Brook in mid-June (Johnston 1997). However, many stream invertebrates have life cycle stages in stream substrates (Hyporheic zone) during the summer months, including summer diapause stages (Pugsley and Hynes 1983) and refugees from flooding. During such period where larger diurnal variations were present in both surface and intragravel water temperatures, it was possible to model intragravel water temperatures at different depths within the substrate.

It is clear that temperatures and thermal regime within the substrate can be markedly different from that in surface waters, and that these differences can have implications for studies of biota inhabiting streams. The substrate provides a generally more stable thermal habitat, but can respond to environmental conditions outside of the stream, such as precipitation, or unusual high flow events.

5.0 Acknowledgments

This is contribution No. 59 of the Catamaran Brook Habitat Reseach Project. The authors would like to thank the following people for their contribution in the present study: P. Hardie for field assitance; J.H. Conlon for his assistance in the preparation of figures; N. El-Jabi and J. Flanagan for reviewing the manuscript.

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Table 1. Monthly stream and intragravel water temperature at Catamaran Brook between 1995 and 1998.

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	intragravel	-	-	-	-	-	-	-	-	-	-	3.37 *	1.21 *
	stream	-	-	-	-	-	-	-	-	-	-	2.21 *	0.12 *
	difference	-	-	-	-	-	-	-	-	-	-	1.16	1.09
1996	intragravel	0.94	1.06	1.24	1.65	5.71	12.10	13.12	13.31	10.76	6.26	3.15	1.57
	stream	0.10	0.11	0.14	0.67	5.20	13.31	14.46	15.19	11.53	6.13	2.75	1.19
	difference	0.84	0.95	1.10	0.98	0.51	-1.21	-1.34	-1.88	-0.77	0.13	0.40	0.39
1997	intragravel	-	1.19	0.98	1.17	7.06	11.01	13.28	13.15	11.01	5.41	2.30	0.84
	stream	-	0.57	0.46	0.80	4.26	11.90	14.33	14.13	11.46	5.21	2.17	0.30
	difference	-	0.63	0.53	0.38	-0.20	-0.89	-1.04	-0.98	-0.45	0.20	0.13	0.54
1998	intragravel	0.75	0.72	0.99	2.58	8.65	11.21	14.13	13.88	11.34	6.92	2.67	1.24
	stream	0.35	0.56	1.95	2.97	9.33	11.93	15.12	14.69	11.73	6.93	2.41	0.96
	difference	0.41	0.15	-0.96	-0.39	-0.68	-0.72	-0.99	-0.80	-0.39	-0.01	0.26	0.28

*. Mean values were calculated with incomplete series due to missing data.

