STREAM WATER TEMPERATURE MODELLING IN FOREST CATCHMENTS

by

Daniel Caissie

Submitted
in partial fulfilment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Major Subject: Civil Engineering

at

Dalhousie University

Halifax, Nova Scotia December, 2003

Your file Votre référence
ISBN: 0-612-89097-X
Our file Notre référence
ISBN: 0-612-89097-X

Dalhousie University

Faculty of Engineering

The undersigned hereby certify that they examined, and recommend to the Faculty of Graduated Studies for acceptance, the thesis entitled "Stream Water Temperature Modelling in Forest Catchments" by Daniel Caissie in partial fulfillment of the requirements for the Doctor of Philosophy.

Dated : December 17, 2003

Supervisor:

Dr. Mysore G. Satish

Co-supervisor:

Dr. Nassir El-Jabi
Université de Moncton
(Adjunct, Dalhousie University

External Examiner:

Dr. Terry D. Prowse
Environment Canada

Examiners:

Dr. Rafiqul Islam

Dr. Matiur Rahman

Dalhousie University

Faculty of Engineering

DATE: December 17, 2003

AUTHOR: Daniel Caissie

TITLE: Stream Water Temperature Modelling in Forest Catchments

MAJOR SUBJECT: Civil Engineering

DEGREE: Doctor of Philosophy

CONVOCATION: May, 2004

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

A	cross sectional area (m^2).
$A_0/2$	the average of the function $f(t)$ for the period N in the Fourier series.
A_1'	coefficient of Markov model based on autocorrelation; R_1 $(1-R_2)$ / $(1-R_1^2)$.
A_2'	coefficient of Markov model based on autocorrelation; $(R_2-R_1^2)$ / $(1-R_1^2)$.
A_3	linearization coefficient of the long-wave radiation (0.46 MJ m^{-2} d^{-1} °C^{-1}).
A_4	linearization coefficient of the long-wave radiation (28.38 MJ m^{-2} d^{-1} °C^{-1}).
A_n	coefficient of the Fourier series.
a_1	empirical constants in the evaporation equation.
a_2	linear regression coefficient.
a_3	estimated coefficients in the sine function of annual component.
a_4	coefficient relating the mean water depth to river discharge.
a_5	linear regression coefficient to explain the equilibrium temperature.
a_t	the white noise process (independent random error following a normal distribution function with a mean of zero and of variance of σ_a^2).
B	Backward shift operator of the autoregressive model.
B_c	cloud cover (0 = clear sky and 1 = total could cover).
B_n	coefficient of the Fourier series.
b_1	empirical constants in the evaporation equation.
b_2	linear regression coefficient.
b_3	estimated coefficients in the sine function of annual component.
b_4	coefficient relating the mean water depth to the river discharge.
b_5	linear regression coefficient to explain the equilibrium temperature.
B_0	coefficient in the equilibrium temperature equation.
B_1	coefficient in the equilibrium temperature equation.
B_2	coefficient in the equilibrium temperature equation.

B_3	coefficient in the equilibrium temperature equation.
B_4	coefficient in the equilibrium temperature equation.
d_r	the relative distance of the earth from the sun.
D_x,	dispersion coefficients in *x* direction ($m^2 d^{-1}$).
D_y,	dispersion coefficients in *y* direction ($m^2 d^{-1}$).
D_z	dispersion coefficients in *z* direction ($m^2 d^{-1}$).
E	evaporation ($mm\ d^{-1}$).
e_a	water vapor pressure in the air (mm Hg).
E_b	the emissive power ($MJ\ m^{-2}$).
e_s	saturated vapor pressure at the water temperature (mm Hg).
$f(t)$	the stream water or air temperature time series (e.g. on a daily basis) in the Fourier series.
G_{SC}	the solar constant (0.0820 $MJ\ m^{-2}\ min^{-1}$)
H_e	evaporative heat transfer ($MJ\ m^{-2}\ d^{-1}$).
H_c	convective heat transfer ($MJ\ m^{-2}\ d^{-1}$).
H_l	net long-wave radiation ($MJ\ m^{-2}\ d^{-1}$).
H_r	reflected short-wave radiation at the water surface.
H_{ref}	reference energy calculated using long-term meteorological conditions.
H_s	solar radiation or net short-wave radiation ($MJ\ m^{-2}\ d^{-1}$).
H_{sed}	total heat flux at the sediment / water interface ($MJ\ m^{-2}\ d^{-1}$).
H_{si}	incoming solar radiation under varied cloud conditions ($MJ\ m^{-2}\ d^{-1}$).
H_{so}	daily clear sky solar radiation ($MJ\ m^{-2}\ d^{-1}$).
H_t	total heat flux at the water surface ($MJ\ m^{-2}\ d^{-1}$).
j	the day of year (January 1 = 1 and December 31 = 365).
k	proportionality constant for the Bowen ratio varying between 0.58-0.66, usually taken as 0.61.
K	thermal exchange coefficient ($MJ\ m^{-2}\ d^{-1}\ °C^{-1}$).
K_s	air temperature residual coefficient in the second order Markov model
n_l/N_l	the ratio between measured bright sunshine hours and maximum possible

	sunshine hours.
N_2	number of observations (days) for a given period T (e.g. March 31 to December 16) during open water conditions.
n_2	parameter for the number of harmonics (annual component).
NASH	Nash coefficient as defined in equation [3.38].
P	wetted perimeter of the river (m).
P_a	atmospheric pressure (mm Hg).
Q	river discharge (m^3/s).
r	reflectivity of the water surface (e.g. 0.05, or 5%).
R_1	the 1-day lag autocorrelation coefficient.
R_2	the 2-day lag autocorrelation coefficient.
$Ra(t)$	air temperature short-term component of the stochastic model.
R_A	daily extraterrestrial radiation in (MJ m^{-2} d^{-1}).
RH	relative humidity (%, from 0 to 100%).
RMSE	root-mean-square error as defined in equation [3.37].
$Rw(t)$	water temperature short-term component in the stochastic model.
$SA(t)$	Annual component in long-term solar radiation.
SF	shading factor of the river reach (0 to 1, depending of forest cover and upland shading).
SNTEMP	Stream Network TEMPerature model
t	time (day).
t_0	estimated coefficients in the annual component sine function.
T	the absolute temperature of the surface in Kelvin (K).
$TA(t)$	the annual component for temperature at time t in days (July 1 = 182).
T_a	air temperature in °C or Kelvin (K) depending on the equation.
T_d	dew point temperature (°C)
T_e	the equilibrium temperature (°C)
T_w	water temperature in °C or Kelvin (K) depending on the equation.

$T_a(t)$	mean air temperature for a given time period (daily, weekly, monthly, etc.).
$T_w(t)$	mean water temperature for a given time period (daily, weekly, monthly, etc.).
V	wind velocity at predetermined height (e.g. 2 or 10m; km h^{-1}).
v_x,	mean water velocity in the x direction (m d^{-1}).
v_y,	mean water velocity in the y direction (m d^{-1}).
v_z	mean water velocity in the z direction (m d^{-1}).
W	river width (m).
x	distance downstream (m).
y	vertical distance or mean water depth (m).
z	longitudinal distance (m).
z_t	time series of the autoregressive model.
α'	the coefficient which estimates the highest maximum water temperature in the logistic function.
β	atmospheric emissivity.
β'	the air temperature at the inflection point of the logistic function.
β_1	coefficient of the autoregressive model.
β_2	coefficient of the autoregressive model.
β_3	coefficient of the autoregressive model.
δ	sun declination (radian).
$\delta(B)$	transfer function of the autoregressive model.
ϕ	the latitude of the site (radian).
ϕ_i	autoregressive operator.
$\phi_w(t)$	component representing the annual component in the energy reference model.
γ'	a parameter for the steepest slope of the logistic function.
δ	the declination at the site (radian).

η	slope of the linear vapor pressure approximation.
θ	specific heat of water (4.19×10^{-3} MJ kg^{-1} °C^{-1}).
θ_i	moving average operator of the autoregressive model.
ρ	water density (1000 kg m^{-3}).
ω_s	the sunset hour angle (radian).
σ	the Stefan-Boltzmann constant (4.9×10^{-9} MJ m^{-2} K^{-4}).
σ_a	variance in the Box-Jenkins model.
$\zeta(B)$	transfer function of the autoregressive model.

ACKNOWLEDGEMENTS

I would like to express my profound gratitude and appreciation to my supervisor Dr. M. G. Satish who provided me with encouragement and guidance throughout the realization of this project. I have benefited greatly from his talent as a professor and researcher. I also wish to thank him for his care and effort during my studies at Dalhousie University as well as for reviewing this thesis with the provision of valuable suggestions and advice.

Special thanks are also express to Dr. N. El-Jabi of Université de Moncton who acted as co-supervisor of this research. He has been of great support during this research project and his valuable advice and suggestions have been greatly appreciated.

It is my pleasure to express my sincere appreciation to Dr. R. Islam and Dr. M. Rahman for serving as members of my guiding committee, as well as to Dr. T.D. Prowse for acting as the external examiner. Their evaluation and suggestions have significantly improved the present thesis.

I also wish to thank my employer, the Department of Fisheries and Oceans, and especially Mr. G. Chaput and Dr. M. Chadwick for their support during this particular research initiative. Without their support, this project would not have been possible. I would also like to thank everyone who has contributed in one way or another to the realization of this research; in particular to Mr. J. Conlon for providing countless reviews of the present documents as well as for the provision of maps and figures; to the people at the Catamaran Brook Habitat Research Project who collected many years of data that made this and other research projects possible.

Finally, I wish to express my sincere appreciation to my wife Linda as well as to Marc-André and Julien for their patience, support, and encouragement during the period of this study.

ABSTRACT

Water temperature influences most physical, chemical and biological processes of the river environment. It plays an important role in the distribution of fishes and on the growth rates of many aquatic organisms. Therefore, a good understanding of the thermal regime of rivers is an essential tool for the management of fish habitat. The modelling of water temperatures is key to the understanding of river thermal regimes as well as being invaluable for environmental impact assessments. This study deals with the modelling of river water temperatures using four different models: a deterministic model, a stochastic model, a simplified deterministic model, and an energy reference model.

The objective of the study consists of the development of a new and simplified deterministic model based on the equilibrium temperature concept in addition to the development of an energy reference model. These newly developed models were compared to the more classic deterministic and stochastic models. The equilibrium temperature model was based on a simplified function of meteorological parameters explaining the equilibrium temperature, which was thereafter used to calculate total energy flux at the water surface. This energy component was subsequently used to relate variations in water temperatures using a heat exchange coefficient. The energy reference model was based on the long-term meteorological parameters, and thus represents the long-term energy. This long-term energy component was then used with the corresponding annual component to predict river water temperatures.

Following the development of the models, they were applied to two thermally different river systems in a similar meteorological area, namely Catamaran Brook and the Little Southwest Miramichi River (NB). Catamaran Brook is the smaller of the two systems (10 m wide), with a mostly closed riparian canopy. By contrast, the Little Southwest Miramichi River is a larger and wider river (80-100m), which is more exposed to environmental conditions. Results from the present study showed that all models performed relatively well with root-mean-square error of between 1.26 °C and 1.61 °C (1992-99). Nash coefficients were observed in the range of 0.92 to 0.95 for all models (1992-99). It was concluded that differences in the modelling performances were related to model concept, data requirement, hydrometeorological conditions as well as timing within the year (e.g., early spring and late summer).

CHAPTER 1

INTRODUCTION

Water temperature has both economic and ecological significance when considering issues such as water quality and biotic conditions in rivers. For instance, water temperature is arguably one of the most important parameters in stream ecology that determines the overall heath of aquatic ecosystems. It influences the growth rate of aquatic organisms as well as their distribution. Water temperatures can also have adverse impacts on aquatic habitat especially when they are outside the optimal thermal range. For instance, sustained high water temperatures have been noted to be detrimental to aquatic resources by limiting suitable habitats. High water temperatures can also result in fish mortalities by impacting directly on fish population and indirectly by limiting fish production in rivers.

River water temperatures can also impact potable water quality as well as human recreational activities such as swimming and fishing. In fact, the pollution of a watercourse is highly related to river water temperature, as temperature determines the rate of decomposition of organic matter, the dissolved oxygen content, and chemical reactions in general. River water temperature can also impact the efficiency and operation of hydraulic structures. For example, at low water temperatures, the formation of river ice and/or frazil ice at hydro stations can severely impact on power generation (i.e., reduced hydroelectric performance). In winter, river water temperature can influence the presence and/or absence of an ice cover within rivers reaches. Some water usages, such as irrigation, can also be influenced by river water temperature. For instance, crop irrigation often demands a specific range of water temperatures otherwise plant growth or even their survival can be at risk.

Early studies dealing with river water temperature have focused mainly on determining empirical relationships between air and water temperatures as well as on studying factors related to river thermal processes (e.g. groundwater influences, daytime vs. nigthttime temperatures, etc.). Following these mostly descriptive studies, research then focused on the development of water temperature models that can be classified into two distinct groups, deterministic and stochastic models. Deterministic models employ an energy budget approach to predict river water temperature, while stochastic models use the autocorrelation properties of a time series as well as statistical relationships among parameters. Deterministic and stochastic models have evolved since the early 1960s, however, few studies have focused on new modelling approaches, specifically on the development of simplified deterministic models or models that incorporate important characteristics of both deterministic and stochastic approaches. This study will therefore focus on the development of new water temperature models based on these new concepts. Classic deterministic and stochastic models will also be applied for comparative purposes.

1.1 Objectives of the thesis

Although many past studies have modelled river water temperature, few have modelled water temperatures for rivers having different thermal conditions within a similar meteorological area. Therefore, the present research will consider, as part of its objective, the application of water temperature models on rivers of different thermal regimes. For instance, models will be applied on a small brook and a larger river system, both located within the Miramichi River basin. Smaller brooks usually experience a higher level of shading (due to riparian vegetation), and groundwater contribution, as opposed to larger rivers which are often wide and shallow as is the case for the Miramichi River (New Brunswick, Canada).

In addition, previous studies dealing with the modelling of water temperatures have mostly been applied for a short period of time, ranging from a few weeks to a few years. Long-term modelling studies of water temperatures are scarce in the literature, although they are important in the assessment of models (e.g., cold vs. warm summer). As a consequence, the present study is also unique in its consideration of long-term data (i.e., 8 years). Within these 8 years of data, a wide range of hydrometeorological conditions was present, which will permit the comparison of models under these varied conditions.

It was also within the objective of this study to apply four different types of water temperature models: 1) deterministic, 2) stochastic, 3) equilibrium temperature and 4) an energy reference model. Two of these models, the equilibrium temperature and the energy reference model, are completely new water temperature models. This study will also compare the relative modelling performances for each model using the root-mean-square error (RMSE) and the Nash coefficient (NASH). Due to unreliable site specific relative humidity data (during some years), this study will also analyse the impact of using relative humidity data from a nearby meteorological station (i.e., Miramichi Airport) in the application of the deterministic model. Water temperature modelling results will be compared for these different sources of relative humidity data (Catamaran Brook meteorological station data, Miramichi Airport data, and using a mean value for relative humidity).

1.2 Scope of the thesis

Literature on river water temperature has indicated that most research on the thermal regime of rivers can be classified into the following categories: 1) descriptive studies of thermal conditions, 2) influence of water temperatures on aquatic habitat, 3) forestry impact on the thermal regime of rivers, 4) modelling studies [statistical, deterministic and stochastic] and 5) climate change studies. Each field of study has contributed significantly to the overall understanding of the river thermal regime and its impact on aquatic and human life. These research findings are also important in the understanding and the development of new water models. With this consideration, the present study will initially introduce some information related to each subject. In Chapter 2, an extensive literature review will describe water temperature of rivers in general, including a review of existing water temperature models. This chapter will provide information related to the different processes involved in river thermal conditions, and how scientific research has evolved over the years, from the early studies to the present modelling approaches. Chapter 2 will also present information dealing with forestry activities and their impact on the thermal conditions in rivers. These data are relevant to the understanding of the role which different energy components play, such as the role of solar radiation vs. convective heat transfers, for example. This chapter will also present information related to anthropogenic impacts from a wide variety of activities (water withdrawal, reservoir operation, climate change, and others). Finally, this chapter will provide a review of existing water temperature models. Chapter 3 will focus on the development of four water temperature models. The first is a classic deterministic model chosen because it has been used in many previous studies and is useful for comparative purposes. The second model described in Chapter 3, is a completely new water temperature model based on the equilibrium temperature concept. The third is a stochastic model which was modified slightly from that reported in previous studies to improve on the characterization of long-term water temperatures. The fourth is also a completely new model, based on the energy reference (long-term energy). Similar to the equilibrium temperature concept model, it uses new approaches of modelling river water temperatures.

In Chapter 4, all models were calibrated and validated using the same data set (i.e., same water temperature time series). For instance, 3 years were used for model calibration (1992-94), while the remaining 5 years (1995-99) were used for model validation. The calibration period included a wide range of meteorological conditions (high/low air temperatures and river discharge), which were representative for the two studied rivers. Similar meteorological conditions were also observed during the validation period, which was important in the evaluation of water temperature models. Results are presented graphically to compare the performances within and among years and models. Residual time series are also presented to show the departure or difference between observed and predicted water temperatures. Model performance comparison tests are carried out in Chapter 4, specifically the root-mean-square error (RMSE) and the Nash coefficient (NASH). Chapter 5 provides a discussion on model performances and examines the potential cause for different model performances. Chapter 6 provides a summary of research findings and conclusions followed by research recommendations for future studies dealing with water temperature modelling.

CHAPTER 2

BACKGROUND

This chapter is devoted to an extensive literature review about the thermal behaviour of rivers and a review of existing water temperature models. Therefore, this chapter will also examine at literature data related to the characterization of river water temperatures, including human impact studies, and how aquatic resources are affected by these changes in the thermal regime. Following this, a literature review of the different modelling approaches will be provided.

2.1 Thermal regime of rivers

The thermal regime of rivers can be affected by many parameters and conditions which are important to the overall understanding of heating and cooling processes of watercourses ranging in size from headwater streams to large rivers. For instance, water temperature in rivers can be affected by such meteorological conditions as air temperature, solar radiation, wind speed and others. Stream water temperature is also dependent on the physical characteristics of the river environment such as the degree of shading, water depth, stream substrate as well as many other factors. These meteorological / physical attributes of the river will ultimately influence spatial and temporal variation in river water temperatures. Equally important to studying these influences on water temperatures, is understanding the implication of the river thermal regime on aquatic resources as well as how it can be modified by human impacts or anthropogenic perturbations.

Before undertaking a thorough study of river thermal conditions, it is important to look at the various processes involved in determining river temperatures and their associated fluctuations (seasonal, daily, diurnal). For instance, Figure 2.1 shows the interaction of the different processes acting on water temperatures ($T_w = f$(air temperature, solar radiation, relative humidity, etc...)).

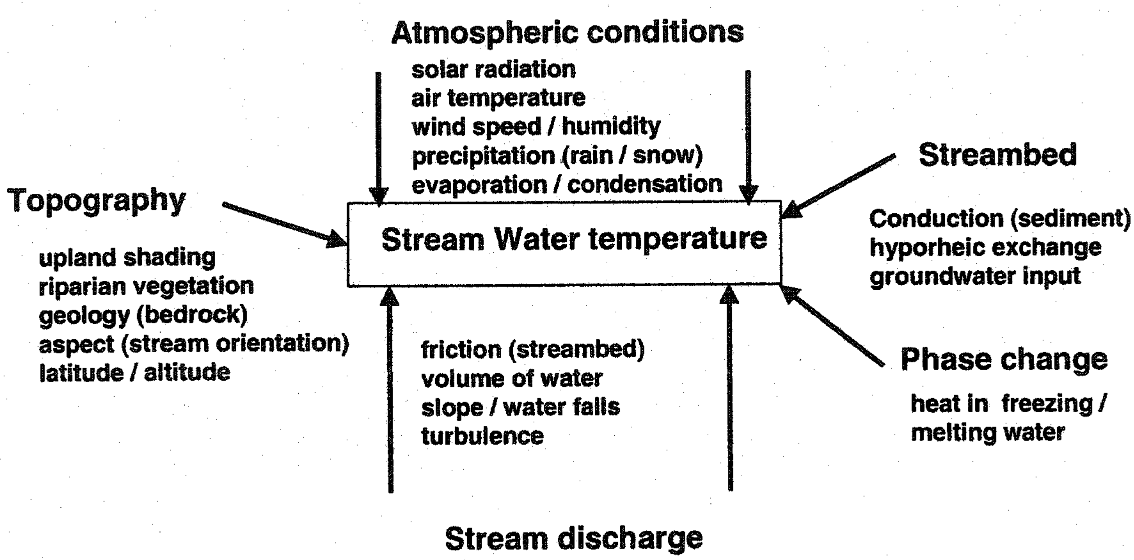

Figure 2.1 Factors influencing the thermal regime of rivers

These factors can generally be classified into four different groups, 1) atmospheric conditions, 2) topography, 3) stream discharge and 4) streambed. The first and among the most important factors are related to *atmospheric conditions*. Atmospheric conditions are mainly responsible for the heat exchange processes that take place at the water surface. Important parameters include solar radiation, air temperature, relative humidity, wind speed, and the type and amount of precipitation. Some of these factors play a greater or less important role in the thermal regime of river depending on cofactors such as topography. For instance, *topography* or the geographical setting of the river can influence the atmospheric conditions it experiences. Significant factors in topography include latitude and altitude, riparian vegetation, geology, aspect and upland shading (e.g., prairie vs. mountain). Topographical conditions can be modified by human activities such as the removal of riparian vegetation, resulting in alteration to the river thermal regime. The next group of factors, mostly a function of river hydraulics is included under *stream discharge*. Some of these factors such as the volume of water are extremely important while others such as slope and waterfalls are important to a lesser extent. Streambed friction is related to stream discharge and is therefore included within this group.

The last group of factors influencing the thermal condition in rivers is labelled as *streambed.* These factors include all heat exchange processes that occur at the streambed level. These factors include streambed heat conduction, hyporheic water exchange, and groundwater contribution. The importance of the some of these factors has not yet been thoroughly studied in river thermal processes research, however, their mention and discussion remains relevant. Rather than using the above grouping, other studies have divided factors influencing the thermal regime of rivers into two main categories, namely internal and external factors (or drivers) (Poole and Berman 2001). In the referenced study, the external factors consisted of the net energy and water inputs, whereas internal factors were related to fluvial processes and characteristics, i.e. riparian zone, interaction between surface and subsurface waters, etc.

Descriptive studies of the thermal regime of rivers date back many years. For instance, Macan (1958) studied the seasonal trends in water temperatures as well as the influence of sunshine and other parameters on water temperatures. Despite the fact that this was mainly a descriptive study, it made important observations, namely that diurnal variations in water temperatures were more significant during periods of clear sky than during overcast days. Other studies compared the seasonal variations in water temperatures (Hopkins 1971). For instance, this study showed that the greatest diurnal fluctuations occurred in summer while the lowest fluctuations occurred in winter for the Hinau stream in New Zealand. In early 1970s an attempt was made to categorise the thermal regime of rivers using altitude and latitude as the dominant factors (Smith 1972), however, it became apparent that such a classification would not hold true due to the complex nature of rivers. Since then, no attempt has been made to classify rivers by different thermal regimes. Many studies have further illustrated the fact that rivers and their thermal conditions are indeed very complex and difficult to classify (Smith 1975; Smith and Lavis 1975). Ward (1985) showed, by studying many rivers in the Southern Hemisphere, that the thermal regime of rivers was dependent on many factors. He noted that diurnal fluctuations generally increased in the downstream direction, as water sources were less dominated by groundwater and streams became more open and more exposed to meteorological conditions. These diurnal fluctuations eventually decreased again further downstream with increased water depths (Ward 1985). This study concluded that differences in the thermal regime in the Southern Hemisphere compared to Northern Hemisphere rivers were more related to size than process. He also noted that a significant portion of the land in the Southern Hemisphere was in arid and semi-arid region (e.g. Australia), which makes a full inter-comparison difficult. Although a relationship between mean water temperature and basin elevation was observed by Webb and Walling (1986), it is difficult to generalise these findings because cold headwater streams are usually observed at higher elevation. More recently, Arscott et al. (2001) have shown that water temperatures can be a function of parameters such as stream order and groundwater contribution as well as the input from cold water tributaries. Water temperatures within a stream environment can vary dramatically within a few meters depending on microthermal conditions as shown by Clark et al. (1999). The thermal regime can also be a function of the type of river. For instance, Mosley (1983) showed that braided rivers could be subject to very high water temperatures due to their shallow water depths and because these rivers are highly exposed to meteorological conditions.

A number of studies have looked at the thermal regime of rivers during summer open water condition, while others have focused on pre-winter conditions (at the end of the autumn cooling period and at the onset of an ice cover) where supercooling conditions are present in rivers. Under such condition, crystal ice which is known as frazil or anchor ice forms within the water column. Energy exchange under such thermal conditions has been described by Tsang (1982) as well as others (Hammar and Shen 1995; Shen et al. 1995).