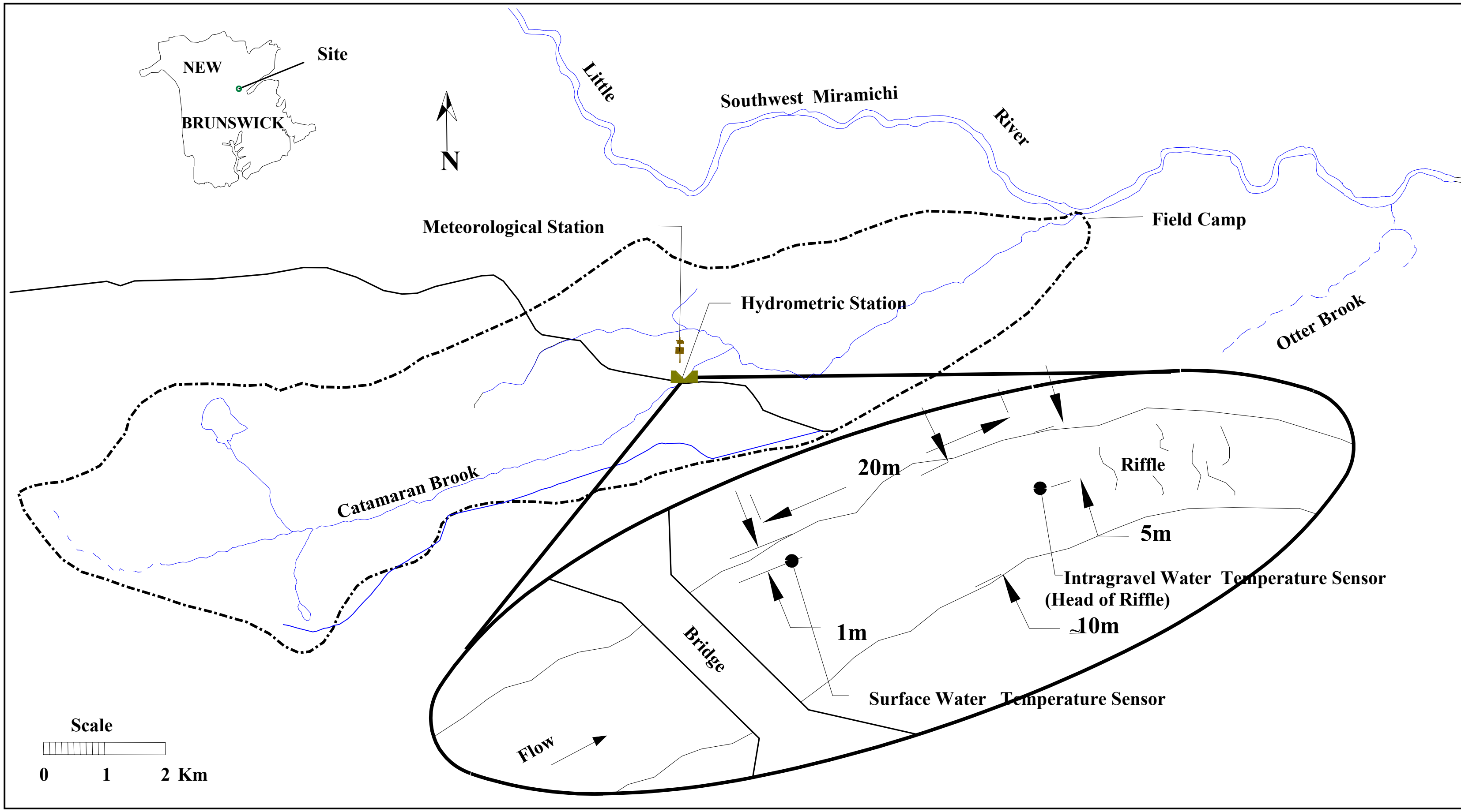

Figure 1. Catamaran Brook showing the location of the hydrometric station, the meteorological stations and the surface and intragravel water temperature sampling sites.