Although river thermal regimes are naturally complex, they are often further complicated by human activities. Water temperature can be affected by anthropogenic perturbations on the local or global scale. For instance, on the local scale the thermal regime of forested ecosystems can be affected due to timber harvesting within a drainage basin, within specific timber harvesting block, or along a stream. The thermal regime of rivers can also be influenced on the local scale by thermal effluent discharges such as those from power generating stations or industrial processing plants. River thermal conditions can be altered by a reduction in streamflow due to water withdrawal (e.g. water abstraction). Such water withdrawals are often the result of irrigation projects, municipal water supplies, and hydroelectric development among others. On a global scale, climate change is expected to be responsible for changes in river thermal regime. Climate change will potentially affect salmonid populations by restricting their habitat or modify their distribution (Meisner et al. 1988; Meisner 1990b; Moore et al. 1997). In Atlantic Canada, an expected increase in air temperature of 2-6°C over the next 100 years will ultimately result in increased river water temperatures that could also influence aquatic biota (Swansburg et al. 2002). Fisheries and aquatic resources will need to adapt to these new climatic conditions, and it is believed that the distribution of specific species change significantly. Furthermore, angling opportunities are very much dependent on the thermal conditions in rivers. High water temperature events may result in the closing of sections of rivers to angling, which could result in a significant loss of revenue to outfitters. Even in situations where rivers are not closed to angling, it is generally observed that fishing success declines significantly during high water temperature events. Therefore, a thorough understanding of river water temperature as well as potential anthropogenic impacts is of high importance in the overall management of fisheries and aquatic resources.

2.1.1 River water temperatures and aquatic habitat

Many biological factors and conditions, as well as stream productivity are strongly linked to stream water temperature. Moreover, any changes to the river thermal regime will ultimately change biotic distribution and growth. It is therefore important, initially, to have a good understanding of the biological implications of changes in river thermal regimes. Many studies reported in the literature have considered the thermal regime of rivers to address their effect on stream biota and water quality. For example, it has been recognised that the biological activity in streams follows the Van't Hoff rule, which states that the biological activity doubles for every 10°C increase of water temperatures (as reported in Brown and Krygier 1967).

Stream water temperature can influence a wide range of aquatic organisms from invertebrates (Cox and Rutherford 2000a; Hawkins et al. 1997) to salmonids (Lee and Rinne, 1980). For instance, fishes have a specific temperature preference, which ultimately determines their distribution within a stream ecosystem (Coutant 1977; Wichert and Lin 1996). A review by Coutant (1999) provides valuable information about thermal effects on aquatic organisms as well as factors influencing the thermal condition in rivers. For example, water temperatures are important for salmonid growth conditions (Edwards et al. 1979; Elliott and Hurley 1997), for the timing of fish movement, (Jensen et al. 1998) and the triggering of smolt runs in the spring (Hembre et al. 2001). Water temperature has also been observed to affect the swimming performance of fishes (Myrick and Cech 2000). The growth of aquatic insects is also highly influenced by stream thermal conditions (Markarian 1980). This study showed that the growth of aquatic insects was directly proportional to the degree-days experienced by the population. Water temperatures can be used to model aquatic ecosystem processes. For instance, a water temperature regression model using a 5-day to 7-day period was successfully used to predict the growth of brown trout (Crisp and Howson 1982). River water temperatures can also influence conditions within the stream substrate including intragravel water temperatures (Crisp 1990a; Evans et al. 1995; Cox and Rutherford 2000b) and therefore the rate of development of salmonid eggs (Combs and Burrows 1957; Combs 1965; Alderdice and Velsen 1978; Beer and Anderson 2001). For instance, water temperature was observed to influence the emergence timing of Atlantic salmon fry as reported by Johnson (1997). In this study, although river discharge was identified as an important factor, river water temperature was noted to be the dominant factor in the timing of emergence. Peterson et al. (1977) showed that water temperature during egg fertilisation can have an influence on mortality, and that the optimal incubation temperature was near 6 °C. Studies have shown that intragravel water temperatures are highly different than surface water temperatures depending on time of year (Shepherd et al. 1986; Hartman and Leahy 1983). Cox and Rutherford (2000b) found that simple regression could be used to explain mean monthly water temperatures as a function of depth. Any modifications or changes in stream water temperatures, either naturally occurring or human induced, can modify intragravel water temperatures since they are interlinked (Caissie and Satish 2001).

High stream water temperatures can have adverse effects on fisheries resources by limiting fish habitat and ultimately fish mortality. For example, high stream water temperatures between 23°C and 25°C have been observed to affect the mortality of trout (Lee and Rinne, 1980; Bjornin and Reiser 1991). Juvenile Atlantic salmon can tolerate slightly higher temperatures than trout, in the range of 27°C to 28°C (Garside 1973). However, it has been shown that the response to high temperature events can depend on life stages as well, i.e. juvenile vs. adult (Huntsman 1942; Garside 1969). Huntsman (1942) noted moralities of Atlantic salmon due to high temperature events affected larger salmon first followed by small salmon and then parr. This particular study also showed the importance of summer rainfall events during drought conditions. Precipitation events were noted to stimulate salmonid migration into rivers, where they subsequently died due to high water temperatures. Diurnal variability in water temperatures can also impact the mortality, stress and energy reserves of salmonids (Thomas et al. 1986). At high stream water temperatures, salmonids tend to change their behaviour and seek thermal refuges (Torgersen et al. 1999). For instance, salmonids have been observed to aggregate at higher densities within small, but colder, refuge spaces (Ebersole et al. 2001) or move into colder tributaries (Cunjak et al. 1993). Ebersole et al. (2001) showed that approximately 10-40% of fish were observed close to thermal refuges during midday high water temperatures. This aggregation of fish resulted in higher densities than those observed elsewhere in the stream. It has often been suggested in the literature that water temperatures exceeding 23°C were stressful to juvenile Atlantic salmon. Lund et al. (2002) confirmed this by studying biomarkers of temperature stress in Atlantic salmon parr, which were exposed to high water temperatures in both the laboratory and in the wild. This study showed strong evidence that juvenile salmon are experiencing protein damage as a result of high water temperatures of significant duration. Prolonged summers with low discharge and high water temperatures can also influence the fish growth and conditions, as measured by fork length (Swansburg et al. 2002). This particular study showed that low discharge and high water temperatures generally resulted in poorer growth (i.e., smaller fish).

Most observations related to the thermal condition in rivers and their influences on aquatic habitat have been carried out in summer. In fact, most variations in stream water temperatures occur in open water conditions during the summer months, although small temperature changes have been monitored in winter (Marsh 1990). Winter conditions in rivers where temperatures remain close to 0°C results in different behaviour of salmonids (Cunjak and Power 1986; Cunjak 1988). Studies have shown that salmonids' activities during such time of year were very limited.

During summer conditions, water temperature changes on a seasonal basis, with daily fluctuations (Vannote et al. 1980). On a seasonal basis, the water temperature varies between low values in the spring (depending on latitude) to a maximum water temperature in mid-summer, which is then followed by a cooling period until the onset of winter. This natural process of heating and cooling of river temperatures is highly dependent on meteorological conditions as well as physical conditions of the river and therefore is important in the overall ecological functioning of rivers. As well, the stream biota is highly linked to this natural thermal process (Vannote and Sweeney 1980). For example, headwater streams generally tend to be colder due to higher groundwater inputs and the presence of more stream cover. Alternatively, lower sections of rivers tend to be warmer due to a longer travel time and the opportunity for more heating to occur. Diurnal variations are also dependent on the climate and on the physical characteristics of the river. These seasonal, daily variations and changes along river reaches of water temperatures are all important for aquatic resources, as outlined in the River Continuum Concept (Vannote et al. 1980).

2.1.2 Thermal regime of rivers in forested ecosystems

Literature about the thermal regime of rivers in forested ecosystem is voluminous, especially in regard to the topic of the impact of streamside forest removal (e.g., Gray and Edington 1969; Lynch et al. 1984; Beschta et al. 1987). This literature is very important for the overall understanding of the thermal behaviour of rivers and river temperature modelling because it provides information about many issues such as heat transfer processes and the role of solar radiation vs. heat conduction, among others. Generally, the thermal condition of a river is dependent on the size of the river and the land-use within the drainage basin. Smaller streams and brooks do not behave in a similar fashion to large rivers in forested ecosystems and therefore temperature fluctuations are different.

Similarly, stream water temperatures of urban drainage basins behave differently than those of forested basins (LeBlanc et al. 1997).

Many studies related to water temperature of forested basins have been carried out to assess the level of impact from timber harvesting activities (Brown and Krygier 1967; Hewlett and Fortson 1982; Rishel et al. 1982; Johnson and Jones 2000). Changes in water temperatures and the affect on aquatic habitat due to timber harvesting have been well documented in a review by Beschta et al. (1987). According to this review, only a few studies prior to the 1960s had looked at the impact of timber harvesting on thermal regime of forest ecosystems. Of greater concern before this period, was the impact of timber harvesting on the increase in runoff as well as the increase in sedimentation. This section will therefore focus on the knowledge related to river water temperature within forested ecosystems.

In late 1960's, a few studies were carried out to address timber harvesting activities and their impacts on the river thermal regime (Brown and Krygier 1967; Brown 1969). Before this period most research carried out on river water temperatures was mainly oriented towards addressing general characterisation of river thermal regime or problems related to thermal effluent (Raphael 1962; Ward 1963). With an increasing concern over the impact of forestry activities on aquatic resource, studies became focused on river water temperatures in relation to timber harvesting practices. For instance, Brown and Krygier (1967) showed an increase of 7.8°C in mean monthly maximum water temperatures in Oregon's Alsea River basin as a result of timber harvesting. They also showed that stream size can be an important factor on the level of impacts. This study was among the first to point out that small streams are highly vulnerable to increases in water temperatures due to their small size and volume (i.e., low thermal capacity). This study also discussed the potential impact of mud-slides, which presumably changes the channel morphology that can result in increased water temperatures. Other studies have shown that when surface water temperatures are altered by timber harvesting, intragravel water temperature is also affected (Ringler and Hall 1975).

To develop some predictive capabilities for addressing streamside forest removal, Brown (1970) showed that water temperature in rivers was directly proportional to the heat "load" and inversely proportional to streamflow (or discharge). Thus, he established a formula to provide an estimate of changes in water temperatures due to streamside vegetation removal. Brown (1970) showed that solar radiation accounted for close to 95% of the total heat input. He also discussed the impact of timber harvesting on increased summer baseflow and its relation to water temperatures. Brown and Krygier (1970) found similar increases in water temperatures due to timber harvesting with no streamside buffers. They observed a slight recovery in the year following timber harvesting and concluded that summer maximum water temperatures approached pre-logging levels after approximately 6 years.

Swift and Messer (1971) looked at the effects of 6 different harvesting treatments in small catchments and showed stream temperature increases of 6.7 °C due to timber harvesting. This study noted that the forest removal on the stream banks tended to increase daytime heating and nighttime cooling of stream water. Other studies also found increase water temperatures following removal of streamside vegetation (Feller 1981; Hewlett and Fortson 1982, Holtby and Newcombe 1982). Partial removal of forest within the riparian buffer zones can also influence stream water temperatures as reported by Feller (1981). This study showed that a 66 % removal of the overstory resulted in an increase of 5°C in summer daily mean water temperatures. Based on calculations, Hewlett and Fortson (1982) projected an increase in water temperature of 3.2°C due to timber harvesting, however they observed an increase in the order of 9°C, in the Southeastern Piedmont, Georgia. Their studied stream had a buffer of over 12 m on each side of the stream. They further hypothesised that the greater increase in water temperatures was due to warming of soil and shallow groundwater near the stream. The importance of soil/shallow groundwater heating influence on river temperature remains an unresolved issue when dealing with water temperature models. For instance, a more recent study suggests that increases in water temperature due to soil heating after forest removal remain low overall, but may be more important during summer storm events (St-Hilaire et al. 2000). Timber harvesting has been noted to increase mean and maximum water temperatures, however, Rishel et al. (1982) have shown significant changes in the duration of these high water temperature events as well.

Long-term studies carried out in Carnation Creek, (BC) found that changes in water temperatures due to timber harvesting can ultimately impact on the fisheries resources. For instance, Holtby and Newcombe (1982) noted increases in summer water temperatures in Carnation Creek, particularly in mean and maximum stream temperatures, as well as increases in diurnal variations. Holtby (1988a) showed that the impact of timber harvesting was noticeable throughout the year including summer and winter months. Such intra-annual changes in water temperatures have been observed to affect the development of stream biota (Scrivener and Andersen 1984; Holbty 1988b). For instance, higher winter temperatures after logging in Carnation Creek resulted in earlier downstream movement of fish by as much as six weeks (Scrivener and Anderson 1984), which could potentially affect their time of arrival at sea and food availability.

A long-term study (30 years) carried out in Salmon Creek, Oregon also showed that timber harvesting contributed to higher water temperatures (Beschta and Taylor 1988). They observed potential association between major flood events and subsequent higher temperatures, and hypothesised that these higher water temperatures were the result of changes in channel morphology. Another long-term study (1969-1989), involving increases in water temperature due to timber harvesting was carried out by Hostetler (1991). This study observed an increase of over 8°C monitored in a distance of less than 1.3 km of stream after the removal of trees from the stream bank.

The important role riparian buffers plays in protecting streams from heating was also evident from data presented by Burton and Likens (1973), where they showed that successive opening of the streamside canopy did contribute to increases in water temperatures. They also pointed out in their study that water temperatures tend to recover in buffered section of streams. They suggested that this could be due to the mixing of stream water with colder groundwater or substrate. Studies have used deterministic models with a shading component to calculate changes in the solar input depending on riparian vegetation. For example, Theurer et al. (1985) used such a model on the Tucannon River (USA) to evaluate the effects of restoration of streamside vegetation. Using a threshold of 20°C for unsuitable aquatic habitat, they demonstrated that revegetation could significantly limit both daily maximum and daily mean water temperatures. A similar study was carried out more recently by Chen et al. (1998a) where they developed a model to calculate solar input based on sun position, stream location, orientation and other relevant parameters. The application of this model was then tested for the Upper Grande Ronde watershed in Northeast Oregon (Chen et al. 1998b). They showed that such a model can be used to study hypothetical riparian restoration scenarios. The importance of riparian vegetation in protecting water quality standards remains an important issue (Brown and Huber 1998) and its restoration can be an effective means of protecting streams from heating (LeBlanc and Brown 2000). The cumulative effect of large-scale timber harvesting on water temperatures was also considered by Bartholow (2000), however, this study only addressed a hypothetical situation.

Larson and Larson (1996) looked at a very simplified hypothetical situation of streamside vegetation, and they concluded that solar input accounted for less than 20% of the total energy component. It was difficult to draw any conclusions from this study, as it was based on a hypothetical situation with no real data and direct field measurements. This may explain the large difference between this study and the reported solar input by Brown (1970). A rebuttal to this paper was provided by Beschta (1997), where he showed that streamside vegetation was not only important to protect streams against high water temperatures, but the vegetation (e.g. roots) also served to protect the stream by providing better stream bank stability.

Riparian buffer zones (or buffer strips) not only provide protection against solar radiation but also have been observed to act as a "blanket", thus reducing energy loss from the stream (Murray et al. 2000). This study estimated that when riparian buffers were removed from the riverbank, it takes between 5-15 years for the river to recover to its natural thermal regime due the vegetation re-growth. More recently, Johnson and Jones (2000), using long-term data, observed a maximum temperature increase of 7 °C due to riparian vegetation removal.

Based on a compilation of data from different West Coast studies, Mitchell (1999) showed that removal of streamside vegetation resulted in increased stream water temperatures, especially at higher temperatures. Changes were not observed at water temperatures below 3°C; however, an increase in the order of 2-3°C was observed for water temperatures exceeding 15 °C. This study used mean monthly water temperatures during pre and post timber harvesting for the analysis.

Many studies have been carried out to determine the impact of forest removal. Few however, have looked at the affect of varying the buffer width. Zwieniecki and Newton (1999) carried out such as study with 14 streams with riparian buffers ranging from 8.6 m to 30.5 m. Initially they studied the natural warming trends in streams prior to harvesting. Following the forest removal, they noted a higher than normal warming trend which they attributed to timber harvesting. They also observed a rapid recovery downstream (in the order of 150 m) from the buffered zone. This study concluded that despite substantial harvesting, the buffer zones were adequate to maintain water temperatures within the normal warming trends of fully covered streams with the exception of occasional small local increases.

A significant understanding of river thermal regime can be acquired through studying the literature on the impact of timber harvesting on rivers. The following points emerged from the literature. It was first noted that solar input played a dominant role in the overall thermal conditions of rivers. The size of stream (i.e. volume of water) was also noted to be an important factor in determining the water temperature fluctuations, while timber harvesting on small streams was associated with the greatest change in water temperatures. Near stream soil heating has been identified as a potential source of heat transfer to the stream environment. Groundwater contribution was also shown to be an important factor, especially in small streams. For instance, Shanley and Peters (1988) showed that groundwater played an important role, not only in streamflow generation but also to the thermal conditions in a small Georgia Piedmont watershed. Streamside vegetation was identified in the literature as being one the most important factors in preventing increases in water temperature. However, it remains unclear whether this is a result of preventing solar radiation from reaching the stream directly and/or through a protection of the river against convective heat transfer or microclimate (transfer of mass). For instance, the potential effects of microclimatic conditions near buffered zones have been discussed in a few studies (Chen et al. 1995; Brosofske et al. 1997), however, none of these studies specifically addressed stream water temperatures changes due to changes in microclimate.

2.1.3 Climate change and other anthropogenic perturbations

Although a great deal of research has been carried out on the impact of timber harvesting on stream water temperatures, the thermal regime of rivers can be affected by many other anthropogenic perturbations. These studies are found in the literature in a variety of forms. They include changes in stream water temperatures due to thermal pollution from industrial processes or thermal generating stations, changes in water temperatures due to reduction in river flow (e.g. irrigation), and modification of river thermal regime below dams (due to water releases) among others. More recently studies have been carried out to evaluate changes in water temperatures due to climate change (Meisner 1990a), although it is difficult to have a global perspective on water temperature trends due to a lack of data in many parts of the world (Webb 1996). These anthropogenic perturbations can modify the thermal regime of rivers and as a result can ultimately affect the fisheries and aquatic resources.

A reduction of river discharge, resulting from water withdrawal or water diversion projects (e.g. hydroelectric), has been shown to affect water temperatures (Morse 1972). For instance, Hockey et al. (1982) studied the impact of water withdrawal on water temperatures in the Hurunui River (New Zealand) using a deterministic model. The model was calibrated for a discharge of 62 m^3/s and was run at 10 m^3/s for similar meteorological conditions. They found that at 10 m^3/s, the river water temperatures would exceed critical values of 22°C for over 6 hours. Other studies have shown that water releases through instream flow requirements are a key component in keeping rivers from reaching excessively high temperatures in summer (Sinokrot et al. 1997). Another study carried out by Dymond (1984) showed that decreased river discharge resulted in higher maximum and minimum temperatures. This study proposed a simplified equation to express the changes in water temperatures under reduced flow. In testing the simplified equation, Dymond (1984) showed an error of approximately 17% compared to a full energy budget equation when discharge was reduced from 3 m^3/s to 2 m^3/s. Water withdrawal is predicted to increase over the next 25 years (Postel et al. 1996), and this is expected to further affect water temperatures.

Bartholow (1991) studied the impact of water withdrawal on the Cach la Poudre River near Fort Collins Colorado (USA) using a deterministic model, i.e. SNTEMP (Stream Network TEMPerature model; Theurer et al. 1984). The study was carried out to study the thermal habitat condition of rainbow and brown trout, in a site where over 16 irrigation diversions were present along a 31 km section of the river. The study showed that an increase in riparian vegetation from 13% to 23% would provide little improvements in cooling water temperatures; however, increasing the river discharge by 3 m^3/s would maintain water temperature at acceptable levels. Morin et al. (1994) modelled the impact of river diversion on water temperatures of the Moisie River in Quebec. The proposed diversion was to account for approximately 13% of the area in the upper basin. This study predicted that a reduced flow situation could increase water temperature by 1°C to 2°C depending on the reduction level. The researchers also noted in their modelling that changes would be more significant in the upper basin (i.e. the area most impacted by reduced flow) and that smaller changes in water temperatures would be observed in the lower basin. Sinokrot and Gulliver (2000) showed that the reduction of river flow can greatly influence the thermal regime, specifically resulting in the increased occurrence of high temperature events. In their study, they demonstrated that the gradual decline in the number of days with temperature exceeding 32°C in the Platte River (USA) was a function of increasing river discharge.

The thermal regime of rivers is also influenced downstream of reservoirs. As reported by Troxler and Thackston (1977) cold water releases from reservoirs can have a profound impact on the downstream thermal regime. They studied 5 facilities which had water release close to 10°C and they used an energy budget model to study the differences in heat fluxes. While gathering meteorological data, they noted significant changes in microclimatic conditions downstream of reservoirs. For instance, the cooled air resulting from the water release within the valley promoted the formation of fog, which prevented natural heat exchange between the river and the atmosphere. A significant reduction in solar radiation was therefore observed. This study showed that modifications to the thermal regime of rivers as a result of reservoir operation can be significant, as well as unexpected. Water releases have been noted to significantly modify the thermal habitat and influence the growth rate of fishes downstream of reservoirs (Robinson and Childs 2001). Webb and Walling (1993a) showed that water temperatures downstream of reservoirs were overall warmer which resulted in an increase in mean annual temperature. This study also showed that water temperatures below reservoirs experience the greatest differences in winter compared to natural conditions. In summer, downstream temperatures tend to be colder and the annual component (annual cycle) is often delayed. In a similar study, Webb and Walling (1993b) showed that changes in the thermal regime downstream of reservoirs tended to eliminate winter freezing conditions and reduce summer high temperatures. When studying the stream biota, they noted that predicted change between hatching and emergence could be advanced by over 50 days (Webb and Walling 1993b). Water temperatures below reservoirs show changes not only in the annual cycle, but also in the diurnal variations (Webb and Walling 1996). This study showed that water temperatures in the regulated system did not exceed 20°C, which was not the case for the unregulated system.

Cold water release downstream of reservoirs can be beneficial to aquatic resources, especially when trying to attain specific water temperature objectives (Michell et al. 1995). However, releases of steady water flow at relatively constant temperatures downstream of reservoirs can also result in varied diurnal variations in water temperatures (Lowney 2000). This study showed that thermal conditions downstream of the reservoir were such that at a location equivalent to 1/2 day of travel time downstream, diurnal variations in water temperatures were at maximum. Such maximum diurnal variations were more important than those observed naturally, and these could have potential adverse affects on aquatic biota. Also, minimum diurnal variations in water temperatures were observed at approximately 1 day of travel time downstream of reservoirs. Such changes in diurnal pattern could create zones or reaches within the river where fish would not be able to sustain high temperatures or would experience colder than normal temperatures. Similar patterns in water temperatures downstream of reservoirs to those observed by Lowney (2000) had been predicted by Duttweiler (1963). Relatively warm water temperature releases in winter are especially problematic in northern latitude rivers, where natural water temperatures would normally be close to 0°C. The resulting increase in winter water temperatures at these sites could have potentially greater impacts on aquatic habitat (e.g. incubation of salmonid eggs) than those posed by summer conditions.

Although reservoirs usually change the thermal regime of rivers downstream, some studies have shown that it was also more difficult to improve both water temperature and quality downstream of reservoirs (Malatre and Gosse 1995). The current knowledge suggests that reservoirs simply tend to regulate river flow and temperature. A long-term study in the UK (15 years) however showed that this was not necessarily the case (Webb and Walling 1997). This study showed that reservoirs resulted in a highly complex thermal regime that was far different from the simple regulation of the natural thermal regime. In fact, they observed that the thermal regime downstream of reservoirs was generated by complex hydrometeorolgical conditions, which were themselves modified by reservoir operations.

Thermal pollution from thermal generation stations or nuclear power plants, for example, can also adversely affect aquatic resources by reducing the area of suitable habitat (Bradley et al. 1998; Wright et al. 1999). Studies dealing with the modelling of water temperature under thermal effluent conditions have shown good agreement between predicted vs. observed water temperatures (Paily and Macagno 1976). In some extreme cases, the effluent could be creating a thermal plume across the river, extending from bank to bank, which could act as a complete thermal barrier for migrating fishes. In recent years, climate change has been identified as an important source of aquatic disturbance or thermal pollution on a large to global scale (Mohseni and Stefan 2001; Stefan et al. 2001). For instance, Sinokrot et al. (1995) noted that water temperature below reservoir and dams could be significantly affected by global warming, especially if water is released or discharged from the surface of reservoirs. In fact, their study pointed out that under a global warming scenario, any body of water which releases water from the surface (i.e. reservoirs, dams and lakes) will most likely experience the greatest impact due to increase in water temperature. Some climate change studies have suggested increasing riparian vegetation along streams as mitigation measures against high water temperatures (Cooter and Cooter 1990). When researching water temperature time series and climate change, very few long-term data sets are available to enable the implication of climate change on the thermal conditions of rivers to be effectively studied. One study from Scotland analysed 30 years of water temperature data (Langan et al. 2001). In studying long-term trends, they found no increases in mean annual water temperatures; however, winter and spring maximum temperatures increased by approximately 2°C over that time period. Webb and Nobilis (1997) carried out another related study, in which they analysed 90 years of water temperature data from north-central Austria. Annual water temperature could be explained using annual air temperature, however, only 51% of the variance was explained due to a weaker statistical association in winter. No specific trend was reported in water temperatures in this long-term study. Foreman et al. (2001) studied long-term trend in water temperatures from simulated historical temperatures obtained using a deterministic model and they noted an increase of 0.12 °C per decade in British Columbia (BC) Canada (1941-98).

Depending on changes in climate, global warming could potentially extirpate specific species of aquatic biota or dramatically modify their distribution within river systems as pointed out in recent studies (Minns et al. 1995; Houghton et al. 2001; Schindler 2001). Other studies have pointed out that in many parts of North America, fish are already experiencing their upper lethal limit in water temperatures (Sinokrot et al. 1995; Eaton et al. 1995). In Eastern Canada, studies show that the air temperature is expected to increase between 2-6°C in the next 100 years (Parks Canada 1999). Such an increase in air temperature will undoubtedly translate into higher stream water temperature as well as higher groundwater temperature as they are interlinked (Meisner et al. 1998). It was also estimated that climate change could result in an overall loss of juvenile Atlantic salmon habitat in the order of 4% (Minns et al. 1995). This study also noted that the smoltification age could decrease by 8% to 29%, depending on the area. A more recent study showed that projected increases in water temperatures due to climate change could also affect the growth of juvenile Atlantic salmon (Swansburg et al. 2002).

Studies on the Fraser River (BC) have showed that climate change could potentially alter the timing of peak flows as well as increasing summer water temperatures by 2099 (Morrison et al. 2002). They calculated an increase of 5% in the mean annual flow and a decrease of 18% in peak flow. Peak flows are also expected to occur 24 days earlier in the season, which could impact on summer water temperatures. The summer temperatures are projected to increase by 1.9°C, which would result in an increase in the number of days with water temperature exceeding 20°C.

Water temperature modelling studies are becoming increasingly more important to improve our understanding of the natural processes of aquatic ecosystem and also enable us to address the potential impacts of anthropogenic perturbations, such as climate change. Therefore, the objective of the next section will be to provide a review of existing water temperature models.

2.2 Review of existing water temperature models

Much has been learned over the past few decades about the temporal and spatial variability of water temperature in rivers. Advances have been made in the development of water temperature models, ranging from simple to complex models. These models have been classified into two distinct categories, deterministic or statistical (Marceau et al. 1986). This classification will also be used in this study. Other studies have modelled water temperatures using a deterministic model whereas the analysis of errors was carried out by stochastic processes (Bravo et al. 1993). For instance, they used a deterministic model where a stochastic formulation was used to account for uncertainty due to model assumptions, errors in parameters, and river temperature measurements.

A deterministic model is a conceptual modelling approach which takes into account cause and effect relations between meteorological parameters and the river environment. Alternatively, the statistical approach to predict water temperature is based on relating water temperatures to relevant meteorological parameters (e.g. air temperature). This latter approach can also consider the autocorrelation in the water temperature time series such as in the case of stochastic models. Each of these approaches has advantages and disadvantages in their application. For instance, the deterministic modelling approach is better adapted to the analysis of thermal effluent problems where mixing of water from different sources and different temperatures occurs. Also, the deterministic modelling approach is very useful when analysing different scenarios dealing with changes in input parameters (e.g. solar radiation, air temperatures, etc.).

A major drawback of deterministic models is the complexity of the modelling as well as the number of input parameters required to run the model. In fact, it occurs frequently that the required input parameters are not available close to the study area, and therefore input parameters are often obtained a distance (e.g. 50-100 km) from the study site for modelling purposes.

The statistical / stochastic modelling approach is a method that requires very few parameters and thus is simpler to apply. This approach can provide very good results with air temperature as the model's single input parameter. The stochastic modelling approach is particularly well adapted for climate change studies where air temperature is often the only parameter projected with a good level of certainty. Both the deterministic modelling and the stochastic modelling are relevant depending on the problem under investigation and the data availability.

2.2.1 Deterministic models

Before describing the basis of deterministic models, it is important to define their domain of application as it can vary depending on the problem under investigation. For instance, two types of thermal problems are encountered in practice, namely small-scale changes and large-scale changes in water temperatures. These are also referred to as near-field or far-field space domain problems. An example of a near-field space domain problem, is an effluent pipe discharging into a river. Another example would be the thermal exchange at the confluence of two rivers having different temperatures. In the near-field type problems, the modelling typically focuses on the mixing zones similar to the technique used to model the mixing of tracer elements. In near-field domain problems, fluid properties and/or density, and not meteorological conditions, are the dominant factors affecting the heat exchange processes. Modelling within the near-field space domain is usually in the scales of metres rather than kilometres. Beyond the near-field domain is the far-field domain, where local mixing processes are no longer a dominant factor and where meteorological heat exchange between the river and atmosphere becomes important. Examples of far-field problems include the modelling of water temperatures along a river reach for 10's to 100's of kilometres. The present modelling study will focus exclusively on far-field type problems, wherein meteorological factors are the dominant forces responsible for changes in water temperatures.

In the analysis of far-field problems, as in near-field problems, one has to select the model's dimension (0-D, 1-D, 2-D or 3-D) depending on both the type of environment and problem under consideration. For instance, for the application of a deterministic model in a lake or a reservoir environment, the space domain may be 3 dimensional by including the depth as an important factor. Depth becomes important when lakes and reservoirs are stratified and posses an appreciable vertical gradient in water temperatures. By contrast, when carrying out a water temperature modelling within a river environment, the problem is most often reduced to a 1 dimensional problem, where the temperature is simulated along the river's principal axis. This is because water temperature in rivers is relatively uniform in depth (i.e. well mixed) and very small changes are usually observed in the traverse direction (i.e. cross sectional gradient in temperatures). Information in the literature suggests that stratification in river water temperatures is generally not observed at water depth below (4-5 m). Even when stratification becomes important in large rivers under certain meteorological conditions (i.e., low wind speed), Bormans and Webster (1998) have shown that water temperatures can be modelled for different depths.

The deterministic modelling approach consists of considering most relevant energy parameters or energy budget (net short-wave radiation, net long-wave radiation, convection, evaporation/condensation, precipitation, streambed (sediment/geothermal), groundwater and friction) to predict variation in water temperatures (e.g. Raphael 1962, Marcotte and Duong 1973, Vugts 1974; Rinaldi et al. 1979; Morin and Couillard 1990, Morin et al. 1994). Deterministic models are based on equations of conservation of energy, thus estimate the changes in river water temperatures based on energy flux at the stream surface and bottom. This energy flux is expressed in Joules per second (J/s), Watts (W), or calories (cal). The energy flux for a given stream is a function of the surface area of that stream, but most studies express the energy flux per unit of area, i.e. $J/s/m^2$ or W/m^2. A positive energy flux means that energy is entering the river, i.e. resulting in an increased water temperature, while a negative energy flux tends to cool the river system. Deterministic models have the advantage of being able to address conditions in rivers such as the influence of high and low flow on water temperatures, because changes in temperatures are directly proportional to the energy flux and inversely proportional to the river depth (volume of water). These models are also able to consider different scenarios of climatic conditions depending on which energy component is most affected and ultimately will enable us to model this affect on water temperature (Sinokrot et al. 1995; Pilgrim et al. 1998).

In the deterministic modelling, physical characteristics of the stream, such as the average depth of water, degree of stream cover, as well as other parameters, can be important. Also, most meteorological parameters available from weather stations are required in the modelling (e.g. solar radiation, air temperature and relative humidity, wind speed and precipitation), which makes this approach significant in terms of data requirement. Deterministic models have the advantage of being flexible in that they permit the modification of input parameters to study the resultant changes in water temperatures. Lumped models provide output for one point along a river, while distributed models can simulate water temperature at various locations on a given river (Morin et al. 1983; Morin et al. 1987). In many rivers, a one-dimensional mathematical model is sufficient to model water temperature especially when the river is well mixed.

Once calibrated for a given studied region, deterministic models can be applied to different streams provided that the deterministic characteristics of the other streams are known. These models are most suited for thermal effluent problems, as they can consider a volume of water with different temperatures including tributary inflow. For instance, deterministic models have been shown to be effective in considering the influence of tributaries (Noble and Jackman 1979; Gilbert et al. 1986) or thermal discharges (Hills and Viskanta 1976). They can also be used to identify potential changes in water temperatures due to changes in climatic conditions. The disadvantage of deterministic models is in the amount of data required to run them coupled with the time and expense for their development.

Studies have shown that the most important weather parameters in the deterministic modelling approach are air temperature and solar radiation (Sinokrot and Stefan 1994). These parameters are 3 to 4 times more important that others parameters such as relative humidity, cloud cover and wind speed as demonstrated in a sensitivity analysis. The study by Sinokrot and Stefan (1994) also showed that the effect of barometric pressure is insignificant in changes to water temperatures.

The transfer of heat in a body of water, i.e. distribution of temperatures, is a result of three separate processes: 1) molecular diffusion, 2) turbulent diffusion and 3) dispersion. Molecular diffusion occurs through random motion of a tracer (i.e. heat or a contaminant) and is described by Fick's Law, which states that the flux of a tracer is proportional to the gradient of concentration of that tracer. Transport due to molecular diffusion is typically minor compared to other transport mechanisms in rivers. Turbulent diffusion, for instance, occurs as the result of random velocity fluctuation and can also be described using Fick's Law. The coefficient of proportionality for turbulent diffusion is typically much higher than that for molecular diffusion. In a river, the velocity in the mid-section can be significantly higher than that observed near the river-edges. Mixing due to this difference in the velocity gradient represents the transport by dispersion. The general three-dimensional model, when applying the principle of conservation of thermal energy, is expressed as follows:

$$\frac{\partial T_w}{\partial t} + v_x \frac{\partial T_w}{\partial x} + v_y \frac{\partial T_w}{\partial y} + v_z \frac{\partial T_w}{\partial z} -$$

$$\frac{1}{A}\frac{\partial}{\partial x}\left(AD_x \frac{\partial T_w}{\partial x} \right) - \frac{1}{A}\frac{\partial}{\partial y}\left(AD_y \frac{\partial T_w}{\partial y} \right) - \frac{1}{A}\frac{\partial}{\partial z}\left(AD_z \frac{\partial T_w}{\partial z} \right) = \qquad [2.1]$$

$$\frac{W}{\theta \rho A} H_t + \frac{P}{\theta \rho A} H_{sed}$$

where T_w = water temperature (° C).

t = time (day).

x = distance downstream (m).

y = longitudinal distance (m).

z = vertical distance (m), depth.

A = cross sectional area (m^2).

v_x, v_y, and v_z = mean water velocity in respective directions ($m\ d^{-1}$).

W = river width (m).

D_x, D_y, *and* D_z = dispersion coefficients in respective directions ($m^2\ d^{-1}$).

θ = specific heat of water (4.19×10^{-3} MJ $kg^{-1}\ °C^{-1}$)

ρ = water density (1000 kg m^{-3}).

P = wetted perimeter of the river (m).

H_t = total heat flux per area from the atmosphere to the river (MJ $m^{-2}\ d^{-1}$).

H_{sed} = total heat flux per area from the riverbed (MJ $m^{-2}\ d^{-1}$).

This first term in equation [2.1] takes care of the unsteady component in heat transport, thus describing change in temperature over time. The next three terms with a velocity component (v_x, v_y and v_z) are responsible to the transfer of heat with flow, also referred to the bulk flow heat transport. The next three terms of equation [2.1] are responsible for the transfer of heat through dispersion and mixing processes. The terms of the right hand side of the equation represent the heat flux at the air/water surface and at the water/sediment interface.

The heat flux at the water/sediment interface is most often neglected as it is small compared to the heat flux at the air/water surface interface. For instance, (Sinokrot and Stefan 1994) showed using a sensitivity analysis that streambed thermal conductivity accounts for temperature variability of less than –0.12 °C to +0.15 °C. This means that when the heat is transferred from the streambed to the stream, the water temperature changes by less than 0.2°C on a daily basis. Other studies have shown that if the time step is less than daily (i.e. hourly water temperatures), then the streambed thermal conductivity becomes significant and has to be considered in the modelling (Jobson 1977; Sinokrot and Stefan 1993).

In fact, very few studies have quantified the relative importance of heat exchange at the water/sediment interface. To carry out such study, one requires data on the water temperature gradient within the stream substrate. One of the early studies dealing with water temperature data within the steam substrate was carried out by Comer and Grenney (1977), where they showed three different heat transfer processes at the streambed: direct solar radiation, groundwater advection, and conduction. In a related study, Lapham (1989) showed that the water temperature gradient within the stream substrate is mainly a function of conduction and the vertical gradient of the water velocity. Hondzo and Stefan (1994) showed that heat exchange from the streambed can vary between –40 W/m^2 to +5 W/m^2. Such heat flux could account for changes in water temperature of up to 0.8°C at an average depth of 1 m. More recently, data presented by Alexander et al. (2003) showed that the streambed is gaining heat throughout the summer period which is then subsequently release during the winter period. Peak values of streambed heat flux were observed during autumn cooling period. Although these studies have looked at the importance of the heat fluxes from the streambed, most studies dealing with the modelling of water temperatures have successfully modelled water temperatures by neglecting this component.

In near-field type problems, equation [2.1] or a simplified version (neglecting the z component when assuming no vertical gradient, i.e. average depth conditions) is often considered in water temperature analysis. Alternatively, in analysing far-field problems and when the river constitutes a well-mixed environment, water temperature variations along the river reach are usually more important than vertical gradients with depth as well as lateral temperature variability. Furthermore, if we assume that the heat flux from the streambed is small compared to the heat flux at the water surface (Sinokrot and Stefan 1994), then equation [2.1] can be reduced to the following one dimensional equation.

$$\frac{\partial T_w}{\partial t} + v_x \frac{\partial T_w}{\partial x} - \frac{1}{A}\frac{\partial}{\partial x}\left(AD_x \frac{\partial T_w}{\partial x} \right) = \frac{W}{\theta \rho A} H_t \qquad [2.2]$$

In the above one dimensional equation [2.2], the dispersion term is still present; however, the dispersion along the river reach (D_x) is most often small compared to the heat transport by bulk flow (second term in [2.2] with velocity component). Therefore the one dimensional heat transport equation can be further simplified as follows:

$$\frac{\partial T_w}{\partial t} + v_x \frac{\partial T_w}{\partial x} = \frac{W}{\theta \rho A} H_t \qquad [2.3]$$

Equations [2.2] and [2.3] are the most frequently used equations in river water temperature modelling (Borcard and Harleman 1976; Sinokrot and Stefan 1993; Younus et al. 2000). For river reaches, the downstream changes in water temperature are usually small compared to the temporal changes (e.g. diurnal or daily variation). For instance, Torgersen et al. (2001) showed an increase of less than 0.09°C per km in the McKenzie River (Oregon). In such cases, equation [2.3] can be further simplified to the following form:

$$\frac{\partial T_w}{\partial t} = \frac{W}{\theta \rho A} H_t \qquad [2.4]$$

where parameters are the same as in [2.1]. Equation [2.4] has been used in a number of studies to estimate river water temperature at a specific location along a river reach (0-D) using meteorological data only (Morin and Couillard 1990; Marcotte and Duong 1973). Also when conducting a one-dimensional water temperature modelling (i.e. using equation [2.3]), the upstream boundary conditions (i.e. upstream water temperatures) are required to run the model. Previous studies have used equation [2.4] to calculate the upstream boundary conditions to run the one-dimensional water temperature model (Sinokrot and Stefan 1993; Younus et al. 2000).

Independently of equations used to simulate water temperatures, the total heat flux (H_t) at the river surface has to be calculated. The total heat flux is considered to be the summation of the different heat flux components such as:

$$H_t = H_s + H_l + H_e + H_c \quad [2.5]$$

where H_t = total heat flux at the stream surface (MJ m^{-2} d^{-1}).
H_s = net short-wave radiation at the stream surface (MJ m^{-2} d^{-1}).
H_l = net long-wave radiation at the stream surface (MJ m^{-2} d^{-1}).
H_e = evaporative heat transfer at the stream surface (MJ m^{-2} d^{-1}).
H_c = convective heat transfer at the stream surface (MJ m^{-2} d^{-1}).

Other heat fluxes can also be considered, e.g. heat flux due to rainfall (Marcotte and Duong 1973), however these are often insignificant in the overall temperature variability and they are therefore neglected.

Solar radiation

Many studies have shown that the principal source of heat energy to a river comes from solar radiation. Solar radiation when measured at the earth's surface includes both the direct and diffuse short-wave radiation (also termed global radiation). The solar radiation, which is not absorbed by the atmosphere, typically consists of short-wave radiation in the range of 0.3 μm to 4.0 μm depending on latitude, time of day, season, cloud cover, and other factors. The solar radiation above the atmosphere, also termed the extraterrestrial radiation, has been monitored using space observation and a solar constant of 1.367 kJ m^{-2} s^{-1} has been adopted (ASCE 1990).

On cloudless days the atmosphere is relatively transparent to short-wave radiation and 70-80% of the total radiation can reach the earth's surface. The difference or reflected radiation is accounted for by dust particles and gases, among others. The solar radiation can be measured using a variety of devices, including radiometers and pyranometers. A pyranometer estimates the radiation by measuring both the direct sun beam radiation and the diffuse sky radiation. Using pyranometric data, the clear sky solar radiation at the earth's surface can be calculated at specific sites and latitude using an envelope curve passing through solar radiation data for cloudless days.

The clear sky solar radiation (e.g., in absence of vegetation) can be estimated by a number of physically-based equations (Dingman 2002). Alternatively, daily values of solar radiation can be estimated using the following empirical equation (ASCE 1990):

$$H_{si} = (0.25 + 0.50\, n_1/N_1)\, R_A \qquad [2.6]$$

where H_{si} = the estimated incoming solar radiation under varied cloud conditions (MJ m^{-2} d^{-1}).

n_1/N_1 = the ratio between measured bright sunshine hours and maximum possible sunshine hours.

R_A = the extraterrestrial radiation (MJ m^{-2} d^{-1}).

Therefore, daily values of solar radiation under clear sky conditions are obtained when $n_1/N_1 = 1$, which gives:

$$H_{so} = 0.75\ R_A \qquad [2.7]$$

where H_{so} = daily clear sky solar radiation (MJ m^{-2} d^{-1}).

Values of extraterrestrial radiation, R_A, can be calculated using the following equation (ASCE 1990):

$$R_A = (24(60)/\pi)\ G_{SC}\ d_r\ [(\omega_s)\sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\sin(\omega_s)] \qquad [2.8]$$

where all angles are expressed in radian,

R_A = the daily extraterrestrial radiation in (MJ m^{-2} d^{-1})

ϕ = the latitude of the site

δ = the declination

G_{SC} = the solar constant (0.0820 MJ m^{-2} min^{-1})

ω_s = the sunset hour angle and

d_r = the relative distance of the earth from the sun.

The declination is given by:

$$\delta = 0.4093 \sin(2\pi\ (284 + j)/365) \qquad [2.9]$$

where j is the day of year (January 1 = 1 and December 31 = 365).

The relative distance of the earth from the sun is given by:

$$d_r = 1 + 0.033 \cos(2\pi\ j/365) \qquad [2.10]$$

The sunset hour angle, ω_s, in radian can be obtained from the following equation:

$$\omega_s = \arccos(-\tan(\phi)\tan(\delta)) \quad [2.11]$$

Using equations [2.7] to [2.11], the clear sky solar radiation for any particular site can be estimated. Clear sky solar radiation at sites of different latitudes as presented in Figure 2.2 was determined using the above equations. Solar radiation reaches a maximum at the summer solstices and a minimum during the winter solstices for sites at latitude higher than 10°. For low latitude sites, the solar radiation can reach its maximum at other times of year (Figure 2.2).

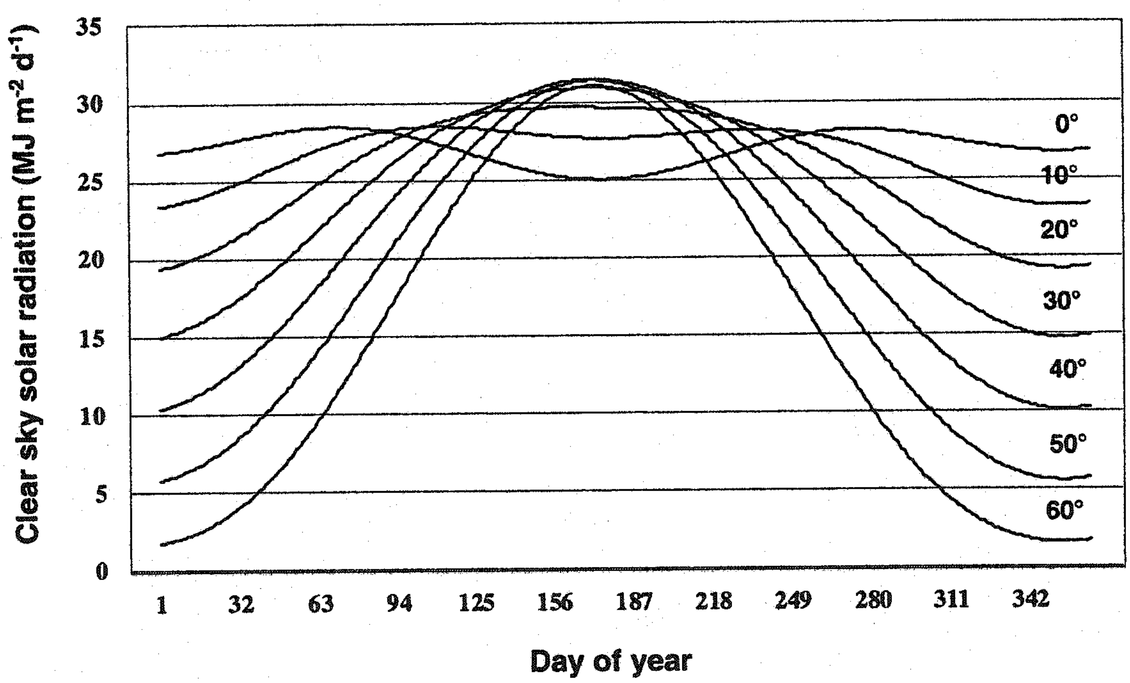

Figure 2.2 Clear sky solar radiation at different latitudes (based on a solar constant of 0.082 MJ m^{-2} min^{-1})

In New Brunswick, solar radiation has been monitored on a continuous basis at very few sites. One such site exists at the Fredericton Airport, where Environment Canada has been monitoring solar radiation since 1913. Long-term data at Fredericton, which is the closest in proximity to the Miramichi River (area of interest), show that solar radiation varies between 4.17 MJ m^{-2} d^{-1} (Dec.) to 19.9 MJ m^{-2} d^{-1} (Jun.) (Table 2.1). From these long-term solar radiation readings and the clear sky solar radiation values at Fredericton, the cloud cover index (i.e. n_l/N_l, which is the ratio between measured bright sunshine hours and maximum possible sunshine hours) can be estimated using equation [2.6]. Cloud cover in the Fredericton region shows very consistent results within the year, with values ranging from 0.42 to 0.57, except for November and December, which shows lower values at 0.31 and 0.38 (Table 2.1).

Data on solar radiation are also available for the Miramichi River, from the Catamaran Brook meteorological station from 1990 to 1998 (latitude 46° 52.7' N; detailed information on the Catamaran Brook meteorological station and its measured parameters is provided in section 3.2). Solar radiation data show values ranging from 2.76 MJ m^{-2} d^{-1} (Dec. 1996) to a maximum value of 21.0 MJ m^{-2} d^{-1} (Jun. 1995) (Table 2.2). Mean monthly solar radiation are similar to those observed in Fredericton, and ranged from 3.19 MJ m^{-2} d^{-1} (Dec.) to 18.8 MJ m^{-2} d^{-1} (Jun.). Clear sky values are also presented for comparative purposes.

Table 2.1 Mean daily solar radiation (H_{si}), MJ m^{-2} d^{-1}, in Fredericton (NB) (station 8101600; 45° 55' N and 66° 37' W) from 1913 to 1993 (data provided by Environment Canada). Monthly cloud cover index (n_l/N_l), ratio of sunshine hours to maximum sunshine hours.

Month	Mean 1913-93[1]	Mean cloud cover index[2]
January	5.47	0.49
February	8.68	0.57
March	12.4	0.53
April	15.1	0.43
May	18.0	0.42
June	19.9	0.45
July	19.7	0.48
August	17.3	0.49
September	13.1	0.47
October	8.59	0.42
November	4.96	0.31
December	4.17	0.38

[1] Data on solar radiation obtained from Environment Canada.
[2] Cloud cover index calculated from equation [2.6].

Table 2.2 Calculated clear sky solar radiation (H_{so}), MJ m^{-2} d^{-1} at the Miramichi River and measured solar radiation (H_{si}), MJ m^{-2} d^{-1} at the Catamaran Brook Meteorological station.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1990	n/a	n/a	n/a	n/a	15.6	19.8	18.0	17.6	11.3	5.87	3.60	3.19
1991	4.02	7.29	9.67	15.6	17.6	20.5	18.8	14.7	12.4	6.67	4.12	2.60
1992	4.27	6.29	12.4	15.4	20.8	16.1	17.4	14.7	12.8	7.51	4.80	3.01
1993	4.56	7.49	12.8	12.8	15.0	18.2	17.7	17.7	12.2	7.03	4.25	2.82
1994	3.03	8.45	8.49	14.3	14.9	n/a	n/a	17.3	11.6	9.98	5.15	3.68
1995	2.66	7.69	9.15	14.9	16.9	21.0	18.9	20.0	15.5	6.90	4.79	3.66
1996	4.29	5.37	12.7	13.0	16.4	20.6	15.6	18.6	10.9	8.84	4.57	2.76
1997	4.48	6.88	11.5	15.3	15.3	n/a	n/a	16.0	10.3	7.39	4.53	3.32
1998	3.49	7.78	9.59	15.4	17.3	15.7	19.3	17.4	11.1	6.62	4.00	3.66
Mean[1]	3.85	7.16	10.8	14.6	16.7	18.8	18.0	17.1	12.0	7.42	4.42	3.19
H_{so}[2]	8.27	12.2	18.1	24.4	29.2	31.3	30.2	26.2	20.3	14.0	9.17	7.14

[1] average H_{si} from 1990-98; [2] clear sky (H_{so})

Net short-wave radiation at the stream surface can be calculated by the difference between incoming solar radiation and reflected radiation at the water surface given by:

$$H_s = H_{si} - H_r \qquad [2.12]$$

where H_s = net short-wave radiation (MJ m^{-2} d^{-1}).

H_{si} = incoming short-wave radiation (MJ m^{-2} d^{-1}).