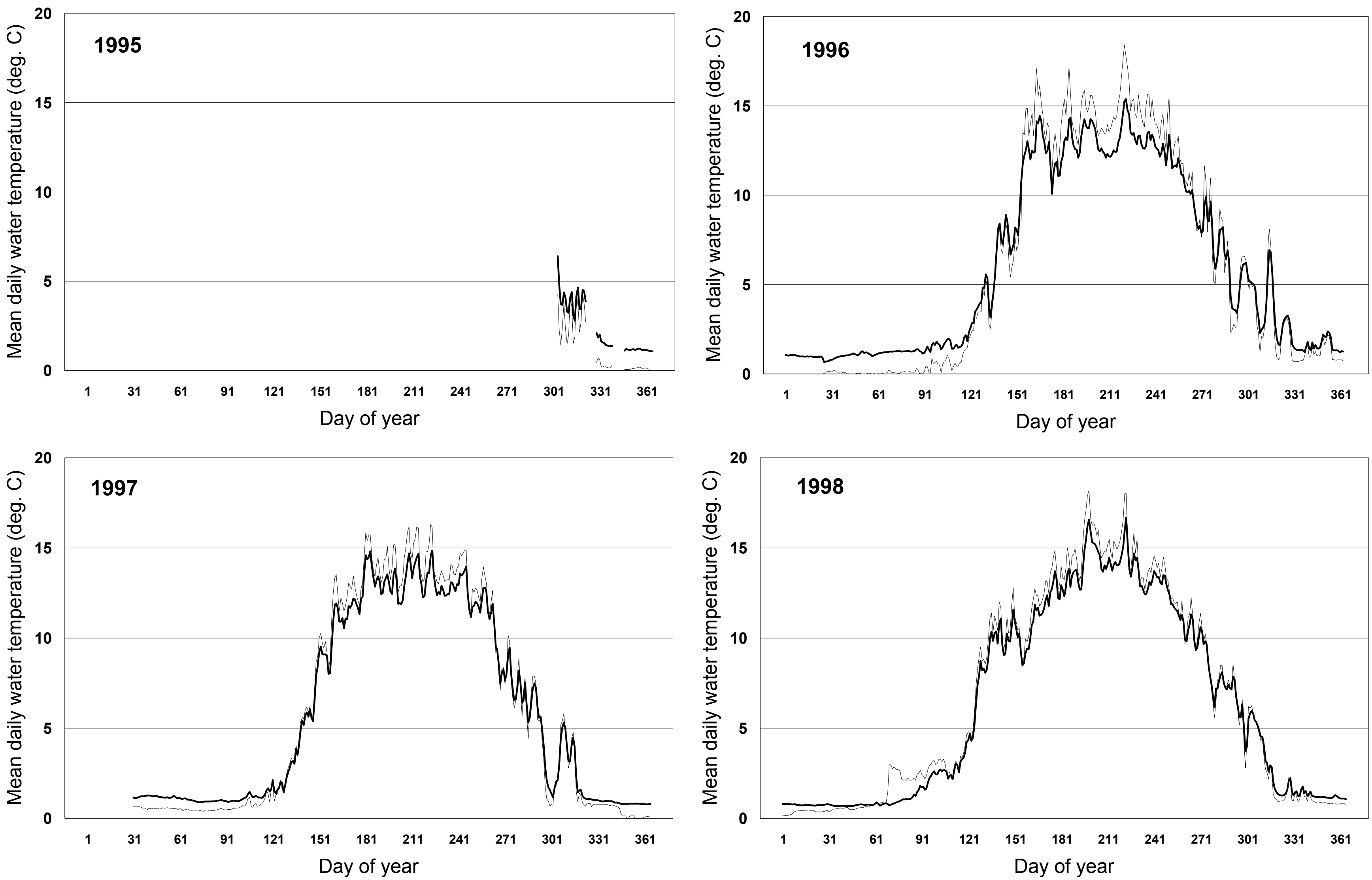

Figure 2. Mean daily surface water and intragravel temperatures at Catamaran Brook between 1995 and 1998. Darker line = intragravel temperture; lighter line = surface water temperature.