H_r = reflected short-wave radiation at the water surface (MJ m^{-2} d^{-1}).

Of the total incoming solar radiation, as measured using the pyranometer, a portion is reflected when the radiation reaches a particular surface, e.g. water surface. In the case of estimating the reflected solar radiation, different equations can be used. For instance, Raphael (1962), Kim (1993) and Kim and Chapra (1997) showed that reflected solar radiation is a function of many factors including solar altitude (solar angle), cloud cover and water conditions (e.g. bubbles, suspended particles, etc). Raphael (1962) showed that although cloud cover did play a role on reflectivity, solar altitude was the main and most important factor. These studies showed that reflected radiation is very similar for solar altitude over 40°, however, significant differences are observed for lower solar angles (Figure 2.3; Table 2.3).

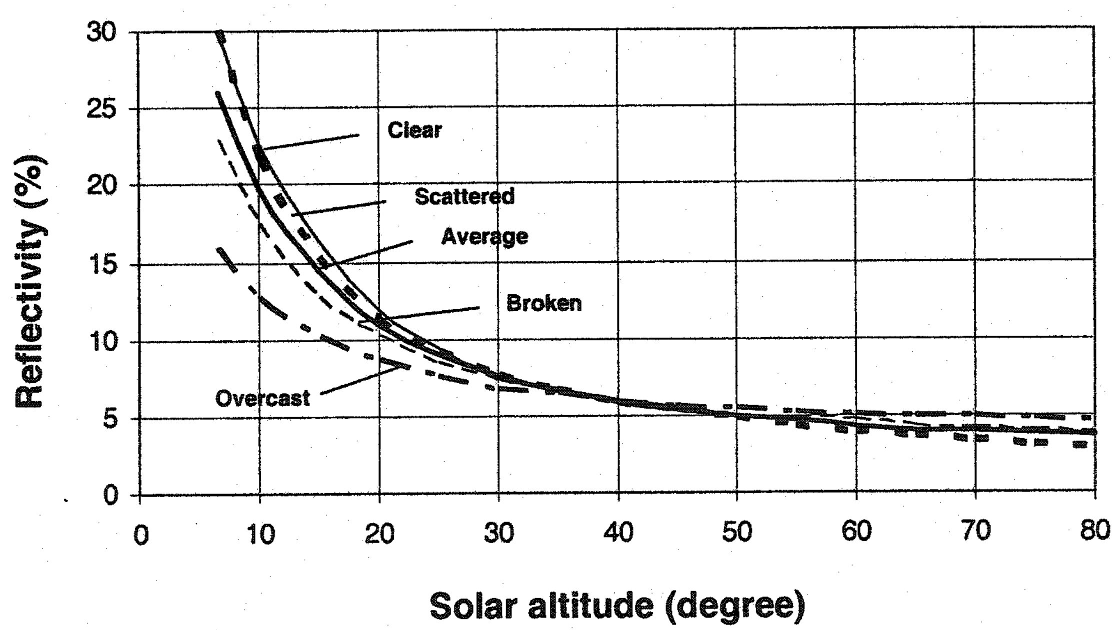

Figure 2.3 Influence of solar altitude and cloud cover on reflectivity (adapted from Raphael 1962).

Figure 2.3 shows that reflected radiation is highest for clear sky at low solar altitude and lower for overcast sky. Also, reflected radiation is less than 3-5% for solar altitude higher than 40° (Table 2.3; Figure 2.3). It is important to point out that the actual solar radiation at low solar altitude is quite low. For instance, Raphael (1962) showed that when studying the net incoming radiation (i.e. the difference between the incoming short-wave radiation and the reflected radiation) under an average value of reflectivity, the error introduced was small for most solar altitudes. As a result of these observations, many studies have been carried out with the consideration of a constant value for reflectivity.

Table 2.3 Changes in reflectivity (%, reflected solar radiation) as a function of solar altitude (adapted from Kim 1993).

Solar altitude (degree)	Reflectivity (%)
0	100
10	34.8
20	13.4
30	6.0
40	3.4
50	2.5
60	2.1
70	2.1
80	2.1
90	2.0

Studies using a constant reflected radiation have used a value of 3-5% of the net incoming radiation reaching the stream (Morin and Couillard 1990) and therefore the equation becomes:

$$H_s = (H_{si} - H_r)\ (1 - SF) \qquad [2.13a]$$

$$H_s = (H_{si} - rH_{si})\ (1 - SF) \qquad [2.13b]$$

$$H_s = (1 - r)\, H_{si}\ (1 - SF) \qquad [2.13c]$$

where H_s = net incoming solar radiation reaching the stream (MJ m^{-2} d^{-1}).

H_{si} = incoming solar radiation as measured by pyranometer (MJ m^{-2} d^{-1}).

SF = shading factor of the river reach (0 to 1, depending of forest cover and upland shading).

r = reflectivity of the water surface (e.g. 0.05, or 5%).

The shading factor (*SF*) has been considered in many studies as a bulk coefficient, thus representing shading for whole river or the studied reach (Marcotte and Duong 1973; Sinokrot and Stefan 1993; Mohseni and Stefan 1999). Many of these studies have estimated the shading factor as an adjusted parameter during the calibration period rather than relying on at-stream data. Other studies have made attempts to better estimate shading based on local river observations. For instance, Webb and Zhang (1997) and Webb and Zhang (1999) used a function which considered the angle of the sun and the stream bank height to estimate the amount of shading. Other field methods have been described to estimate streamside shading at specific locations (e.g. Bartholow 1989) including hand-held meters. In most water temperature modelling studies, to have such a level of precision in the estimation of streamside vegetation may not be that important. However, if the ultimate objective of the study is to determine the impact of streamside forest removal at specific sites on the overall thermal condition of the river, then such data may be important. Such a study was conducted by Chen et al. (1998a) and Chen et al. (1998b) where a computer program was developed and used to estimate the amount of solar radiation reaching the stream based on factors such as sun position, stream location and orientation as well as riparian vegetation characteristics.

When all relevant parameters affecting the net incoming short-wave radiation, such as shading factor and water surface reflectivity are obtained, then the net short-wave radiation can be calculated using equation [2.13c].

Net Long-wave radiation

Most objects emit energy through long-wave radiation as a function of their temperature. This is the case as well for long-wave energy flux between the river environment and the atmosphere. Long-wave radiation is transported through electromagnetic waves, and the emitted radiation follows the Stefan-Boltzmann Law given by:

$$E_b = \sigma T^4 \qquad [2.14]$$

where E_b = the emissive power (MJ m^{-2}).

σ = the Stefan-Boltzmann constant (4.9 x 10^{-9} MJ m^{-2} K^{-4}).

T = the absolute temperature of the surface in Kelvin (K).

A surface directly obeying equation [2.14] is called an ideal radiator or a black body radiator. Most actual surfaces emit long-wave radiation less than those of black bodies, and equation [2.14] is therefore reduced by an emissivity factor, which typically ranges between 0.88 (rocks) and 0.97 (water).

When considering the net long-wave radiation at the surface of a water body, the equation is given in the following form:

$$H_l = 0.97\sigma \; [\beta T_a^4 - T_w^4] \qquad [2.15]$$

where H_l = net long-wave radiation (MJ m^{-2} d^{-1}).

T_w = absolute water temperature (Kelvin, K), or °C + 273.15.

T_a = absolute air temperature (Kelvin, K), or °C + 273.15.

σ = Stefan-Boltzmann constant (4.9 x 10^{-9} MJ m^{-2} K^{-4}).

β = further reduction factor due to the atmospheric emissivity.

Equation [2.15] reflects the fact that the emissivity of water is taken at 0.97; however, the atmospheric emissivity is a more complicated function as reported in the literature (Raphael 1962; Marcotte and Duong 1973; Morin and Couillard 1990). Atmospheric emissivity is a function of the distribution of moisture, temperature, ozone, and carbon dioxide, among others, of which moisture is the dominant factor (Raphael 1962). The atmospheric emissivity can be obtained graphically as a function of vapor pressure and cloud cover as reported by Raphael (1962), or using the following equations (Marcotte and Duong 1973):

$$\beta = 0.65 + 0.15 \sqrt{25.4\, e_a} + 0.002\, B_c \qquad [2.16a]$$

or the equation given by Morin and Coulillard (1990):

$$\beta = (0.74 + 0.0065\, e_a (1 + 0.17 B_c^{\,2}) \qquad [2.16b]$$

as well as the equation used by Sinokrot and Stefan (1994):

$$\beta = (1 - 0.261 \exp[-7.77 \, x \, 10^{-4} T_a^2]) \, (1 + 0.17 B_c) \qquad [2.16c]$$

where e_a = water vapor pressure in the air (mm Hg).

B_c = cloud cover (0 = clear sky and 1 = total could cover).

T_a = air temperature, °C.

The water vapor pressure (e_a) can be obtained from tables or it can be calculated using the following approximation equations (Chow et al. 1988):

$$e_a = 4.583 \exp\left(\frac{17.27\, T_a}{237.3 + T_a}\right) \cdot \frac{RH}{100} \qquad [2.17a]$$

or the equation provided by Morin and Couillard (1990):

$$e_a = 0.75 \exp[54.721 - 6788.6\,(T_a + 273.15)^{-1} - 5.0016 \ln(T_a + 273.15)] \cdot \frac{RH}{100} \qquad [2.17b]$$

where RH = relative humidity (%, from 0 to 100%).

These equations have been used to calculate effective back radiation (net long-wave radiation), which is the difference between the long-wave radiation from the atmosphere and the long-wave radiation leaving the body of water. The net long-wave radiation in [2.15] is generally a negative term in the total heat budget, which tends to decrease the water temperature in rivers. The streamside vegetation (e.g., closed or partially closed canopy) could also be a sources of long-wave radiation; however, no information could be found in the literature where this component was considered in water temperature modelling.

Evaporative heat transfer

When the vapor pressure of the air is less than the saturated vapor pressure at the temperature of the water surface, then water evaporates at the surface, thus removing heat from the body of water. Duttweiler (1963) pointed out that the evaporative heat flux is a parameter which is difficult to estimate with a good level of accuracy. In fact, Dake (1972) showed that different approaches to the estimation of evaporative heat transfer can result in significantly different estimates. The Lake Hefner as well as the Penman's and Meyer's equations were all compared and differences in evaporative heat transfer were observed. Dake (1972) also observed that some equations provided underestimates of evaporation (-12 to -15%), especially when applied in hotter climates. Although no information was found related to condensation in the stream water temperature modelling literature, in some cases this component may be important to consider.

Evaporation is a diffusive process as a function of the vertical transport of water vapor and physically-based equations follow a Fick's Law (Dingman 2002). One commonly used equation in stream water temperature modelling to estimate evaporative heat lost is based on the following evaporation equation:

$$E = (a_1 + b_1\, V)\,[e_s - e_a] \qquad [2.18]$$

where E = evaporation (mm d^{-1}).

a_1, b_1 = empirical constants.

V = wind velocity at predetermined height, e.g. 2 or 10m (m/s or km h^{-1}).

e_s = saturated vapor pressure at the water temperature (mm Hg).

e_a = water vapor pressure in air (mm Hg).

In equation [2.18] the evaporation is a function of two components, determined by the empirical constants a_1 and b_1. The first component (a_1) is the molecular rate of evaporation, i.e. when the wind velocity is $V = 0$. As pointed out by Duttweiler (1963), the molecular rate of evaporation can be neglected without introducing significant errors because the coefficient (a_1) is usually small. The second component (b_1) takes into consideration the wind effect on evaporation. Others studies have used a similar equation but with the evaporative heat lost as a function of V^2 rather than V in equation [2.18] (e.g., Kim and Chapra 1997; Foreman et al. 1997).

In practice, many studies found in the literature dealing with evaporative heat transfer have neglected the molecular evaporative heat loss ($a_1 = 0$) and therefore the evaporative heat transfer equation can be calculated using Morin and Couillard (1990), which is based on Raphael (1962). To obtain the evaporative heat flux from the evaporation equation [2.18], one needs only to factor in the latent heat of vaporization, which gives the following equation:

$$H_e = -0.07\ V\ \left[e_s - e_a\right] \qquad [2.19]$$

where H_e = evaporative heat transfer (MJ m^{-2} d^{-1}).

V = wind speed at predetermined height, e.g. 10 m (km h^{-1}).

e_s = saturated vapor pressure at the water temperature (mm Hg).

e_a = water vapor pressure in air (mm Hg).

Rather than using a constant coefficient of 0.07 in equation [2.19], Duttweiller (1963) showed that the wind exchange coefficient can actually be a function of the surface area, e.g. such as in case of reservoirs. However, the proposed equation showed little variability over a wide range of reservoir surface areas, and would be of limited use in a river environment where the area is small and does not change drastically. The evaporative heat flux is generally a negative term in the heat budget equation; however this term can also be positive (i.e., during period of condensation).

Convective heat transfer

Convective heat transfer, which is also referred to as sensible heat, depends on the temperature difference between the water and the air, as well as wind speed. Sensible heat transfer occurs as a process of turbulence at the contact between the atmosphere and the river environment when they are at different temperatures. Sensible heat transfer has been shown to be similar to that of evaporative heat flux (i.e., equations based on Fick's Law) and can be expressed using a bulk aerodynamic equation (Dingman 2002). However, most water temperature modelling studies have used the Bowen ratio approaches (Bowen 1926) which is given by:

$$\frac{H_c}{H_e} = k\frac{(T_w - T_a)}{[e_s - e_a]}\frac{P_a}{1000} \qquad [2.20a]$$

where H_c = convective heat transfer (MJ m^{-2} d^{-1}).

H_e = evaporative heat flux (MJ m^{-2} d^{-1}).

k = proportionality constant varying between 0.58-0.66, usually taken as 0.61.

V = wind speed at predetermined height, e.g 10 m (km h^{-1}).

P_a = atmospheric pressure (mm Hg).

T_a = air temperature (°C).

T_w = water temperature (°C).

The above equation can be rearranged taking into consideration of the evaporative heat flux and the following equation has been suggested (Raphael 1962):

$$H_c = -0.042\ V\ \frac{P_a}{1000}\ (T_w - T_a) \qquad [2.20b]$$

or

$$H_c = 0.042\ V\ \frac{P_a}{1000}\ (T_a - T_w) \qquad [2.20c]$$

where parameters have been defined above.

The amount of heat loss (or heat gain) through convective heat is usually small (e.g. when T_a-T_w is small), but not negligible. As pointed out by in previous studies (Duttweiller 1963), even when the convective heat transfer is small, it is important in the overall variability in river water temperatures. This is because the other heat budget terms tend to balance one another (i.e. net short-wave radiation (gain), net long-wave radiation (loss) and evaporative heat flux (loss)).

Once the total heat flux is calculated, equation [2.5], the variation in water temperatures using a deterministic model can be calculated using [2.1] to [2.4] depending on the problem under investigation.

2.2.3 Model based on the equilibrium temperature concept

The deterministic modelling approach can be quite elaborate if we consider all relevant heat fluxes at both the water surface and the stream bottom interface. Deterministic models can also be quite demanding in terms of model development and data requirement, which makes simpler models very attractive. Previous studies have looked at potential ways of expressing the total heat flux component of a deterministic model in the form of a simpler equation (Edinger et al. 1968; Jeppesen and Iversen 1987;

Morse 1978) or predicting water temperatures using graphical techniques (Krajewski et al. 1982). One such simplification can be obtained when we assume that the total heat flux at the water surface is proportional to the difference between the water temperature and an equilibrium temperature T_e. Under such conditions, the total heat flux can be represented as a linear function of water and equilibrium temperatures (Edinger et al. 1968). A number of studies have considered using the equilibrium temperature concept to better understand thermal conditions in rivers (LeBosquet 1946; Edinger et al. 1968; Novotny and Krenkel 1973). If such an equilibrium temperature T_e can be calculated, then the problem of heat exchange can be reduce to Newton's law of cooling, i.e. total heat flux of equation [2.5] would be given by (Morin and Couillard 1990):

$$H_t = K(T_e - T_w) \qquad [2.21]$$

where T_w = the water temperature (°C)

T_e = the equilibrium temperature (°C)

K = thermal exchange coefficient (MJ m^{-2} d^{-1} $°C^{-1}$).

This equilibrium temperature, T_e, is the water temperature that the river is seeking or trying to reach to obtain equilibrium but can never reach as meteorological conditions are always changing. Early studies involving the equilibrium temperature concept mostly dealt with the understanding of behaviour of cooling ponds as a result of waste heat discharge or thermal effluent conditions (LeBosquet 1946; Duttweiler 1963). From these early studies, the concept of heat loss was best characterised by the air/water temperature differences. The equilibrium temperature was defined as the natural temperature of the river environment, without artificially added heat. In studies of cooling ponds, such an estimate of the equilibrium temperature was obtained from a shallow insulated tray of water mounted approximately 1.2 m above the ground (Duttweiler 1963). This approach using the equilibrium temperature concept made it possible for LeBosquet (1946), to show that the excess heat in rivers due to thermal effluents decreases exponentially in the downstream direction. In studying the equilibrium temperature, Duttweiler (1963) noted that the water temperature was similar to the equilibrium temperature, following a periodic function, except for a decreased amplitude, a phase lag and a transient term decreasing exponentially with time. Using this periodic function for the equilibrium temperature, it was possible to model the temperature profiles below reservoirs with different initial conditions. It was interesting to note that Duttweiler (1963) showed, using the equilibrium temperature concept, similar behaviour of water temperatures below reservoirs, i.e. conditions of "nodes" (i.e. minimum diurnal variation) and "antinodes" (i.e. maximum diurnal variation) as reported by Lowney (2000).

Edinger et al. (1968) studied the response of the thermal exchange coefficient as well as the equilibrium temperature based on meteorological variables. They discussed the fact that the equilibrium temperature crosses the water temperatures twice a day. On a longer time scale, such as annually, the equilibrium temperature crosses the mean water temperature twice a year, once on the warming trend and once on the cooling trend of the seasonal component. Furthermore, this study also provided some insights into the properties of both the equilibrium temperature and the thermal exchange coefficient (K). They showed that the thermal exchange coefficient could be expressed as a linear function of wind velocity.

Novotny and Krenkel (1973) also used the concept of the equilibrium temperature to show that thermal behaviour of rivers is different than that of lakes. This study showed that the thermal exchange coefficient was mainly a function of wind velocity and to a lesser extent air temperature. Boutin et al. (1981) studied the equilibrium temperature and the thermal exchange coefficient using water temperature data at different time scales. They noted that the thermal exchange coefficient varied seasonally based on the seasonal pattern of wind velocity. This particular study showed the importance of the dew point temperature as a parameter related to the equilibrium temperature. Gu et al. (1998) used the concept of the equilibrium temperature to quantify the effect of river discharge on the river thermal regime. This study showed relatively good agreement between time-averaged river temperatures as a function of discharge. Also, diurnal amplitudes in water temperature were related to diurnal amplitudes of the equilibrium temperature, which followed an exponential decay with increasing discharge. They concluded, using the equilibrium temperature concept, that increased river discharge through water releases below reservoirs can provide a good opportunity to reduce river water temperatures.

In a study of the potential impact of climate change on river water temperatures, Mohseni and Stefan (1999) used the equilibrium temperature concept to show that the thermal behaviour of rivers under both high and low air temperatures was different. This study showed that the thermal behaviour of rivers could be represented in four different temperature ranges. At very low air temperatures (less than -10°C), river water temperatures are at/or near freezing point. At higher air temperatures (-10 to 0°C) river water temperatures are very close to 0°C, and groundwater is often a dominant factor. At moderate air temperatures (0 to 20 °C), water temperatures tend to change linearly with both air temperatures and the equilibrium temperature. At high air temperatures (> 20°C), which often correspond to low water conditions, water temperatures tend to rise slower in a non-linear fashion with air temperatures. For air temperatures exceeding 20°C, this study showed the importance of evaporative cooling, which tends to level off river water temperatures.

2.2.4 Statistical / stochastic models

An alternative approach to the deterministic model in predicting stream water temperatures is the use of statistical models, i.e. regression or stochastic models. The statistical modelling approach is often simpler than the deterministic approach because it requires very few input parameters. Moreover, such a model usually requires only air temperatures as input parameter and associated stream water temperatures for model calibration. A statistical relationship between air and water temperatures is often determined by classical regression analysis or by using time series analysis such as the Box-Jenkins modelling approach (Box and Jenkins 1976).

Ward (1963) was among the first to study the annual variations in stream water temperature using a statistical approach. Subsequent studies have looked at modelling stream water temperatures by different approaches: regression, autoregressive model, Kalman filter, etc. Many have used a regression approach linking water to air temperatures (Stefan and Preud'homme 1993, Jourdonnais et al. 1992). Most of the initial work in stochastic water temperature modelling was realized in the early 1970's (Kothandaraman 1971, Kothandaraman 1972, and Cluis 1972). The pioneer work of Morse (1970) and Kothandaraman (1971) concentrated on large river systems, which have smaller daily fluctuations in water temperatures. In contrast, smaller rivers are more affected by shade (stream cover) and groundwater, and relatively good results have been observed by the stochastic modelling approach (Caissie et al. 1998), even when studying maximum daily temperature (Caissie et al. 2001). Studies have shown that the statistical modelling approach is very effective when studying potential climate change (Mohseni et al. 1998; Mohseni et al. 1999). For instance, Mohseni et al. (1998) used a logistic type function and they showed a good agreement between weekly air and water temperature data. Mohseni and Stefan (1999) have also observed a non-linear behaviour between air temperature and water temperatures. Other studies have shown that water temperature data can be extracted from measurements made during visits to streamflow gauging stations (Grant 1977). This study used an envelope curve to represent the annual component of maximum temperatures.

2.2.4.1 Simple regression models

Regression type models have been used quite widely in the understanding of the river thermal regime and the prediction of water temperatures. Most of these models have made use of air temperature to explain water temperatures in rivers for different time scales (Smith 1981; Crisp and Howson 1982; Mackey and Berrie 1991; Mohseni et al. 1998; Erickson and Stefan 2000). These studies have mainly used two different types of regression models, namely simple linear regression equation or logistic type functions. The logistic regression type functions have been preferred by some because they can consider a non-linearity in the air / water temperature relationship.

The simple linear regression equation is given by:

$$T_w(t) = a_2 + b_2\, T_a(t) \qquad [2.22]$$

where $T_w(t)$ = mean water temperature for a given time period (daily, weekly, monthly, etc.)

$T_a(t)$ = mean air temperature for the same time period as water temperatures (daily, weekly, monthly, etc).

a_2, b_2 = regression coefficient.

The simple regression model suggests that water temperature is linked linearly to air temperatures and that any increases in air temperatures will increase water temperatures. This approach has been applied in a variety of thermal conditions throughout the world (Ward 1985), including alpine streams (Johnson 1971). As pointed out by Erickson and Stefan (2000), using a simple linear regression model can give different results based on a number of factors including the time scale (e.g., daily, weekly and monthly). For instance, using the same water temperature data, they showed that the slope of the regression line tends to increase with increasing the time scale. Another study showing similar results was carried out by Pilgrim et al. (1998), where they lumped together all water temperature data for a number of sites in Minnesota. This particular study also showed that the slope of the regression increased with the time scale (Figure 2.4; daily, weekly and monthly). Higher intercepts (i.e., b_2 coefficient of the regression) were also observed for daily values compared to those of monthly temperatures. This study showed that a significant improvement in the model's performance can be accomplished when considering monthly predictions (R^2 = 0.89) rather than daily predictions (R^2 = 0.70), when all data are lumped together.

A number of parameters other than time scale have been observed to influence the slope and intercept of the regression line. For instance, water release from reservoirs has been observed to be an important factor affecting the air / water temperature relationship, as has been groundwater in rivers dominated by groundwater (Smith 1981; Mackey and Berrie 1991; Erickson and Stefan 2000). In the case of groundwater dominated rivers, the regression line tends to be less responsive to air temperatures and therefore smaller slopes have been observed (Figure 2.4). Although groundwater dominated streams showed milder slopes, the intercept has been observed to remain relatively high, which reflects the importance of groundwater at low air temperatures.

A comparison of slopes and intercepts based on literature data is possible on a monthly basis (Table 2.4). This table shows that some rivers tend to have a steeper slope and close to unity, with a relatively small intercept (e.g. Minnesota and Little SW Miramichi River). These rivers are highly linked to air temperatures. Other rivers have a higher intercept, presumably because winter temperatures are above 0°C, which also results in a milder slope. The three groundwater dominated rivers studied by Mackey and Berrie (1991), showed a significantly lower slope and a higher intercept (Table 2.4).

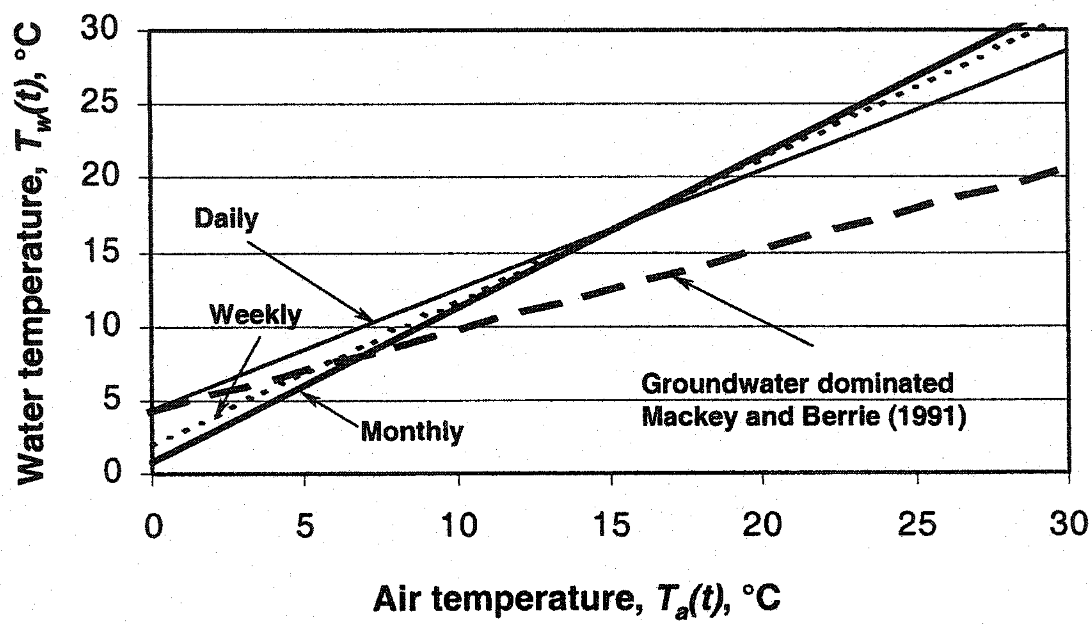

Figure 2.4 Linear associations between air and water temperatures as a function of time periods (daily, weekly and monthly) and sources of water.

Not all water temperature studies have considered a linear regression model to link air and water temperatures. Others studies have hypothesised that the thermal behaviour in rivers is a non-linear function. Therefore, for a given increase in air temperature, it is possible that water temperatures will not always increase at the same rate, especially at high (> 30°C) and low (< 0°C) air temperature. This could be due to factors such as evaporative cooling for high air temperatures and/or heat conduction from the ground and groundwater at low air temperature. Under such conditions, the air / water relationship may not be linear, and other regression type models such as the logistic type functions have been proposed (Mohseni et al. 1998).

Table 2.4 Comparison of different linear regression models for monthly air / water temperature relationships.

Sites / Location	a_2	b_2	R^2
Minnesota (39 rivers)[1]	0.90	1.06	0.92
UK (36 rivers)[2]	2.0	0.89	0.92
Krems River, Austria[3]	2.4	0.69	0.92
UK (7 rivers)[4]	1.0	0.98	0.91
Chalk River (3 rivers)[5]	4.8	0.61	n/a
Little SW Miramichi R.[6]	0.86	0.98	0.94
Catamaran Brook[6]	1.1	0.74	0.92

1. Pilgrim et al. (1998); 2. Webb (1987), Webb (1992); 3. Webb and Nobilis (1995)
4. Smith (1981); 5. Mackey and Berrie (1991); 6. D. Caissie (DFO, unpublished data).

2.2.4.2 Logistic function regression models

The logistic type function used by Mohseni et al. (1998) to determine the air to water relation is given by:

$$T_w(t) = \frac{\alpha'}{1 + e^{\gamma'(\beta' - T_a(t))}} \qquad [2.23]$$

where $T_w(t)$ = mean water temperature for a given time period (daily, weekly, monthly, etc.)

$T_a(t)$ = mean air temperature for the same time period as water temperatures (daily, weekly, monthly, etc).

α' = the coefficient which estimates the highest maximum water temperature.

β' = the air temperature at the inflection point

γ' = a function of the steepest slope of the logistic function.

For instance, Mohseni et al. (1998) studied over 573 water temperature sites on a weekly basis using the logistic regression. They observed a coefficient of determination, R^2, higher than 0.9 for over 84% of the sites. This study pointed out that the water temperatures were non-linear and that the air / water temperature relation could also show some level of hysteresis with season. This study also showed that the largest deviation from the fitted function was usually in autumn and spring, when air temperatures were between 0°C and 12°C. The explanation was that at this time of year, the air / water temperature relation can depend on a number of unaccounted conditions rather than only air temperature.

These two regression approaches (linear and non-linear) have been used successfully in the modelling of river water temperatures. However, these studies have also shown that the time scale is very important and that reasonable modelling results were only obtained on weekly or monthly basis. In fact, daily regression models did not provide an acceptable fit, with R^2 in the range of 0.45 and 0.83 (Pilgrim et al. 1998). One reason for this is that, on a daily basis, water temperature time series have some level of autocorrelation. Consequently, in order to effectively model water temperatures on a daily time scale, the autocorrelation in water temperatures has to be considered using a stochastic modelling approach.

2.2.4.3 Stochastic Models

The analysis of stream water temperatures by the stochastic modelling approach began in the early 1970s with the works of Kothandaraman (1971), Kothandaraman (1972), and Cluis (1972). Although stochastic models have not been as popular as deterministic models, a number of studies have shown that this modelling approach is very effective at predicting river water temperature (Song et al. 1973; Marceau et al. 1986; Caissie et al. 1998). Other stochastic modelling studies have considered Kalman filters in the modelling (Chiu and Isu 1978). Most of the early stochastic modelling approaches consisted of separating the water temperatures into two different components, namely the long-term periodic seasonal component (or annual component) and the short-term non-seasonal component or the short-term residual time series. The annual component represents the seasonal changes of water temperature or long-term conditions. The short-term component represents the departure from the long-term annual component as a result of above and/or below normal air temperature. Some studies have focused on the statistical analysis of the short-term component to better understand stochastic models (Gillett and Long 1974).

Therefore, the water temperature, $Tw(\mathrm{t})$, of a given river system can be represented by two components, the long-term annual component, $TA(\mathrm{t})$, and the short-term component, $Rw(\mathrm{t})$, such that:

$$Tw(t) = TA(t) + Rw(t) \qquad [2.24]$$

where t represents the day of year (e.g. July 1 = 182).

Annual component in air and water temperatures

The annual component in water and air temperature was initially studied by Ward (1963) using a sine function, but it can also be represented using a Fourier series analysis (Kothandaraman, 1971) or a combination of the two (Caissie et al. 2001). The annual component can be calculated from daily water and air temperatures. When using a Fourier series analysis, different harmonics can be calculated using the following equation:

$$TA(t) = \frac{A_o}{2} + \sum_{n_2=1}^{\infty} \left(A_n \left[\cos\left((t-j-1)\frac{2 n_2 \pi}{N_2}\right)\right] + B_n \left[\sin\left((t-j-1)\frac{2 n_2 \pi}{N_2}\right)\right]\right) \quad [2.25]$$

where $TA(t)$ = the annual component for temperature at time t in days (July 1 = 182).

N_2 = number of observations (days) for a given period T (e.g. March 31 to December 16) during open water conditions.

n_2 = number of harmonics used.

j = first day of observation within the period T (day 90, March 31).

$A_o/2$ = the average of the function $f(t)$ for the period N.

$$A_n = \frac{2}{N_2} \sum_{t=1}^{N_2} f(t) \cos\left(\frac{2\pi\, n_2\, t}{N_2}\right) \quad [2.26a]$$

with:

and where $f(t)$ is the stream water or air temperature time series (e.g. on a daily basis).

$$B_n = \frac{2}{N_2} \sum_{t=1}^{N_2} f(t) \sin\left(\frac{2\pi\, n_2\, t}{N_2}\right) \quad [2.26b]$$

The first question that often arises in the application of equation [2.25] is, "how many harmonics should be considered?" Kothandaraman (1971) studied the implication of considering many harmonics in the application of a stochastic model, and it was found that the first harmonic ($n_2 = 1$) explained most of the variation in both the stream water and air temperature annual component. The selected period N_2 for a particular study was also shown to be an important consideration as reported in the literature (Tasker and Burns 1974; Caissie et al. 1998). For instance, Caissie et al. (1998) showed that when using a Fourier Series, the choice of the period is crucial to properly fit the annual component. They also showed that the required period may have to be longer than the study period to provide a best fit of the annual component. For streams in Atlantic Canada, this period was chosen between March and December. As an example, Caissie et al. (2001) used a period from March 31 to December 16, a period within the year of 260 days ($N_2 = 260$), and the first day of observation was on day 90 ($j = 90$; March 31).

Another method for calculating the annual component in water temperatures was suggested by Cluis (1972). This method consists in fitting a sine function to represent the annual component, given by:

$$TA(t) = a_3 + b_3 \sin\left(\frac{2\pi}{365}(t + t_0)\right) \qquad [2.27]$$

with a_3, b_3 and t_0 being estimated coefficients. Coefficients in equation [2.27] can be calculated by minimizing the sum of squared residuals (i.e., errors) between observed and estimated temperatures of the annual component. Once the annual component is obtained, the short-term component can be calculated.

Modelling the short-term component in water temperature

The methods used to model the non-seasonal component in water temperature (or the short-term component) varied in approach. This modelling approach can involve multiple regression analysis (Kothandaraman, 1971), second-order Markov process (Cluis, 1972), autoregressive models (Song and Chien 1977), and/or Box-Jenkins time series analysis (Marceau et al. 1986). To calculate the short-term component in both air and water temperatures time series, air/water temperatures are obtained by subtracting the actual air and water temperatures from the annual components. The short-term component in air and water temperature can then be used to calibrate the stochastic model.

The following model was proposed by Kothandaraman (1971), which is based on multiple regression analysis between water temperature residuals and air temperature residuals given by:

$$Rw(t) = \beta_1 Ra(t) + \beta_2 Ra(t-1) + \beta_3 Ra(t-2) \qquad [2.28]$$

where $Rw(t)$ is the short-term water temperature component at time t and $Ra(t)$, $Ra(t\text{-}1)$, and $Ra(t\text{-}2)$ are the short-term air temperature component at time t and for a 1 day (t-1) and 2 day (t-2) lag time. β_1, β_2, and β_3 are regression coefficients. This model states that the water temperature residual for a given day is a function of the air temperature residuals of the present day and the previous 2 days.

Another approach presented in the literature is based on the autoregression nature of water temperature time series or a second-order Markov model. This approach was used to represent the short-term residual series, and the equation was given by Cluis (1972):

$$Rw(t) = A_1^{'} Rw(t-1) + A_2^{'} Rw(t-2) + K_s Ra(t) \qquad [2.29]$$

with $A_1' = R_1 (1-R_2) / (1-R_1^2)$ and $A_2' = (R_2-R_1^2) / (1-R_1^2)$ after Salas et al. (1980). R_1 and R_2 represent the autocorrelation coefficients for a lag of one and two days respectively. Previous studies have shown that a one and two day lag autocorrelation is sufficient to capture the physical forcing within the water temperature time series (Cluis 1972). Once A_1' and A_2' are obtained using the autocorrelation coefficient, K_s can be estimated by minimizing the mean sum of squared errors in equation [2.29]. This is possible using the actual $Rw(t)$ during the calibration period and the calculated $Rw(t)$ with air temperatures (i.e. $Ra(t)$). A range of K_s values (0.05-0.5) can be used in a computer program to obtain the minimum value of the mean sum of squared errors.

The third approach used to model short-term residuals of water temperature time series is the Box-Jenkins model (Marceau et al. 1986). When the internal structure of a time series can be represented by a linear function of its past events, then the processes is termed a *pth* order autoregressive process AR(p). When the internal structure of a time series can be represented by a linear function of past random errors then the process is termed a *qth* order moving average process MA(q). If the internal structure of a time series is a combination of both an autoregressive and a moving average process then it is termed a mixed process or ARMA (p,q) (Hoff 1983).

A *pth* order autoregressive process is expressed as (Box and Jenkins 1976):

$$\phi_i(B)\, z_t = a_t \qquad [2.30]$$

where z_t = the studied time series.

B = the backward shift operator.

a_t = the white noise process (independent random error following a normal distribution function with a mean of zero and of variance σ_a^2).

ϕ_i = the autoregressive operator such that:

$$\phi_i(B) = 1 - \phi_1 B - \phi_2 B^2 - .... - \phi_p B^p \qquad [2.31]$$

A *qth* order moving average process is expressed as:

$$z_t = \theta_i(B) a_t \qquad [2.32]$$

where θ_i = the moving average operator such that:

$$\theta_i(B) = 1 - \theta_1 B - \theta_2 B^2 - ..... - \theta_q B^q \qquad [2.33]$$

Therefore, the mixed autoregressive-moving average or ARMA models is expressed as:

$$\phi_i(B) z_t = \theta_i(B) a_t \qquad [2.34]$$

where the parameters have been defined above.

When studying a process using a transfer function model, the process has an input time series component that can be expressed by the ratio of two terms similar to the mixed autoregressive-moving average such that:

$$z_t = \delta^{-1}(B)\zeta(B)X_t + \phi_i^{-1}(B)\theta_i(B)a_t \qquad [2.35]$$

where $\delta(B)$ and $\zeta(B)$ are the transfer function components which can take the form of a polynomial function similar to $\phi_i(B)$ and $\theta_i(B)$ (equation 2.31 and 2.33),

X_t is the input time series, i.e. water temperature time series.

The last term of equation [2.35] represents the autoregressive-moving average process with the white noise series. In previous studies, the following transfer function and autoregressive-moving average process has been used (Marceau et al. 1986).

$$\phi_i(B) = 1 - \phi_1 B;\ \theta_i(B) = 1;\ \zeta(B) = \zeta_0;\ \delta(B) = 1 - \delta_1 B \qquad [2.36]$$

Which resulted in the following model using equation [2.35]:

$$z_t = \frac{\zeta_0}{1 - \delta_1 B} X_t + \frac{1}{1 - \phi_1 B} a_t \qquad [2.37]$$

where ζ_0, δ_1, and ϕ_1 are estimated parameters, a_t is the white noise series (average of zero and a variance of σ^2_a) and X_t the input time series (Box et Jenkins 1976). For modelling stream water temperatures, Z_t becomes $Rw(t)$ while X_t represents the residuals of air temperature $Ra(t)$ at times t.

Therefore equation [2.37] becomes:

$$Rw(t) = \frac{\zeta_0}{1 - \delta_1 B} Ra(t) + \frac{1}{1 - \phi_1 B} a_t \qquad [2.38]$$

Therefore, the short-term component in water temperatures is linked to the short-term in air temperatures using equation [2.38]. Caissie et al. (1998) have shown that regardless of the modelling approach used to predict the short-term component, (i.e., linear regression, second-order Markov process or Box-Jenkins model) the stochastic model provided very similar results. In fact, that study showed that these approaches all overestimated and/or underestimated water temperature during similar periods within the year and that there were no significant advantages to using the more complex Box-Jenkins modelling approach.

CHAPTER 3

WATER TEMPERATURE MODELS AND STUDY AREA

3.1 Water temperature models

As described in chapter 2, different modelling approaches can be used to model river water temperatures. These are classified in two categories, deterministic or stochastic models. Based on previously defined equations, the present chapter will describe the specific modelling approaches and equations which will be used in this study. This chapter will also describe two newly developed water temperature models, which will be tested using Catamaran Brook and Little Southwest Miramichi River data. The first model described will be the deterministic model. Different variations of this model have been used in numerous studies (e.g. Raphael 1962, Marcotte and Duong 1973; Sado 1983; Morin and Couillard 1990, Morin et al. 1994). Following the deterministic model, a new model will be developed based on the equilibrium temperature concept. The equilibrium temperature will be described initially in a simplified formulation, which will then be used for the modelling of water temperatures. A third model will be presented, based on the stochastic modelling approach (Cluis 1972; Caissie et al. 1998), i.e. using a second-order Markov process. The last modelling approach presented in the present study will focus on a new method of modelling water temperatures which uses the long-term annual component in the calculation of the reference energy. This long-term reference energy will be used in combination with the short-term heat fluxes at the river surface to predict water temperature variations in rivers.

3.1.1 Deterministic model

Depending on the type of problem under investigation, equation [2.1] to [2.4] can be used to model river water temperatures as a 0-D to a 3-D problem. For a river reach with relatively uniform water temperature or for a reach where the longitudinal variations are small compared to changes over time, it has been shown that water temperatures can be modelled using the following equation (Marcotte and Duong 1973; Morin and Couillard 1990; Sinokrot and Stefan 1993):

$$\frac{\partial T_w}{\partial t} = \frac{W}{\theta \rho A} H_t \qquad [3.1]$$

where T_w = water temperature (° C).

t = time (day).

A = cross sectional area (m^2).

W = river width (m).

θ = specific heat of water (4.19×10^{-3} MJ kg^{-1} $°C^{-1}$)

ρ = water density (1000 kg m^{-3}).

H_t = total heat flux from the atmosphere to the river (MJ m^{-2} d^{-1}).

This equation [3.1] will be used in the present study as the basis of the deterministic modelling approach. This approach is used to model or predict river water temperature at a specific point along the river using meteorological data (Marcotte and Duong 1973). Due to its simplicity, equation [3.1] does not involve any boundary conditions, unlike other heat transport problems (i.e. equation [2.1] to [2.3]). Equation [3.1] does, however, require initial conditions for water temperature which are not always available. Marcotte and Duong (1973) showed that regardless of the initial water temperature input into the model, the deterministic model rapidly converges to the real solution in less than 10 days.

To predict water temperatures using equation [3.1], the total heat flux (H_t) at the river surface has to be calculated. In the present study, heat fluxes at the water / sediment interface (H_{sed}) presented in equation [2.1] are neglected as studies have shown that this contribution on a daily basis is very small (Sinokrot and Stefan 1994). Therefore the total heat flux at the surface is give by:

$$H_t = H_s + H_l + H_e + H_c \qquad [3.2]$$

where H_t = total heat flux at the stream surface (MJ m^{-2} d^{-1}).
H_s = solar radiation or net short-wave radiation (MJ m^{-2} d^{-1}).
H_l = long-wave radiation (MJ m^{-2} d^{-1}).
H_e = evaporative heat transfer (MJ m^{-2} d^{-1}).
H_c = convective heat transfer (MJ m^{-2} d^{-1}).

The net short-wave radiation was obtained directly from measured pyranometer data without the necessity to use cloud cover information. The pyranometer data from the Catamaran Brook meteorological station (Figure 3.2) represents an open sky condition (non-obstructed by vegetation; see section 3.2 for more details). To estimate actual solar radiation at the stream level for both Catamaran Brook and the Little Southwest Miramichi River, radiation data were reduced using a bulk shading factor. The reflected short-wave radiation was assumed constant for all solar altitudes. Assuming a constant reflected radiation, the net short-wave radiation can therefore be calculated from the difference between the incoming and the reflected radiation at the water surface using the reflectivity of the water [2.13c]:

$$H_s = (1-r)\ H_{si}\ (1-SF) \qquad [3.3]$$

where H_{si} = incoming solar radiation as measured by a pyranometer (MJ m^{-2} d^{-1}).

SF = shading factor of the river reach (0 to 1, depending of forest cover and upland slopes).

r = reflectivity of the water surface, which is assumed constant.

The reflectivity of the water was estimated at 5% of the incoming radiation similar to Morin and Couillard (1990) and therefore equation [3.3] becomes:

$$H_s = 0.95 \; H_{si} \, (1 - SF) \qquad [3.4]$$

The shading factor (SF) was an estimated parameter for each river, which was used in the calibration of the deterministic model to represent the relative contribution of each energy component.

The net long-wave radiation was described in chapter 2. This component can be calculated using the Stefan-Boltzmann Law. The net long-wave radiation equation used in the present study is give by equation [2.15] and is based on previous studies (Marcotte and Duong 1973; Morin and Couillard 1990; Mohseni and Stefan 1999):

$$H_l = 0.97\sigma \; [\beta \, (T_a)^4 - (T_w)^4] \qquad [3.5]$$

where H_l = long-wave radiation (MJ m^{-2} d^{-1}).

T_w = absolute water temperature (K).

T_a = absolute air temperature (K).

σ = Stefan-Boltzmann constant (4.9 x 10^{-9} MJ m^{-2} K^{-4}).

β = atmospheric emissivity.

The atmospheric emissivity, which was shown to be mostly a function of the water vapor pressure and cloud cover can be expressed using a number of equations (see equation [2.16a], [2.16b] and [2.16c]). In the present study, atmospheric emissivity will be expressed using the following equation given by Morin and Couillard (1990):

$$\beta = (0.74 + 0.0065\, e_a (1 + 0.17 B_c^{\,2}) \qquad [3.6]$$

where e_a = water vapor pressure in the air (mm Hg).

B_c = cloud cover (0 = clear sky and 1 = total could cover).

The water vapor pressure (e_a) required in equation [3.6] can also be estimated using a number of different equations (e.g., equation [2.17a] and [2.17b]). The equation use for water vapor pressure will be the approximation provided by Chow et al. (1988) given by:

$$e_a = 4.583 \exp\left(\frac{17.27 T_a}{237.3 + T_a}\right) \cdot \frac{RH}{100} \qquad [3.7]$$

where e_a = water vapor pressure in the air (mm Hg).

T_a = air temperature (°C).

RH = relative humidity (%, from 0 to 100%).

The cloud cover (B_c) was estimated based on pyranometer data at the Catamaran Brook meteorological station. It was calculated using measured solar radiation at the station and the maximum potential solar radiation under clear sky conditions (equations 2.6 and 2.7).

The next term of the heat budget is the evaporative heat transfer which can be calculated using a number of equations depending on the estimation of evaporation. In the present study, the formulation presented by Raphael (1962) and provided by Morin and Couillard (1990) will be used. The equation is given by:

$$H_e = -0.07\ V\ [e_s - e_a] \quad [3.8]$$

where H_e = evaporative heat transfer (MJ m^{-2} d^{-1}).
V = wind speed at predetermined height, e.g. 10 m (km h^{-1}).
e_s = saturated vapor pressure at the water temperature (mm Hg).
e_a = water vapor pressure in air (mm Hg).

The convective heat transfer depends on wind speed and the temperature difference between the water and air. The equation presented by Raphael (1962) will be used in the present study:

$$H_c = 0.042\ V\ \frac{P_a}{1000}\ (T_a - T_w) \quad [3.9]$$

where H_c = convective heat transfer (MJ m^{-2} d^{-1}).
V = wind speed at predetermined height, e.g 10 m (km h^{-1}).
P_a = atmospheric pressure (mm Hg).
T_a = air temperature (°C).
T_w = water temperature (°C).

For practical problems, the barometric pressure can be assumed constant at 760 mm Hg. This parameter was found insignificant in the water temperature modelling when conducting a sensitivity analysis (Sinokrot and Stefan 1994). However, given that barometric pressure was available at the Catamaran Brook meteorological station, this parameter was used in the deterministic modelling, but not in other models. Once that the total heat flux was calculated, predictions of daily water temperature was carried out using [3.2] and [3.1].

To carry out the water temperature modelling for both river systems, equation [3.1] requires the knowledge of the river width over the cross-sectional surface area (*W/A*), which represents the mean river depth or stream morphology. The following equation was used to calculate the mean river depth (*y*) as a function of discharge (Leopold et al. 1964):

$$y = a_4 \, Q^{b_4} \qquad [3.9]$$

where a_4 and b_4 are coefficients relating the mean water depth to river discharge Q (m^3/s).

3.1.2 Equilibrium temperature model

Studies dealing with the thermal regime of rivers have looked at potential ways of expressing the total heat flux component using a simpler equation. One such simplification involving the total heat flux component can be obtained if we assume that the total heat flux between the atmosphere and the river is proportional to the temperature difference between the water temperature and an equilibrium temperature T_e. Under such conditions, the total heat flux can be represented as a linear function of water and equilibrium temperatures (LeBosquet 1946; Edinger et al. 1968; Novotny and Krenkel 1973). As pointed out by Morin and Couillard (1990), if such an equilibrium temperature

T_e can be calculated, then the problem of heat exchange would be reduced to that of Newton's law of cooling, i.e. total heat flux would be given by [2.21]:

$$H_t = K(T_e - T_w) \quad [3.11]$$

where T_w = the water temperature (°C)

T_e = the equilibrium temperature (°C)

K = a thermal exchange coefficient (MJ m^{-2} d^{-1} $°C^{-1}$).

Previous studies have used the equilibrium temperature concept to simplify the heat exchange formulation and to better understand the river thermal regime under varied conditions (e.g., Edinger et al. 1968; Dingman 1972; Chaudhry et al. 1983; Gu et al. 1998). These studies have expressed both the thermal exchange coefficient K and the equilibrium temperature T_e as functions of meteorological parameters. If for a given river system the thermal exchange coefficient and the equilibrium temperature could be expressed in a simpler form, then water temperature modelling can be greatly simplified. Using the equilibrium temperature concept, one can also look at the influence of different physical and meteorological parameters (e.g. depth of flow, etc) on the overall thermal conditions of rivers (Gu et al. 1998; Mohseni and Stefan 1999).

Therefore, initially we will express the equilibrium temperature in a simpler form using an approximation of the total heat flux component. For instance, the net long-wave radiation (equation [3.5]) can be simplified without the introduction of significant errors (Mohseni and Stefan 1999). In fact, the terms $\sigma(T)^4$ or $\sigma(T+273.15)^4$, depending if the temperature is expressed in degree Celsius or in absolute temperatures (i.e. degree Kelvin), equation [3.5] can be approximated by a linear equation given the typical range of air and water temperatures studied. The approximation is given by:

$$\sigma\,(T_a + 273.15)^4 \;\cong\; A_3\,T_a + A_4 \qquad [3.12a]$$

and

$$\sigma\,(T_w + 273.15)^4 \;\cong\; A_3\,T_w + A_4 \qquad [3.12b]$$

where T_a = air temperature (°C),

T_w = water temperature (°C),

$A_3 = 0.46$ MJ m^{-2} d^{-1} °C^{-1}, and

$A_4 = 28.38$ MJ m^{-2} d^{-1} °C^{-1}.

Linearization values (A_3 and A_4) were provided in Mohseni and Stefan (1999).