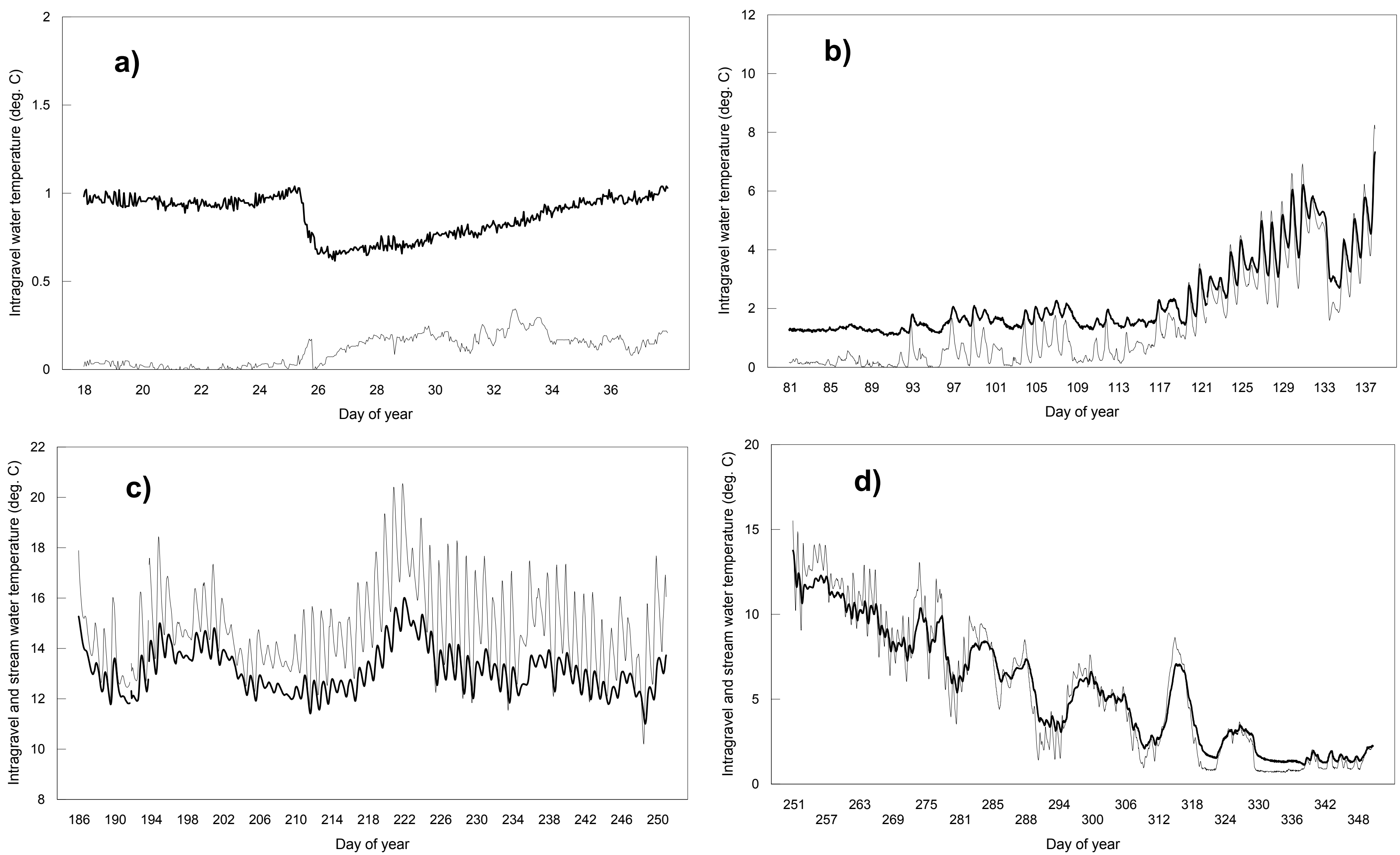

Figure 3. Hourly surface water and intragravel water temperatures at Catamaran Brook in 1996 by season. a) winter period (day 18 = Jan. 18 and day 36 = Feb. 5); b) spring period (day 81 = Mar. 22 and day 137 = May 17); c) summer period (day 186 = Jul. 5 and day 250 = Sep. 7); and d) autumn period (day 251 = Sep. 8 and day 348 = Dec. 14). Darker line = intragravel temperature; lighter line = surface water temperature.