Thus the net long-wave radiation can be expressed as a linear function of temperatures (expressed in °C) in the following form:

$$H_l \;=\; 0.97\,[\beta\,(A_3\,T_a + A_4) - (A_3\,T_w + A_4)] \qquad [3.13]$$

Similarly, the evaporative heat flux can be simplified using an approximation involving the difference between water temperature T_w (°C) and the dew point temperature T_d (°C). For instance, the differences between the saturated vapor pressure (e_s) at the water temperature and the air water vapor pressure (e_a) was shown to be related to the differences in water and dew point temperatures (Edinger et al. 1968) by the following equation:

$$\eta \;=\; \frac{(e_s - e_a)}{(T_w - T_d)} \qquad [3.14]$$

where η = slope of the linear vapor pressure approximation.

e_s = saturated vapor pressure at the water temperature (mm Hg).

e_a = water vapor pressure in air (mm Hg).

T_w = water temperature (°C).

T_d = dew point temperature (°C).

The evaporative heat flux can therefore be expressed as a function of water temperature and dew point temperature in the following form:

$$H_e = -0.07\ V\,\eta\ (T_w - T_d) \qquad [3.15]$$

where V = wind speed at predetermined height, e.g. 10 m (km h^{-1}), and the other parameters were defined in equation [3.14].

The calculation of the equilibrium temperature T_e as a function of meteorological conditions is obtained when the water temperature (T_w) in the total heat flux equation [3.2] is replaced by T_e, and the net heat flux (H_t) is set at zero (Edinger et al. 1968). Therefore:

$$H_s + H_l + H_e + H_c = f(T_e) = 0 \qquad [3.16]$$

or

$$\begin{aligned} &0.95\,H_{si}(1-SF) + 0.97\,[\beta(A_3T_a + A_4) - (A_3T_e + A_4)] \\ &-0.07\,V\eta\,(T_e - T_d) + 0.042\,V\,\frac{P_a}{1000}\left(T_a - T_e\right) = 0 \end{aligned} \qquad [3.17]$$

where the parameters have been defined previously.

For the equilibrium temperature model, the barometric pressure was assumed constant at 760 mm Hg to keep the model simple. After rearranging equation [3.17] the equilibrium temperature can be expressed by:

$$T_e = \frac{0.95\, H_{si}(1-SF) + (0.97\beta\, A_3 + 0.03V)T_a + 0.07V\eta T_d + 0.97A_4(\beta - 1)}{0.97A_3 + 0.07V\eta + 0.03V} \qquad [3.18]$$

which can be further reduced to:

$$T_e = B_1\, H_{si} + B_2\, T_a + B_3\, T_d + B_4 \qquad [3.19]$$

with

$$B_0 = 0.95A_3 + 0.07V\eta + 0.03V \qquad [3.20]$$

$$B_1 = \frac{0.95\,(1-SF)}{B_0} \qquad [3.21]$$

$$B_2 = \frac{0.97\beta\, A_3 + 0.03V}{B_0} \qquad [3.22]$$

$$B_3 = \frac{0.07V\eta}{B_0} \qquad [3.23]$$

$$B_4 = \frac{0.97A_4(\beta - 1)}{B_0} \qquad [3.24]$$

It is worth noting from equation [3.19] that although the equilibrium temperature is a function of many meteorological parameters, it can be reduced to a function of T_a, T_d and H_{si} (incoming solar radiation). All other coefficients B_0 to B_4 are dependent on wind velocity to a large extent. In addition, studies have shown that in temperate regions, the dew point and air temperature showed a relatively strong linear association (Mohseni and

Stefan 1999). In such regions, it can therefore be postulated that the equilibrium temperature will also show a linear association with air temperature.

For these conditions, a new water temperature model can be developed based on equation [3.1] and [3.11], which takes the following form:

$$\frac{\partial T_w}{\partial t} = \frac{W}{\theta \rho A} H_t = \frac{W}{\theta \rho A} K (T_e - T_w) \qquad [3.25]$$

or

$$\frac{\partial T_w}{\partial t} = \frac{K'(T_e - T_w)}{y} \qquad [3.26]$$

where $W/A = 1/y$,

$K' = K/(\theta \rho)$, in which y represents the mean water depth of the river reach.

The K' represents the thermal exchange coefficient including the physical properties of the water, i.e., $\theta\ \rho$. It was hypothesised in the present study that the equilibrium temperature T_e could be expressed as a linear function of air temperature T_a, such that:

$$T_e = f(T_a) = a_5 + b_5 T_a \qquad [3.27]$$

where a_5 and b_5 represent the linear regression coefficients.

The equilibrium temperature concept as a linear function of air temperature will be further investigated. In order to keep the new model simple, a constant thermal exchange coefficient will be calculated for each studied river.

3.1.3 Stochastic model

An alternative approach to the deterministic water temperature model is the stochastic model as presented in chapter 2. This section will describe the equations used in the application of a stochastic model within the present study. Previous studies have shown that stochastic models usually require only air temperatures and a continuous time series of stream water temperature for model calibration. A statistical relationship between air and water temperatures is often determined by classical regression analysis, autoregressive processes, or by using time series analysis such as the Box-Jenkins modelling approach (Box and Jenkins 1976).

The modelling of stream water temperatures using a stochastic model consists, initially, of separating the water temperatures into two different components, namely the long-term periodic seasonal component or annual component and the short-term non-seasonal component. The annual component represents the seasonal changes of water temperature. The short-term component represents the departure from the long-term annual component during any particular day as a result of above or below normal air temperatures.

The stream water temperature, $Tw(t)$, of any given river systems can be represented by these two components, the long-term annual component, $TA(t)$, and the short-term component, $Rw(t)$, such as:

$$Tw(t) = TA(t) + Rw(t) \qquad [3.28]$$

where $Tw(t)$ = the water temperatures on any given day or time (t)

$TA(t)$ = the annual component at time (t)

$Rw(t)$ = the short-term component at time (t), and

t = the day of year (e.g. July 1, t = 182).

Annual component

The annual component can be represented by a Fourier series or a sine function as presented previously in chapter 2. In this study, a sine function will be used to represent the annual component in both air and water temperature (Cluis 1972):

$$TA(t) = a_3 + b_3 \sin\left(\frac{2\pi}{365}(t + t_0)\right) \qquad [3.29]$$

where $TA(t)$= the annual component for temperature at time t in days (Jan. 1 = 1 and Dec 31 = 365).

a_3, b_3 and t_0 are estimated coefficients.

The coefficient, a_3, b_3 and t_0 in equation [3.29] will be calculated using a best-fit equation by minimizing the sum of squared errors between observed water temperatures and the annual component calculated using the above equation.

Short-term component

In the present study, the modelling of the short-term component in water temperature was carried out using a second-order Markov process (Cluis 1972):

$$Rw(t) = A_1^{'} Rw(t-1) + A_2^{'} Rw(t-2) + K_s Ra(t) \qquad [3.30]$$

where $Rw(t)$ = short-term water temperatures at time (t).

$Rw(t\text{-}1)$, $Rw(t\text{-}2)$ = short-term water temperatures at time $(t\text{-}1)$ and $(t\text{-}2)$.

$Ra(t)$ = short-term temperatures at times (t).

K_s = stochastic coefficient relating air to water temperatures, obtained by optimization with the minimum sum of squared residuals.

$A_1' = R_1 (1-R_2) / (1-R_1^2)$.

$A_2' = (R_2-R_1^2) / (1-R_1^2)$

with R_1 = the autocorrelation coefficients for a lag of one day.

and R_2 = the autocorrelation coefficients for a lag of two days.

Once that the short-term component was obtained, the stochastic modelling was carried out by using the above equations [3.30], with [3.29] and [3.28].

3.1.4 Energy reference model

This section will describe a new water temperature model based on the long-term energy component (calculated using long-term meteorological data) coupled with long-term water temperatures. The development of this model was based on the fact that over 90% of the variance in water temperatures can be explained using the annual component similar to the stochastic model (Kothandaraman 1971, Caissie et al. 1998). It was therefore hypothesised that a new water temperature model could be developed based on the deterministic modelling approach that would also incorporate the annual component in water temperatures. To develop such a model, one would need to use a reference energy rather than the absolute energy currently used in the deterministic models. This energy reference model was developed so that when current meteorological conditions become close to the long-term conditions, then daily water temperature variability (increase or decrease) is represented by the long-term annual component. Similarly, any departure in current meteorological conditions from the long-term conditions (i.e., or the reference energy) is reflected by a departure in water temperature from the long-term annual component. This new model will therefore effectively incorporate meteorological parameters having an annual cycle or component such as solar radiation and air temperature. For other parameters, which do not follow a particular annual cycle (e.g., relative humidity and wind speed), their respective long-term means were used to represent the long-term meteorological conditions. Therefore, the reference energy was calculated based on the same equations as the total energy (H_t) of the deterministic model; however calculations were made based on long-term meteorological conditions for the reference energy. Figure 3.1 illustrates the energy reference model where both the long-term and short-term (e.g., 1998) conditions for air temperature and solar radiation are presented as well as the resulting water temperatures.

Because this new water temperature model considers the annual cycle (long-term component) in water temperatures, including the long-term cycle of other meteorological data, the heat flux at the water surface was expressed in terms of the reference energy. The heat flux at the water surface will therefore be expressed as a function of the difference between the total heat flux (H_t) and the long-term heat flux or reference energy flux (H_{ref}) given by:

$$\frac{\partial T_w}{\partial t} = \frac{W}{\theta \, \rho \, A}(H_t - H_{ref}) + \phi_w(t) \qquad [3.31]$$

where H_t = total energy heat flux as presented in the deterministic model (MJ m^{-2} d^{-1}).

H_{ref} = reference energy flux based on long-term meteorological conditions (MJ m^{-2} d^{-1}).

$\phi_w(t)$ = function representing the annual component in water temperatures (°C d^{-1})

It can be observed from equation [3.31] that when the total heat flux (H_t) is higher than the reference heat flux (H_{ref}), increases in water temperature above the annual

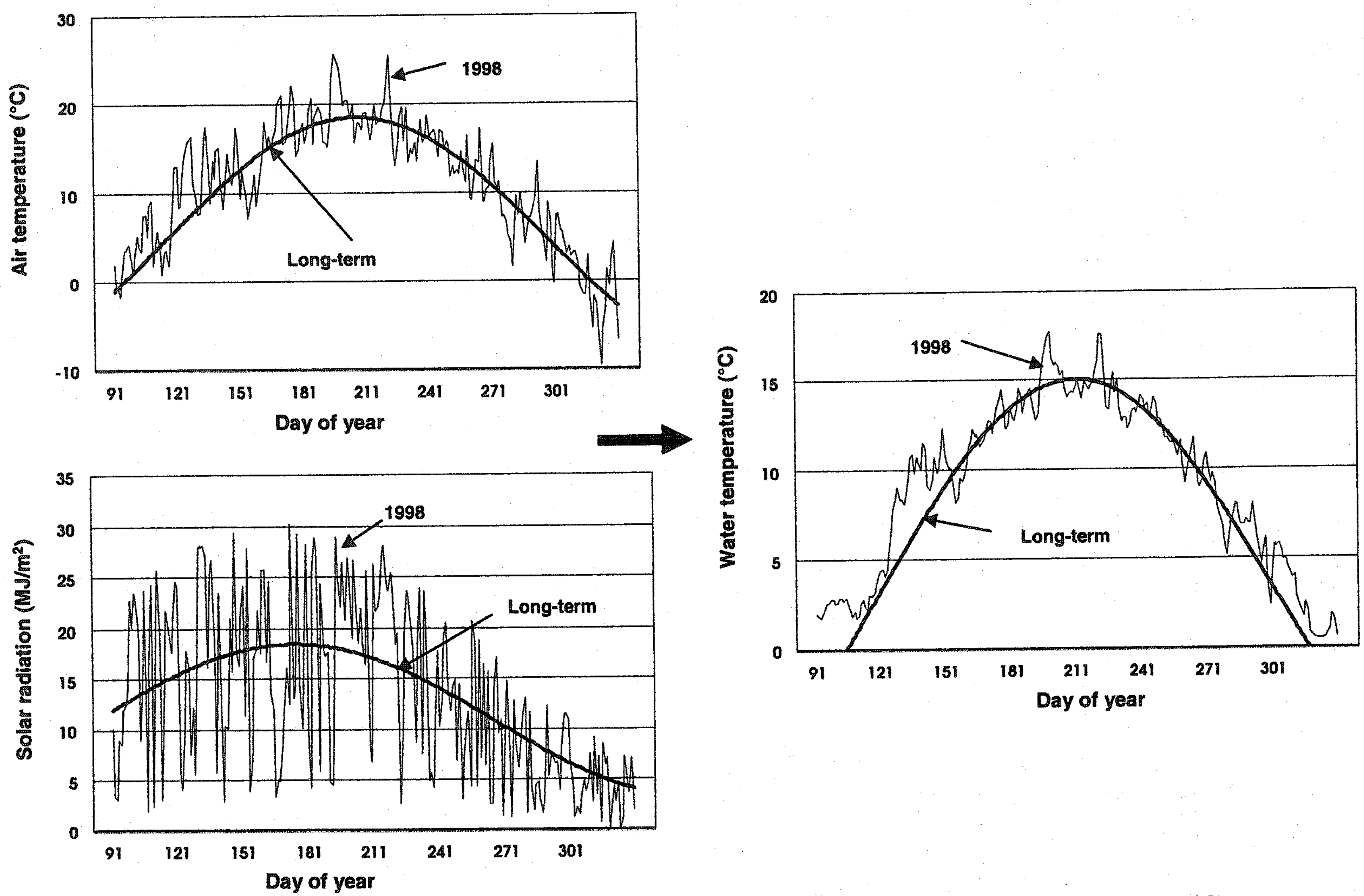

Figure 3.1 Characteristics of the energy reference model showing the long-term and short-term (1998) meteorological components.

component $\phi_w(t)$ would be expected. Similarly, when H_t is below the reference energy (H_{ref}), then a decrease in water temperature relative to the annual component would be observed. A special case of the energy reference model is when the total energy flux (H_t) becomes close or equal to the reference energy flux (H_{ref}), then the trend in water temperatures would become that of the annual component $\phi_w(t)$.

To incorporate the long-term water temperatures in the new model, the annual water temperature component needs to be expressed as a function of time (e.g. daily time step). Equation [3.29] was used with the appropriate transformation to calculate the annual component. The long-term annual daily increments in water temperature are given by the following equation:

$$\phi_w(t) = TA(t) - TA(t-1) \qquad [3.32]$$

where $TA(t)$ represents the annual component at time (t) and $TA(t\text{-}1)$ the annual component at times ($t\text{-}1$).

Then substituting the equation [3.29] in [3.32] gives the following equation:

$$\phi_w(t) = a_3 + b_3 \sin\left(\frac{2\pi}{365}(t - t_o)\right) - a_3 - b_3 \sin\left(\frac{2\pi}{365}(t - t_o - 1)\right) \qquad [3.33]$$

where all parameters have been defined in [3.29]. This equation represents the following form of sine function.

$$\sin(u+v) \;-\; \sin(u-v) \;=\; 2\;\cos u\;\;\sin v \qquad [3.34]$$

where u and v in [3.33] can be expressed as:

$$u = \frac{2\pi}{365}\left(t - t_o - \frac{1}{2}\right) \qquad [3.35a]$$

and

$$v = \frac{\pi}{365} \qquad [3.35b]$$

Therefore $\phi_w(t)$, which represents the changes over time (e.g. daily variation) in water temperatures due to the long-term annual component can take the following form:

$$\phi_w(t) = 2b_3 \sin\left(\frac{\pi}{365}\right) \cos\left(\frac{2\pi}{365}\left(t - t_0 - \frac{1}{2}\right)\right) \qquad [3.36]$$

using a daily time step and where b_3, t and t_0 were defined previously in equation [3.29].

The energy reference model takes into account parameters which are not totally random variables (e.g., air temperature and solar radiation). This model will be calibrated similar to other models, using data from 1992 to 1994, while data from 1995 to 1999 will be used to validate the model. Results will be compared to other model to see if improvement can be realised in the prediction of water temperatures using the long-term energy flux as a reference energy as well as incorporating the annual component in water temperature in the modelling.

3.2 Study area

Stream water temperature data in the present study were collected on two river systems of different size and within a similar hydrometeorological region. Both of these study sites are part of the Miramichi River system in New Brunswick, which is world renowned for its population of Atlantic salmon. This river annually receives between 860 mm and 1365 mm of precipitation, with a long-term average of 1142 mm (Caissie and El-Jabi 1995). On a monthly basis, precipitation was close to 100 mm per month, with values ranging between 72 mm in February and 109 mm in November. 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 although August at 17.7 °C is very close. Between these two extremes, mean monthly air temperature varies gradually, with 7 months of the year experiencing temperatures above freezing. The mean annual runoff was estimated at 714 mm for the Miramichi region with values ranging from 631 mm to 763 mm (Caissie and El-Jabi 1995). The open-water period usually extends from mid-April to late November within the Miramichi River system.

The first study site was located on the Little Southwest Miramichi River at approximately 25 km from the river mouth (at the confluence of Catamaran Brook) (Figure 3.2). Water temperature data have been collected at this site since 1992. The Little Southwest Miramichi River is approximately 80 m in width with an average water depth of 0.55 m. A water temperature sensor was installed on this river at approximately 20 m upstream from the confluence of Catamaran Brook (at approximately 2 m from the True Right bank, near the bottom). The type of sensor used was a model 107B from Campbell Scientific Canada Corp. which incorporates the Fenwal Electronic thermistor probe. This probe was connected to a CR10 data logger. The error associated with this sensor is typically less than 0.2 °C for the range of -30 °C to +40 °C. Water temperature measurements are carried out every 5 seconds during the last minute of every hour to calculate an hourly mean water temperature. Lateral variations in river water temperatures were investigated using measurements with a high precision mercury thermometer taken at approximately 0.5 m intervals (from bank to bank) and at different depths. No variations were anticipated or observed, due to the well-mixed nature (high turbulence) of this river. The data used in the present study were daily mean water temperatures calculated from hourly data (mean of 24 observations). Although the riparian vegetation is mature along the banks of the Little Southwest Miramichi River, this river is nevertheless well exposed to meteorological conditions due to its relatively large width. Therefore, it can be considered as a wide and shallow river for modelling purposes.

A hydrometric station operated by Environment Canada (1951-2000) was located on the Little Southwest Miramichi (station 01BP001) approximately 16 km downstream from the water temperatures sampling point. The drainage area above this hydrometric station measures 1340 km^2. The mean annual flow at the Little Southwest Miramichi River hydrometric station was 32.5 m^3/s or 764 mm of runoff. The river discharge varied from a low of 1.70 m^3/s on January 14, 1959 to a record high value of 861 m^3/s on May 28, 1961. To run the deterministic water temperature model, water depths were required at the water temperature sampling site. Therefore, water levels were measured at the water temperature sampling site from 1999-2001 during open water conditions and for different discharges. These water levels were then related to the mean daily discharges at the Little Southwest Miramichi River hydrometric station. Water levels at the water temperature sampling site were then calculated for 1992 to 1999.

The second study site was located in Catamaran Brook (Middle Reach), approximately 8 km upstream from its mouth. Catamaran Brook at this site is approximately 9 m in width and has a mean depth of water of 0.21 m. The present forest cover at Catamaran Brook is mainly second growth, mature species, estimated as 65% coniferous and 35% deciduous (Cunjak et al. 1990). Catamaran Brook is also the site for a 15-year multi-disciplinary hydrobiological research study aimed at quantifying stream ecosystem processes and the impact of timber harvest (Cunjak et al. 1990). At this site, a water temperature sensor was also deployed in a well-mixed section of the river, similar to Little Southwest Miramichi River installation. Compared to Little Southwest Miramichi River, Catamaran Brook is well sheltered by upland slopes and by streamside vegetation.

To monitor streamflow, Environment Canada installed a hydrometric gauge at mid-basin of Catamaran Brook, which they have operated continuously since 1989 (Figure 3.2). Measured water levels were used to calculate stream discharge. The drainage area at mid-basin, above the hydrometric station, was approximately 27 km^2. The mean annual flow for the Catamaran Brook basin at the gauge was estimated at 0.62 m^3/s or 724 mm of runoff. The spring flood period occurs from late April to early May. The highest measured flow, 13 m^3/s, was recorded on May 3, 1991. The lowest daily flow on record occurred September 3, 1994 at 0.016 m^3/s. The Catamaran Brook streamflow is comprised of different sources, one of which, groundwater discharge, can play an important role during summer rainfall events (Caissie et al. 1996). Water levels at Catamaran Brook as at Little Southwest Miramichi River were obtained from the discharge level relationship (i.e., rating curve) to run the deterministic water temperature model.

Meteorological data for both rivers were obtained from the Catamaran Brook meteorological station, which is located less than 10 km from the water temperature study sites (Figure 3.2). The station was located at the centre of a 400 m x 400 m clearcut area to meet Environment Canada weather station specification (e.g., wind speed, solar radiation). Meteorological conditions measured at Catamaran Brook are reflective of conditions experienced by both river systems due to climate homogeneity within the region (Caissie and El-Jabi 1995). Therefore, this data base will be used for the water modelling of both Catamaran Brook and the Little Southwest Miramichi River.

Air temperature was required for all water temperature models and most of the other parameters measured at the meteorological station were required to run the deterministic model. The air temperature and relative humidity sensor was a Model 207, which contains a Phys-Chemical Research PCRC-11 relative humidity sensor and a Fenwal Electronics UUT51J1 thermistor for air temperature. The thermistor has an accuracy typically within ± 0.2 °C. The relative humidity accuracy was within 1% for values of 25-94% and within 3% for values of 12-100%. The air temperature and relative humidity sensors were installed at approximately 1.8 m from the ground in a well ventilated area. Missing data at Catamaran Brook (i.e., mainly relative humidity) during the period from 1994 to 1999 were supplemented by data from the Environment Canada meteorological station located at Miramichi Airport (approximately 76 km from the Catamaran Brook site).

Solar radiation was monitored using a LI-COR Inc. instrument (Model LI-200SZ) pyranometer. The pyranometer measures global sun plus sky radiation using a silicon photodiode, which has a spectral response from 400-1100 nm. The maximum absolute error is less than ± 5%, but typically less that ± 3%. The pyranometer was installed on a south facing mounting arm at approximately 2.5 m from ground level. Due to the location of the meteorological station within a clearcut area, solar radiation data represents a total exposure to the sky (i.e., unsheltered conditions).

A tipping bucket rain gauge (TE525) made by Texas Electronics Inc. was used to monitor precipitation during the summer period. This gauge directs precipitation into a tipping bucket mechanism. When the bucket is filled to a calibrated level it tips, and a magnet attached to the tipping mechanism activates the signal through a reed switch. A pulse signal is then read by the data logger system. The accuracy of the TE525 tipping bucket is typically ± 1% for rainfall up to 25 mm / hr. The tipping bucket rain gauge was installed at approximately 1.2 m from the ground and it was sheltered by a Alter type wind shield (to reduce the wind effect of on precipitation measurements). Barometric pressure was monitored using a Setra Barometric Pressure Sensor (Model SBP270). This pressure sensor has a range of 800-1100 mbar, with an accuracy of ± 0.2 mbar. The barometric pressure sensor was installed at approximately 2 m from the ground. Barometric data were transformed in to mm Hg to be consistent with previous literature equations and data.

The wind speed and direction was obtained using a propeller type anemometer or an R.M. Young wind monitor (Model 05103). This device, mounted on a 10 m tower,

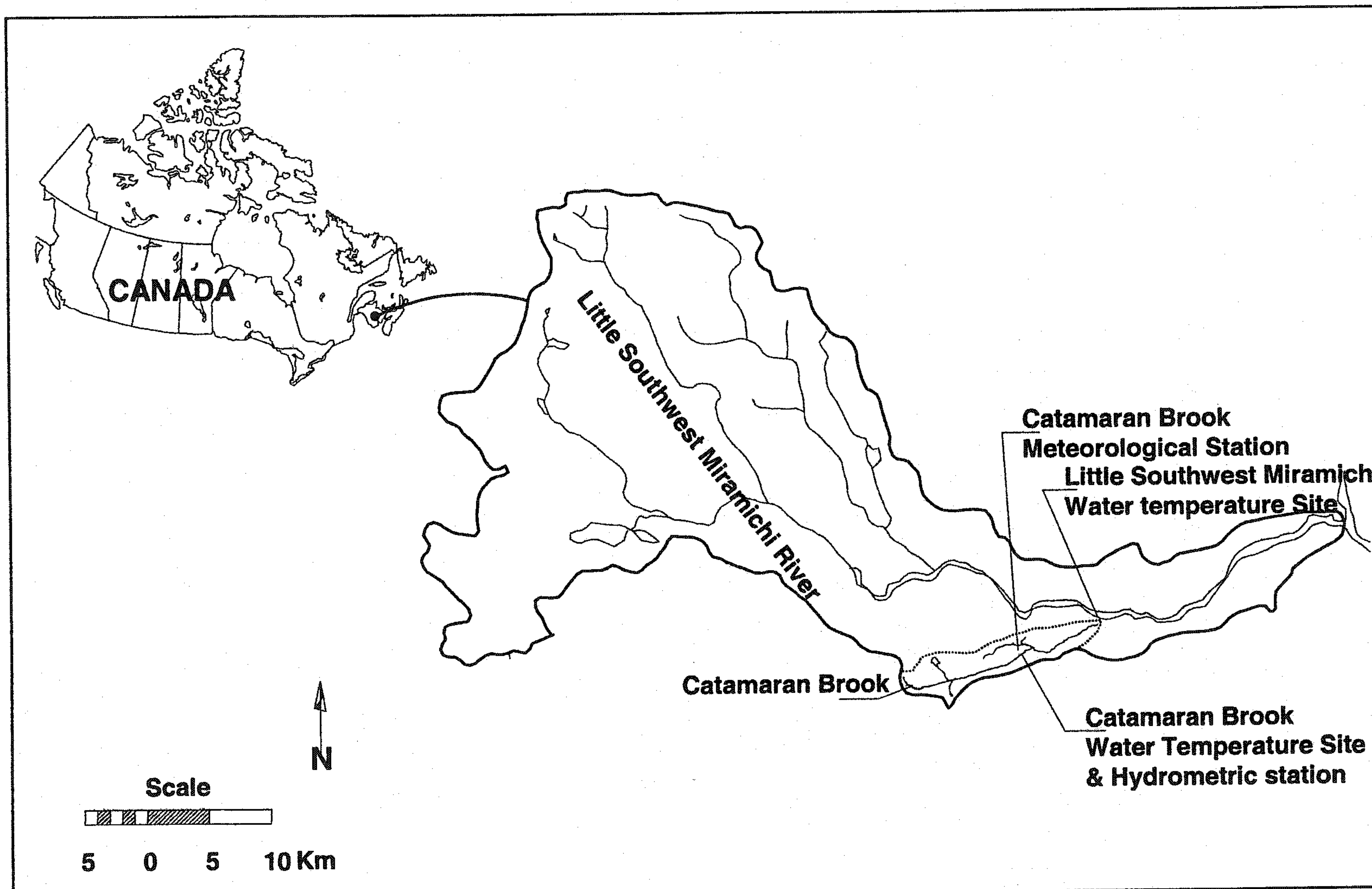

Figure 3.2 Map of the Little Southwest Miramichi River and Catamaran Brook showing the location of the water temperature sites and the meteorological station.

monitors both wind speed and direction. The rotation of the propeller produces an AC signal proportional to the wind speed, which is then monitored by the CR10 data logger. The R.M. Young wind monitoring sensor has a range of 0-60 m/s, with a gusting wind capacity of 100 m/s. The accuracy is typically ± 0.3 m/s for wind speed and ± 3 ° for wind direction. The trees were estimated to be approximately 20 m high in the study area, therefore a 400 m x 400 m clearcut area represents at wind fetch of 10 X the height of trees.

3.3 Modelling performance criteria

To compare modelling performance results for different rivers and different years, the root-mean-square error (RMSE) and the Nash coefficient (NASH) will be used (Janssen and Heuberger 1995; Nash and Sutcliffe 1970). The root-mean-square error provides information related to the mean errors associated to the model's performance. The RMSE is calculated using the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i - P_i)^2}{N}} \quad [3.37]$$

where N = number of daily water temperature observations.
O_i = observed daily water temperature.
P_i = predicted daily water temperature.

Alternatively, the Nash Coefficient provides information related to the level of association between predicted vs. observed values and has a range between 0 and 1. A NASH of zero indicates no association between predicted vs. observed values, while a value of 1 indicates a perfect association. The Nash coefficient is given by the following equation:

$$NASH = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \overline{O}_i)^2} \qquad [3.38]$$

where $\overline{O}_i$ represents the mean daily water temperatures for the period (N) and the other parameters have been defined in [3.37].

CHAPTER 4

OBSERVED DATA
AND MODELLING RESULTS

4.1 Monthly / long-term water temperatures and streamflow

Before presenting water temperature modelling results, it is important to present some long-term thermal characteristics for both Catamaran Brook and the Little Southwest Miramichi River. This was possible because of extensive data gathered through a study of monthly water temperatures as well as long-term daily temperatures. Monthly air temperature data will also be presented for the study area. Monthly air temperatures were collected at the Catamaran Brook meteorological station between 1992 and 1999 for months with water temperatures above 0°C, i.e. April to November (Table 4.1). The mean air temperature within the study area between 1992 and 1999 was 10.3 °C. During this period, a significant range of annual air temperatures (mean of Apr. - Nov.) was observed in the Miramichi area. The coldest year was 1992 at 9.4 °C, while the warmest was 1999 at 11.9°C, a difference of 2.5 °C. The years 1994 and 1995 experienced normal air temperatures. In general, air temperature increased from a low monthly value in the spring (April, 2.8 °C) to a maximum monthly temperature in July at 18.4 °C, and then decreased again in autumn (Nov., -0.4 °C). It was noted that although the month of July showed the highest mean air temperature, the month of August also experienced high temperature at 17.4°C (Table 4.1). In addition, the highest monthly air temperature was observed in August rather than July during some summers (e.g. 1992, 1993 and 1996). Marked variability in air temperature was also observed during the study period. For instance, the coldest month observed during the study period was November 1992 at –2.6 °C. Warmest months all exceeding 19 °C, occurred in 1994 (20.0 °C), 1998 (19.2 °C) and 1999 (19.3 °C).

Meteorological conditions at the Catamaran Brook station were similar between the calibration and validation phases. For example, the mean air temperature was calculated at 9.8 °C (calibration) compared to 10.6 °C (validation). On a daily basis temperatures varied between -13.9 °C and 26.7 °C during the calibration period and between -10.0 °C and 26.3 °C during the validation period. The average conditions (and the range) of wind speed and solar radiation were also comparable between the calibration and validation periods. For instance, the average wind speed during the calibration period was calculated at 4.0 km/h (0.3-12.6 km/h) compared to 3.8 km/h (0.7-12.9 km/h) during the validation period. For solar radiation, mean values of 13.2 MJ/m^2 (0.4-31.5 MJ/m^2; calibration) and 14.0 MJ/m^2 (0.08-31.9 MJ/m^2; validation) were calculated respectively.

Water temperatures at Catamaran Brook (Middle Reach, Figure 3.1) were monitored throughout the study period and monthly temperatures are presented in Table 4.2. The mean water temperature at Catamaran Brook between 1992 and 1999 was calculated at 8.8 °C (i.e., 1.5 °C less than air the temperature, Table 4.1). Similar to air temperature, water temperature at Catamaran Brook showed inter and intra-annual variability during the studied period. Mean annual (Apr. to Nov.) water temperature varied between 7.8 °C (1993 and 1997) and 10.3 °C (1999). Mean water temperature during the coldest summer air temperature (i.e. 1992) was not available at Catamaran Brook, however the highest water temperature year (1999, 10.3 °C) was consistent with high air temperatures. Intra-annual variability showed maximum monthly water temperatures occurring generally in July with a mean value of 15.2 °C. Similar to air temperature, maximum monthly water temperature can occur in July as well as August such as occurred in 1992, 1993 and 1996 (Table 4.2). The warmest monthly water temperature at Catamaran Brook was monitored in July of 1999 at 17.2 °C.

Table 4.1 Monthly air temperatures (°C) at the Catamaran Brook meteorological station between 1992 and 1999.

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Mean
1992	1.7	10.7	15.0	15.2	17.0	13.4	5.3	-2.6	9.4
1993	3.2	8.6	14.8	17.3	18.0	12.5	3.7	-1.1	9.6
1994	3.1	8.0	14.3	20.0	17.1	11.7	7.3	1.4	10.4
1995	1.8	8.6	17.0	19.9	17.6	10.8	8.7	-0.8	10.5
1996	3.0	8.1	15.9	17.6	17.9	12.6	5.8	-0.2	10.1
1997	1.5	8.3	15.1	18.4	16.3	12.6	4.7	-0.8	9.5
1998	4.0	12.5	15.1	19.2	17.4	13.1	6.6	-0.9	10.9
1999	3.8	13.2	18.0	19.3	17.6	16.1	5.3	2.1	11.9
1992-99	2.8	9.7	15.7	18.4	17.4	12.9	5.9	-0.4	10.3

Table 4.2 Monthly water temperatures (°C) at Catamaran Brook between 1992 and 1999.

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Mean
1992	n/a	8.3[a]	11.6	12.2	12.9	11.4	5.4	1.4	n/a
1993	0.62	5.8	10.5	13.4	14.8	10.7	4.5	1.8	7.8
1994	0.82	5.0	12.4	16.6	15.2	10.3	5.6	3.6	8.7
1995	1.2	5.9	13.5	16.2	15.3	9.9	7.2	2.6	9.0
1996	0.90	5.4	13.6	14.4	15.2	11.5	6.0	3.5	8.8
1997	0.49	3.8	11.5	13.9	13.7	11.0	4.8	3.0	7.8
1998	2.7	8.9	11.5	14.7	14.3	11.3	6.5	3.0	9.1
1999	1.6	9.3	15.2	17.2	15.8	14.2	5.8	3.0	10.3
1992-99	1.2	6.3	12.6	15.2	14.9	11.3	5.8	2.9	8.8

[a] mean calculated with missing data.

Monthly water temperature data for the Little Southwest Miramichi River are presented in Table 4.3. The mean annual water temperature at Little Southwest Miramichi River was calculated at 11.2 °C from 1992 to 1999, which was 0.9 °C higher than the air temperature within the same period (Table 4.3). Fewer data were available to compare inter-annual water temperatures at Little Southwest Miramichi River particularly in the spring of 1992, 1994 and 1996. Missing data at this time of year was mainly due to broken probes resulting from the dynamic nature of the spring breakup during ice-out. Mean annual water temperature indicated a range of temperatures between 10.2 °C (1997) and 12.8 °C (1999).

Table 4.3 Monthly water temperatures (°C) at the Little Southwest Miramichi River between 1992 and 1999.

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Mean
1992	n/a	12.7[a]	15.4	16.1	17.7	15.5	7.0	1.8	n/a
1993	1.3	9.1	13.6	18.2	20.0	14.0	5.2	1.6	10.4
1994	n/a	7.3[a]	14.5	20.8	19.0	13.1	7.3	4.4	n/a
1995	1.1	7.7	17.6	22.0	20.8	14.3	9.6	2.4	11.9
1996	n/a	10.0[a]	16.2	17.7	19.4	14.0	6.6	2.8	n/a
1997	0.2[a]	5.5	15.1	19.1	18.5	14.3	5.9	2.9	10.2
1998	3.2	11.6	15.7	19.1	18.6	14.2	6.9	2.4	11.5
1999	2.5	11.7	19.8	21.9	20.0	17.1	6.3	3.0	12.8
1992-99	2.0	9.1	16.0	19.4	19.3	14.5	6.9	2.7	11.2

[a] monthly mean calculated with missing data.

Similar to water temperatures at Catamaran Brook, intra-annual water temperatures at Little Southwest Miramichi River showed the highest values in July at 19.4 °C, although the temperatures in August were almost identical at 19.3 °C (1992-99, Table 4.3). The highest monthly water temperature at Little Southwest Miramichi River occurred in 1995 at

22.0 °C. It was noted that monthly water temperatures at this site were often higher than air temperatures (Table 4.1 and 4.3). This was observed from June and extended to autumn.

Water temperatures for both river systems can also be represented by their respective long-term annual component. This annual component was calculated using mean daily water temperature data. For instance, Figure 4.1 shows the long-term water temperatures, i.e. the mean for each day of each year from 1992-1999, for both rivers, with their associated annual component represented by a sinusoidal function (to be discussed in greater detail in the stochastic modelling section).

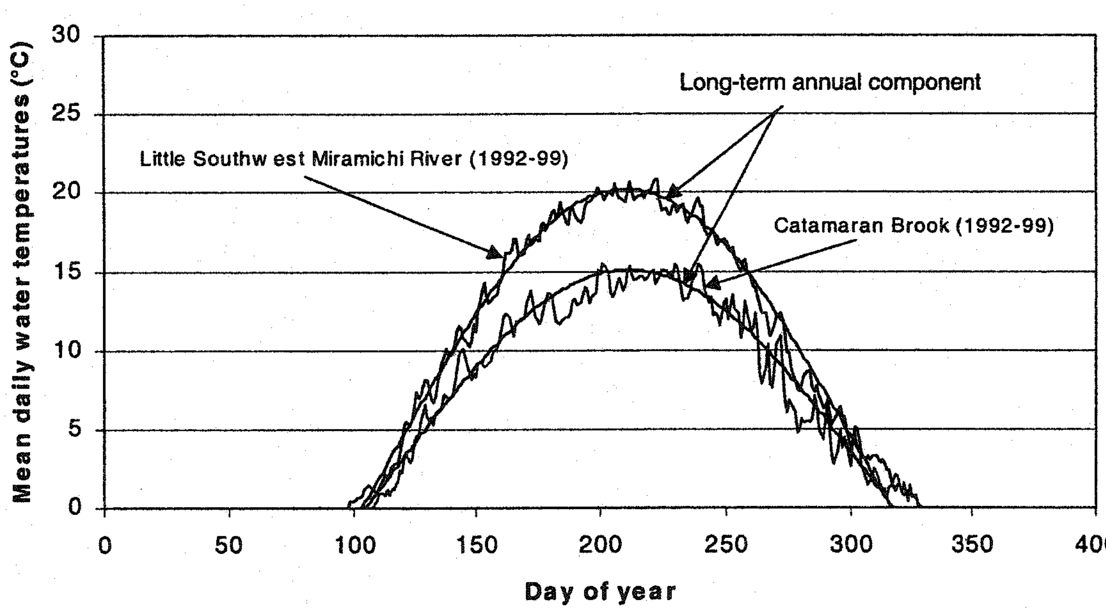

Figure 4.1 Long-term water temperatures at Catamaran Brook and the Little Southwest Miramichi River (NB).

The long-term annual component of water temperatures showed that the thermal regime in the spring was similar within the small and large systems. During this time of year, water temperatures were similar and the departure date from 0°C was identical (April

13 or day 103; Figure 4.1). Thereafter, the warming period extended until the end of July for both rivers, with the Little Southwest Miramichi River experiencing a greater increase in water temperature. The maximum water temperature on the annual component was 20.2 °C for the Little Southwest Miramichi River compared to 15.1 °C for Catamaran Brook. Both rivers experienced their long-term peak temperatures on the same day, i.e. July 30 (day 211).

The greatest difference in water temperatures between small and larger rivers was observed at peak summer temperatures. This difference represented 5.1 °C between Catamaran Brook and the Little Southwest Miramichi River. A cooling period was observed following July 30 for both river systems. Moreover, it was noticed that the Little Southwest Miramichi River cooled at a slightly faster rate during the end of the season (after day 250, Figure 4.1). During this period, long-term mean temperatures for the Little Southwest Miramichi River slipped below the annual component for extended periods of time. Both river systems reached water temperatures close to 0°C in mid-November (Nov 13, day 317), and these temperatures remained close to 0°C throughout the winter period.

Stream discharge may also play a role in the thermal regime of river or in performance of water temperature models. Therefore, inter and intra annual river discharge data for both Catamaran Brook and the Little Southwest Miramichi River were examined (Table 4.4 and 4.5).

Discharge data at Catamaran Brook showed an overall mean value of 0.711 m^3/s (1992-99; Table 4.4), while the overall mean discharge at Little Southwest Miramichi River was 39.9 m^3/s (1992-99; Table 4.5). The highest flow month during the water temperature modelling study was May for both Catamaran Brook (1.84 m^3/s, 1992-99) and the Little Southwest Miramichi River (100.1 m^3/s, 1992-99). Highest annual discharge (Apr. to Nov.) was observed in 1998 for both Catamaran Brook (0.847 m^3/s) and the Little Southwest Miramichi River (45.8 m^3/s). Low flow summer months (Jun. to Sept.) were particularly apparent in August of 1994, 1995, and 1999 in Catamaran Brook, with the lowest monthly flow monitored in September of 1995 (0.046 m^3/s; Table 4.4). The Little Southwest Miramichi River also experienced low flows in these months, and the lowest monthly flow was monitored in September of 1995 as well (5.17 m^3/s; Table 4.5).

Table 4.4 Monthly discharges (m^3/s) at Catamaran Brook between 1992 and 1999 (data from Environment Canada, station no. 01BP002).

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Mean
1992	1.13	1.43	0.384	0.479	0.500	0.139	0.458	0.515	0.629
1993	1.67	1.19	1.17	0.441	0.126	0.108	0.479	0.742	0.741
1994	2.11	2.36	0.653	0.200	0.051	0.070	0.065	0.254	0.720
1995	1.33	2.11	0.297	0.140	0.053	0.046	0.189	1.01	0.647
1996	1.80	1.77	0.403	1.24	0.225	0.243	0.330	0.712	0.840
1997	0.691	3.06	0.524	0.390	0.114	0.116	0.071	0.386	0.669
1998	2.37	1.65	0.706	0.389	0.324	0.346	0.610	0.384	0.847
1999	1.85	1.13	0.152	0.102	0.099	0.331	0.449	0.649	0.595
1992-99	1.62	1.84	0.536	0.423	0.187	0.175	0.331	0.582	0.711

Table 4.5 Monthly discharges (m^3/s) at the Little Southwest Miramichi River between 1992 and 1999 (data from Environment Canada, station no. 01BP001).

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Mean
1992	52.9	76.2	25.2	28.6	26.1	10.2	23.4	22.4	33.1
1993	95.3	60.4	62.6	24.1	14.0	13.5	30.3	38.9	42.4
1994	108.0	133.0	50.6	18.8	9.17	7.61	7.72	14.9	43.7
1995	62.7	118.0	29.2	11.1	5.90	5.17	10.5	47.3	36.2
1996	70.2	88.9	24.4	37.6	15.5	13.3	15.0	37.8	37.8
1997	45.8	166.0	40.1	26.8	13.0	10.1	7.88	15.9	40.7
1998	119.0	82.3	31.7	37.7	21.0	21.0	32.6	21.1	45.8
1999	96.7	76.2	15.9	10.4	12.2	28.7	33.7	40.3	39.3
1992-99	81.3	100.1	34.9	24.4	14.6	13.7	20.1	29.8	39.9

4.2 Deterministic Model

The deterministic model was the first modelling approach carried out on both Catamaran Brook and the Little Southwest Miramichi River. This model was calibrated using 3 years of data (1992-94) and subsequently validated with 5 years of data (1995-99). The deterministic model required the input of many meteorological variables including solar radiation, wind speed, air temperature, relative humidity, and others. Data collected from the Catamaran Brook meteorological station were used to run this model for each river. However, due to a malfunction and intermittent problems with the relative humidity sensor during some years (calibration period, 1992 to Sept 23 1993; validation period, 1995-96), the deterministic model was initially calibrated using best available relative humidity data only, i.e. 1994 data. The minimum sum of squared differences between predicted and observed water temperatures was used during the calibration period to estimate model parameters. After this initial calibration, parameters of the deterministic model were adjusted slightly for the whole calibration period (1992-94) using an average relative humidity for the period with missing data. The average summer relative humidity was calculated at 71% based on data from 1994, 1997-99, i.e. years with sound relative humidity data from the Catamaran Brook meteorological station.

Relative humidity data were also used from the nearby Miramichi Airport meteorological station (data available from 1994 to 1999) to see if potential improvements in the modelling could be realised during those years with limited data from the Catamaran Brook meteorological station. The Miramichi Airport is located at approximately 76 km from Catamaran Brook. A relatively good agreement between the relative humidity of these two stations was observed (Figure 4.2). Approximately 75% of the variance of the relative humidity at Catamaran Brook can be explained using the Miramichi Airport data. Following the above initial calibration, Miramichi Airport relative humidity data were used as well during the calibration period for comparative purposes.

During the validation period, the above three sources of relative humidity data were used, similar to the procedure used during the calibration period. For instance, due to some missing relative humidity data at Catamaran Brook in 1995 and 1996, average summer relative humidity of 71% was used. Actual daily measurements of relative humidity (i.e. from the meteorological station) were used from 1997 to 1999. Miramichi Airport relative humidity data were available throughout the validation period and were used for comparative purposes as well.

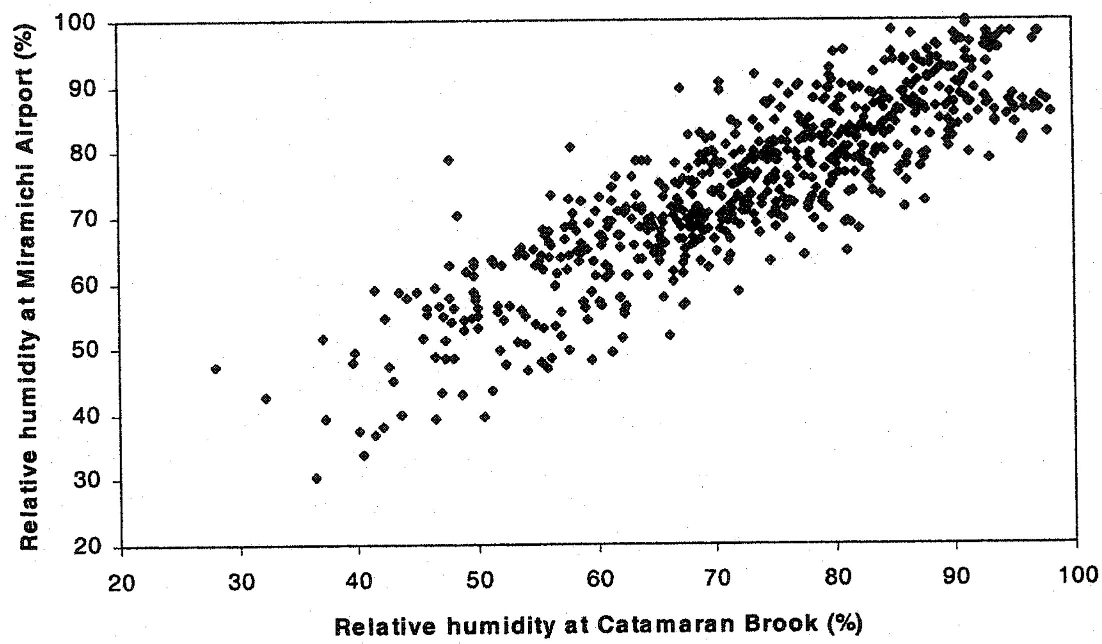

Figure 4.2 Relation between the Catamaran Brook relative humidity (%) and the Miramichi Airport relative humidity (%). The coefficient of determination, R^2, was calculated at 0.75.

To carry out the deterministic water temperature models for both river systems, equation [3.1] required the knowledge of the mean river depth or stream morphology. A power function was used to calculate mean water depth for both Catamaran Brook and the Little Southwest Miramichi River (equation [3.9]). Two regression parameters are required to use equation [3.9], i.e. a_4 and b_4. The coefficient a_4 was calculated at 0.240 for Catamaran Brook, while b_4 was calculated at 0.417 and a corresponding coefficient of determination, R^2, of 0.991. For the Little Southwest Miramichi River, a_4 was calculated at 0.127 while b_4 was calculated at 0.444. The coefficient of determination was 0.982. Using these power functions and river discharge for both Catamaran Brook and the Little Southwest Miramichi River, the mean water depth was then calculated on a daily basis for the period between 1992 and 1999.

The deterministic model was then calibrated by adjusting energy components relative to each other, namely solar radiation, evaporative heat flux and sensible heat. This approach was also used in previous studies (e.g., Morin and Couillard 1990). For instance, the net incoming solar radiation was calibrated using the shading factor (*SF*) in equation [3.4]. The other energy components (evaporative and convective heat fluxes) were multiplied by a factor between 1.0 and 3.0 until predicted water temperatures closely fitted observed temperatures during the calibration period. This calibration was carried out on a computer spreadsheet using different factors until a minimum RMSE was reached. For example, the evaporative heat flux component was multiplied by 1.05 at Catamaran Brook and by 1.6 for the Little Southwest Miramichi River. Similarly, factors for the convective heat transfer were calculated at 1.25 and 2.9 for Catamaran Brook and the Little Southwest Miramichi River respectively. The Catamaran Brook shading factor was calculated at 0.55, while the shading factor for the Little Southwest Miramichi River was calculated at 0.08.

Solar radiation accounted for most of the input of energy with a mean value of 5.56 MJ m^{-2} d^{-1} at Catamaran Brook and 11.38 MJ m^{-2} d^{-1} at Little Southwest Miramichi River (Table 4.6). The net long-wave radiation and energy lost by evaporation were relatively similar among themselves and among rivers (H_l = -3.61 MJ m^{-2} d^{-1} vs. H_e = -3.58 MJ/m^2 at Catamaran Brook, and H_l = -4.66 MJ m^{-2} d^{-1} vs. H_e = -5.33 MJ m^{-2} d^{-1} for the Little Southwest Miramichi River). The smallest energy component was the convective heat transfer, which was calculated at 1.42 MJ m^{-2} d^{-1} for Catamaran Brook and –0.65 MJ m^{-2} d^{-1} for the Little Southwest Miramichi River (Table 4.6).

Predicted vs. observed water temperatures at Catamaran Brook and the Little Southwest Miramichi River using the deterministic model are presented in Figures 4.3a and 4.4a. The residual time series (difference between predicted and observed water temperatures) are presented in Figures 4.3b and 4.4b. The root-mean-square error (RMSE) and the Nash coefficient (NASH) are presented in Table 4.7a. Results showed relatively good agreement between predicted and observed water temperatures for both rivers. Missing meteorological data prevented the modelling of water temperatures during a short period in 1992, 1994 and 1997, thus no comparison was available during these short periods.

The deterministic model performed well in Catamaran Brook during the calibration period, especially during autumn of 1993 and 1994 with a good capture of the water temperature variability. Such was not the case in autumn 1992 where the model significantly underestimated water temperatures toward the end of the season (after day 270; Figure 4.3a). The best modelling results at Catamaran Brook occurred in 1994 with an RMSE of 1.22 °C (Table 4.7a). The year 1992 showed highest RMSE (lowest NASH = 0.804) during the calibration period except in autumn, although relatively good agreement was observed throughout the summer. The deterministic model tended to overestimate peak summer temperatures during all years of the calibration period at Catamaran Brook (Figure 4.3a).