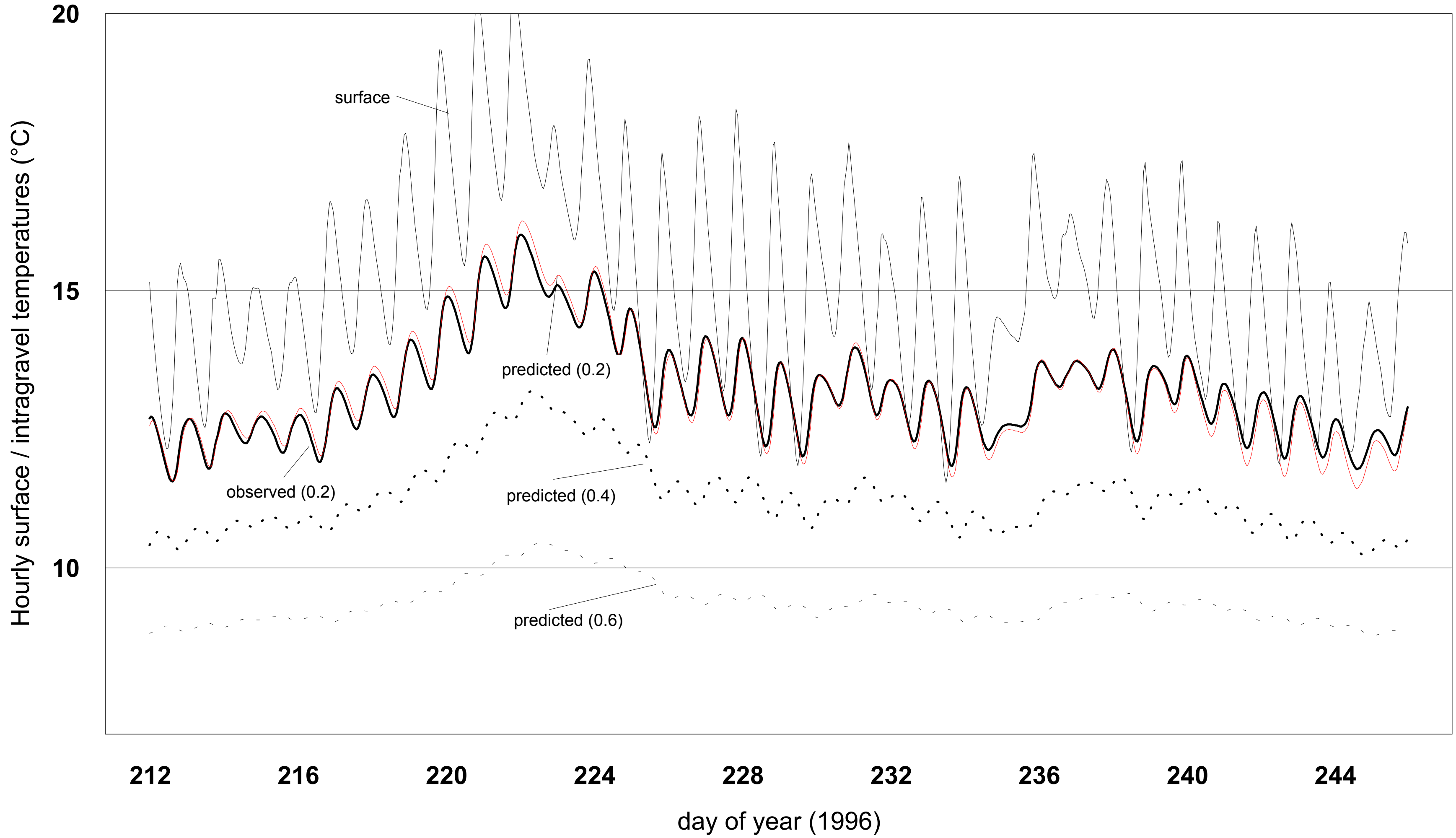

Figure 4. Modelled intragravel water temperatures at different depths (0.2, 0.4, and 0.6 m) within the substrate at Catamaran Brook and comparison between observed values at 0.2 m.

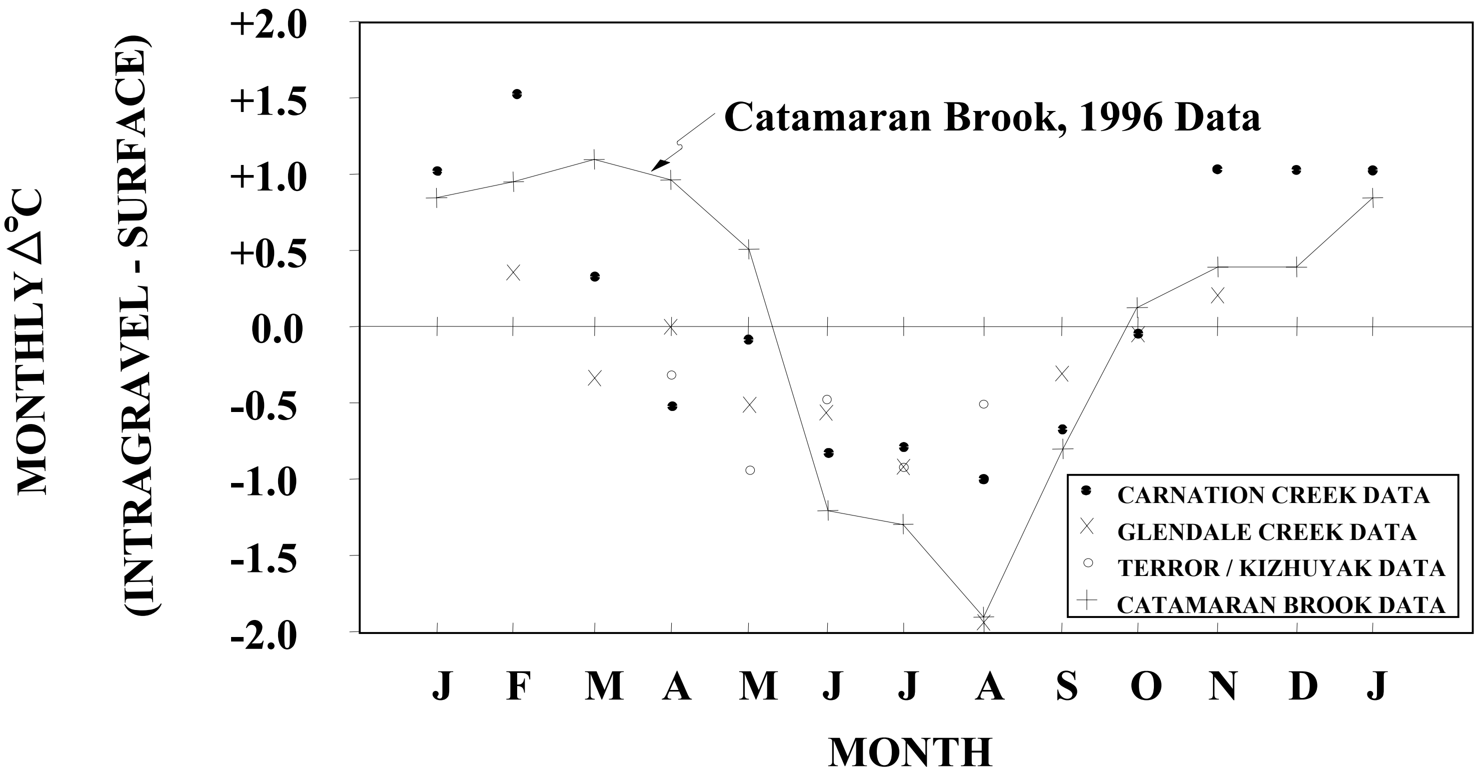

Figure 5. Difference in monthly surface and intragravel water temperature at Catamaran Brook and other selected sites (from Shepherd et. al. 1986).