Similar results were observed during the validation period at Catamaran Brook. The overall RMSE was calculated at 1.61 °C (1995-99; Table 4.7a). Similarly to the calibration period, the model underestimated water temperatures in autumn. The most marked departure in predicted water temperatures during the validation period was noted in autumn 1996 toward the end of the season. The RMSE during the validation period varied between 1.43 °C (1999) and 1.77 °C (1998). Nash coefficient ranged between 0.863 and 0.947 (1995-99; Table 4.7a). It was noted that summers with local relative humidity data showed among the best RMSEs (i.e. 1998 and 1999). As evidenced in the calibration period, summer peak temperatures were also slightly overestimated during the validation period. This was especially noticeable for the summer peak temperatures in 1998. In contrast, the warmest summer on record (1999) showed among the best performance at Catamaran Brook both in terms of low RMSEs and good prediction of peak summer temperatures (Table 4.7a; Figure 4.3a).

Table 4.6 Calculated energy component (MJ m^{-2} d^{-1}) by the deterministic model at Catamaran Brook and the Little Southwest Miramichi River (1992-99).

Year	Solar radiation (H_s)	Net long-wave radiation (H_l)	Evaporative heat flux (H_e)	Convective heat transfer (H_c)
		Catamaran Brook		
1992	4.80	-3.48	-2.97	1.29
1993	5.57	-3.95	-3.23	1.38
1994	5.11	-3.40	-2.59	1.42
1995	6.41	-3.50	-4.41	1.45
1996	5.88	-3.75	-3.98	1.56
1997	4.50	-3.86	-2.76	0.94
1998	5.77	-3.68	-4.06	1.59
1999	6.44	-3.29	-4.66	1.72
Mean	5.56	-3.61	-3.58	1.42
		Little Southwest Miramichi River		
1992	9.82	-4.36	-4.14	0.17
1993	11.40	-5.01	-5.18	-0.92
1994	10.44	-4.29	-4.30	-0.40
1995	13.11	-4.69	-6.33	-1.23
1996	12.03	-4.90	-5.82	-0.71
1997	9.21	-4.76	-4.22	-1.41
1998	11.81	-4.84	-5.91	-0.46
1999	13.18	-4.47	-6.76	-0.28
Mean	11.38	-4.66	-5.33	-0.65

Results of the deterministic model for the Little Southwest Miramichi River are presented in Figure 4.4a, while the residual time series are presented in Figure 4.4b. RMSE and Nash coefficients for this river are presented in Table 4.7a. A relatively good agreement was observed between predicted and observed water temperatures during both the calibration and validation periods. The RMSE during the calibration period was 1.49 °C (NASH = 0.942) compared to 1.55 °C (NASH = 0.945) during the validation period. Unlike Catamaran Brook which showed best modelling performance during years with local relative humidity data, the Little Southwest Miramichi River showed its best performance in 1993 (RMSE = 1.23 °C; calibration) and 1998 (RMSE = 1.22 °C; validation). The overall RMSE was calculated at 1.53 °C (1992-99), which was comparable to but slightly better than Catamaran Brook (1.58 °C). The Nash coefficient was 0.944 for the Little Southwest Miramichi River compared to 0.918 for Catamaran Brook (1992-99; Table 4.7a).

The modelling performance was especially good during autumn in the Little Southwest Miramichi River, i.e. during the initial decrease of the annual component (e.g., day 220-280). In contrast to Catamaran Brook, which under predicted autumn water temperature (e.g. 1992 and 1996), the deterministic model performed better in the Little Southwest Miramichi River in late autumn (during both the calibration and validation periods). Summer peak water temperatures were especially well predicted in the 1996-99 period in the Little Southwest Miramichi River. A slight overestimation was noted in spring of 1997 for this river, which was not observed at Catamaran Brook. It should also be pointed out that spring water temperatures were not always available for the Little Southwest Miramichi River for comparison, due to broken probes, e.g. resulting from a severe ice jam in the spring of 1994.

Water temperature residual time series for both Catamaran Brook and the Little Southwest Miramichi River are presented in Figures 4.3b and 4.4b. A consistent overestimation and underestimation by the deterministic model was observed from these figures at different times throughout the summer. Such was also the case in spring and autumn 1992 at Catamaran Brook (Figure 4.3b). The years 1996 and 1998 also showed consistent over / underestimation for part of the summer and autumn periods at Catamaran Brook. Smallest residuals overall at Catamaran Brook, during the peak summer temperatures, were observed in 1999 (Figure 4.3b). In contrast, the Little Southwest Miramichi River (Figure 4.4b) did not show consistent underestimation in late autumn, as was the case in Catamaran Brook. A few years, where data were available in the spring, showed a consistent overestimation (e.g. 1995 and 1997) with the deterministic model. Throughout the summer period of 1995, and to a lesser extent in 1999, a consistent underestimation was observed (Figure 4.4b).

Results on the impact of using an average summer relative humidity data or data from the Miramichi Airport in the deterministic water temperature modelling was presented in Table 4.7b, for both Catamaran Brook and the Little Southwest Miramichi River. For years with relative humidity data from the Catamaran Brook meteorological station, i.e. 1994, 1997-1999, it was observed that the water temperature modelling was slightly better than when using an average relative humidity. The added uncertainty, when using an average relative humidity, was nonetheless low and it was calculated at 0.08 °C for Catamaran Brook and 0.09 °C for the Little Southwest Miramichi River (based on improvements in RMSEs). It was noted that during the year 1999, the use of an average relative humidity for the Little Southwest Miramichi River yielded better RMSE than actual relative humidity data (Table 4.7b).

When using the daily relative humidity data from the Miramichi Airport, relatively good modelling results were observed for both Catamaran Brook and the Little Southwest Miramichi River (Table 4.7b). Calculated RMSEs were very comparable to those calculated when using relative humidity data from the Catamaran Brook meteorological station. In fact, during 1997 and 1998, RMSEs for both rivers were slightly better with

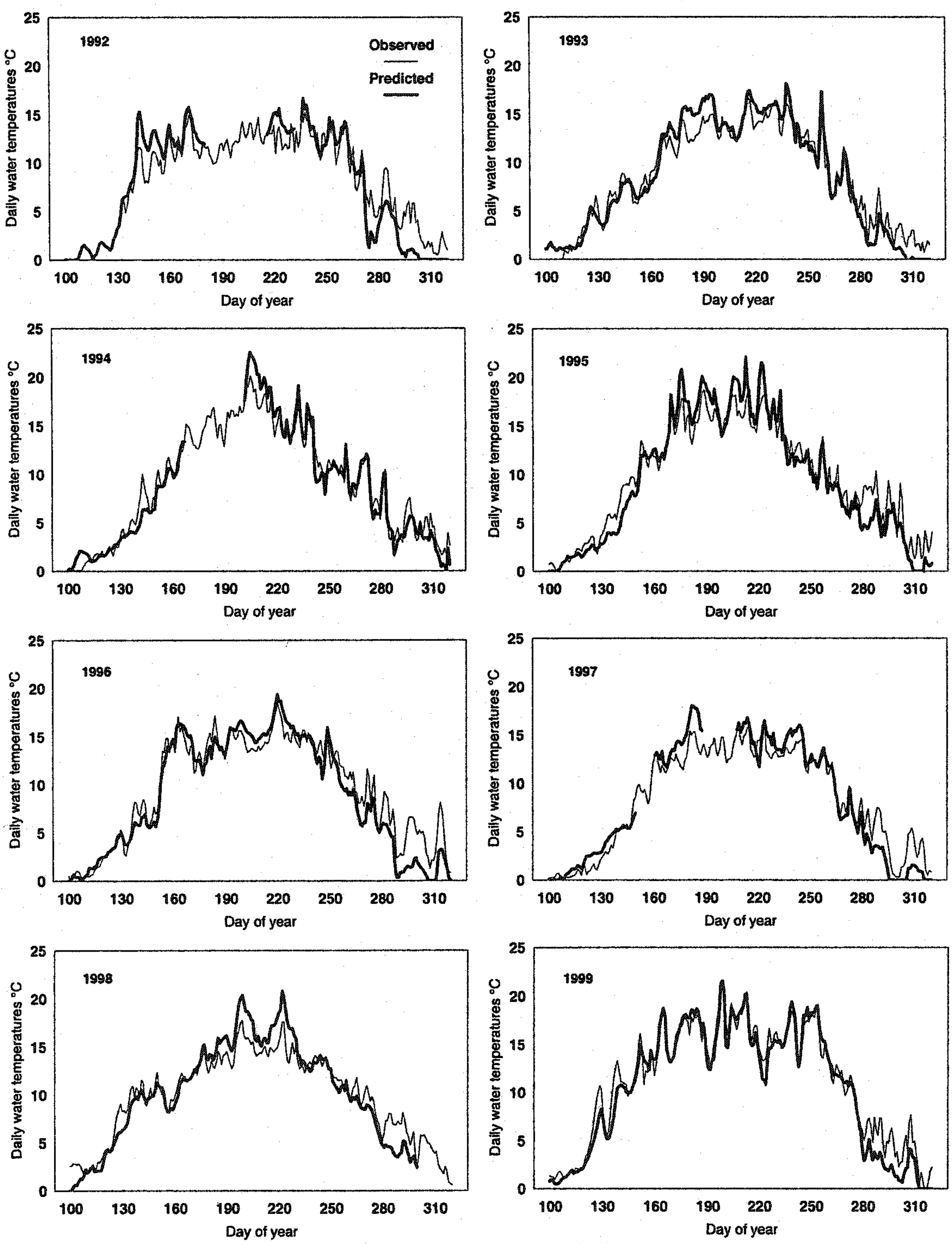

Figure 4.3a Mean daily water temperature modelling at Catamaran Brook (NB) using the deterministic model. (calibration period = 1992-94; validation period = 1995-99).

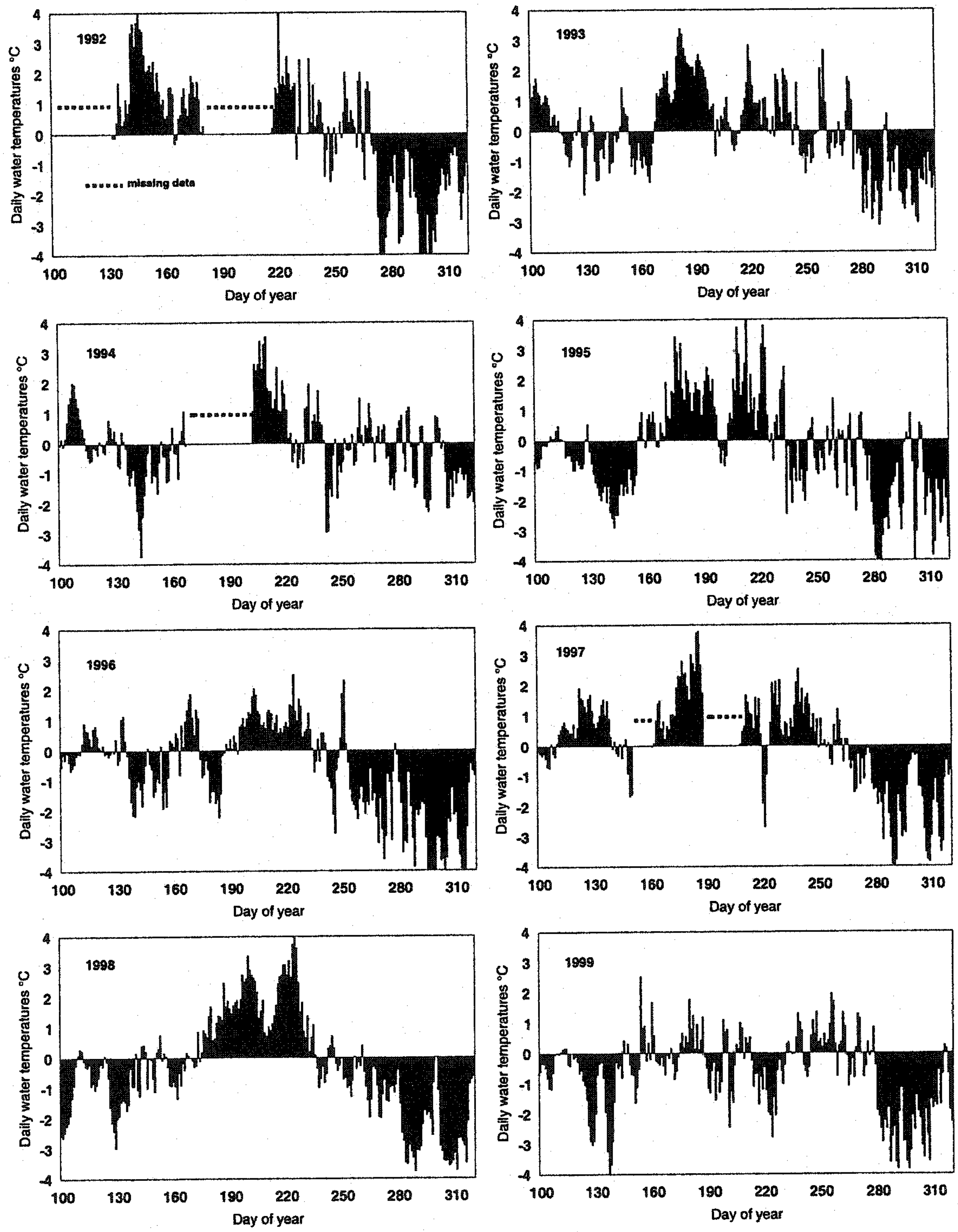

Figure 4.3b Mean daily water temperature residuals at Catamaran Brook (NB) using the deterministic model. (calibration period = 1992-94; validation period = 1995-99).

Table 4.7a Root-mean-square error (RMSE, °C) and Nash coefficient (NASH) calculated for the deterministic model using daily mean water temperatures (from 1992 to 1999) at Catamaran Brook and the Little Southwest Miramichi River, New Brunswick.

Year	Catamaran Brook		Little Southwest Miramichi R.	
	RMSE	NASH	RMSE	NASH
1992-94[a]	1.51 °C	0.915	1.49 °C	0.942
1995-99[b]	1.61	0.919	1.55	0.945
1992[c]	2.04	0.804	1.98	0.899
1993[c]	1.33	0.937	1.23	0.964
1994	1.22	0.952	1.30	0.951
1995[c]	1.63	0.920	1.76	0.931
1996[c]	1.70	0.906	1.85	0.909
1997	1.50	0.925	1.59	0.943
1998	1.77	0.863	1.22	0.960
1999	1.43	0.947	1.27	0.968
1992-99	1.58	0.918	1.53	0.944

[a] Calibration period.
[b] Validation period.
[c] Water temperature predicted using mean relative humidity data (RH = 71%).

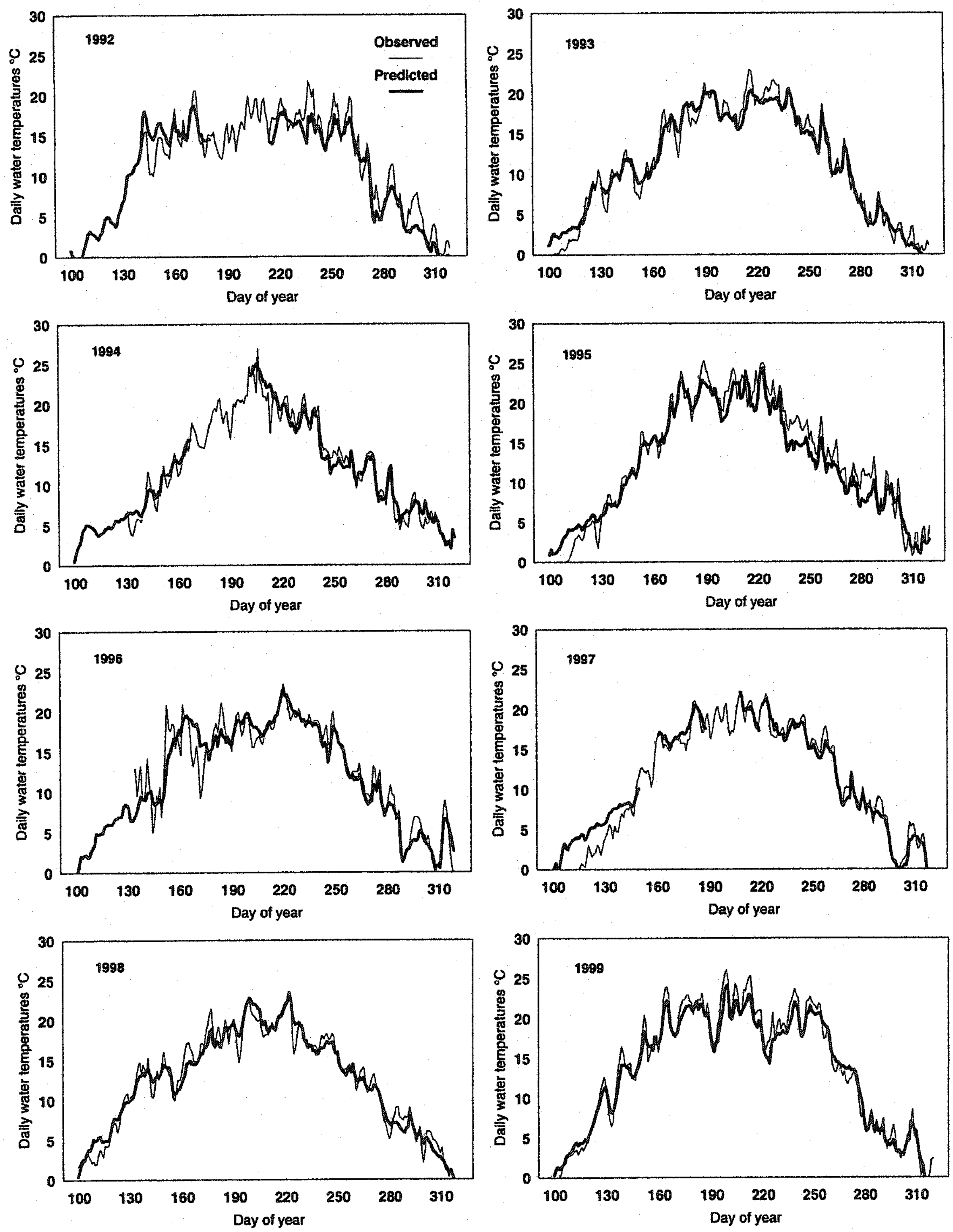

Figure 4.4a Mean daily water temperature modelling at the Little Southwest Miramichi River (NB) using the deterministic model. (calibration period = 1992-94; validation period = 1995-99).

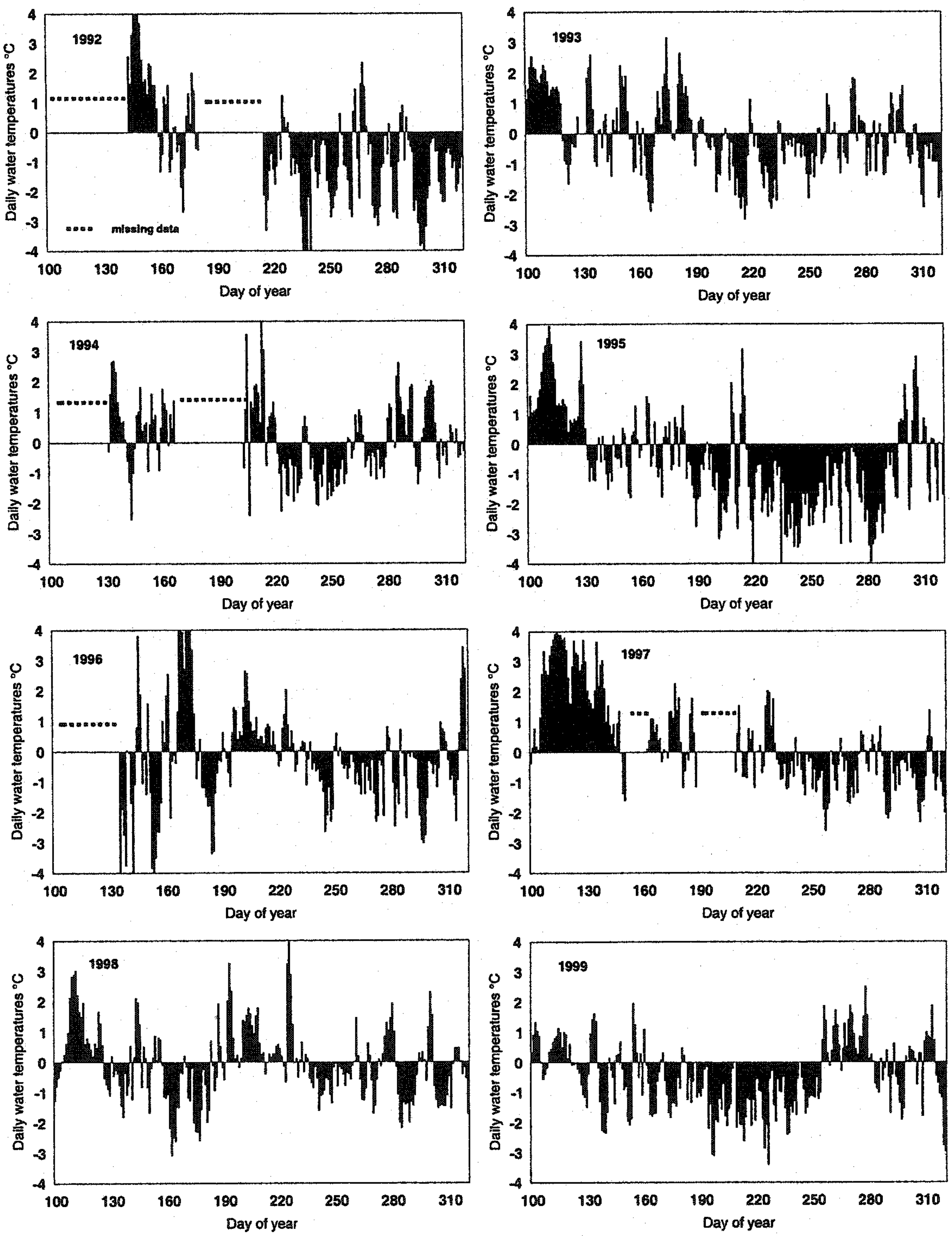

Figure 4.4b Mean daily water temperature residuals at the Little Southwest Miramichi River (NB) using the deterministic model. (calibration period = 1992-94; validation period = 1995-99).

the Miramichi Airport data than those from the Catamaran Brook station (i.e. with data closer to the study sites). The best overall RMSE was observed with the Miramichi Airport data for the Little Southwest Miramichi River in 1998 (RMSE = 1.12 °C).

Table 4.7b Root-mean-square error (RMSE, °C) calculated for the deterministic model using daily mean water temperatures (from 1992 to 1999). Results obtained at Catamaran Brook and the Little Southwest Miramichi River when using different relative humidity data (data from the Catamaran Brook meteorological station, mean value of relative humidity of 71% or data from the Miramichi Airport).

Year	Catamaran Brook			Little Southwest Miramichi R.		
	Cat. Bk[1]	Avg.[2]	Mira.[3]	Cat. Bk[1]	Avg.[2]	Mira.[3]
1992	2.04	2.04	n/a	1.98	1.98	n/a
1993	1.33	1.58	n/a	1.23	1.28	n/a
1994	1.22	1.36	1.18	1.30	1.41	1.34
1995	1.63	1.63	1.39	1.76	1.76	1.78
1996	1.70	1.70	1.64	1.85	1.85	1.90
1997	1.50	1.42	1.35	1.59	1.72	1.53
1998	1.77	1.79	1.59	1.22	1.25	1.12
1999	1.43	1.53	1.70	1.27	1.23	1.38

[1] Water temperature modelling with daily relative humidity data from the Catamaran Brook meteorological station in 1993 (after Sept. 23), 1994, and 1997-99. A mean value of relative humidity (71%) was used in 1992, 1993 (before Sept. 23), and 1995-96.

[2] Water temperature modelling using an average relative humidity value of 71% for all years.

[3] Water temperature modelling using the daily relative humidity data from the Miramichi Airport station.

4.3 Equilibrium temperature model

The equilibrium temperature model is based on the development of equation [3.19]. It was noted that the coefficients in this equation were to a large extent influenced by wind velocity, as most other parameters were constants (see equations [3.20] to [3.24]). Using data from the Catamaran Brook meteorological station, these coefficients were thus calculated as a function of wind velocity (Figure 4.5). It can be noted from this figure that as wind speed decreases, the solar radiation coefficient (B_1) increases and therefore T_e will be predominantly influenced by solar radiation (H_{si}) at low wind speed. The air and dew point temperature coefficients (B_2 and B_3) were of similar magnitude at low wind speed as well as being lower than the solar radiation coefficient (Figure 4.5). At higher wind speed, these coefficients level off with the dew point temperature coefficient dominating over air temperature. It was also noted that the mean summer dew point temperature was less than mean air temperature (e.g. T_a = 12.7 °C and T_d = 7.0 °C; mean summer values). This means that at higher wind speed, the relative contribution of these coefficients to the equilibrium temperature would be very similar. The last coefficient of equation [3.19], i.e. B_4, showed negative values throughout the range of studied wind velocities. This coefficient also showed increasing values with increasing wind velocities. Therefore, the coefficient (B_4) tends to decrease the equilibrium temperature at low wind speed. These results show that the equilibrium temperature is dominated by solar radiation only at very low wind speed. For more common meteorological conditions, the equilibrium temperature should be a function of both air and dew point temperatures.

To test the applicability of the water temperature model developed based on the equilibrium temperature, the first step was to test if there was a good relationship between dew point temperatures and air temperatures within the Miramichi River basin. This could result in a good relationship between the equilibrium temperature and air temperature. Meteorological data in the Miramichi River showed a relatively good agreement between dew point and air temperatures for air temperatures ranging between –5°C and +30°C

(Figure 4.6a). Therefore, the next step was to test the relationship between the equilibrium temperature and the air temperature. When applying equation [3.19] to the Miramichi River meteorological data, it was observed that the dew point and air temperature association resulted in a relatively good relationship between equilibrium temperatures and air temperatures (Figure 4.6b).

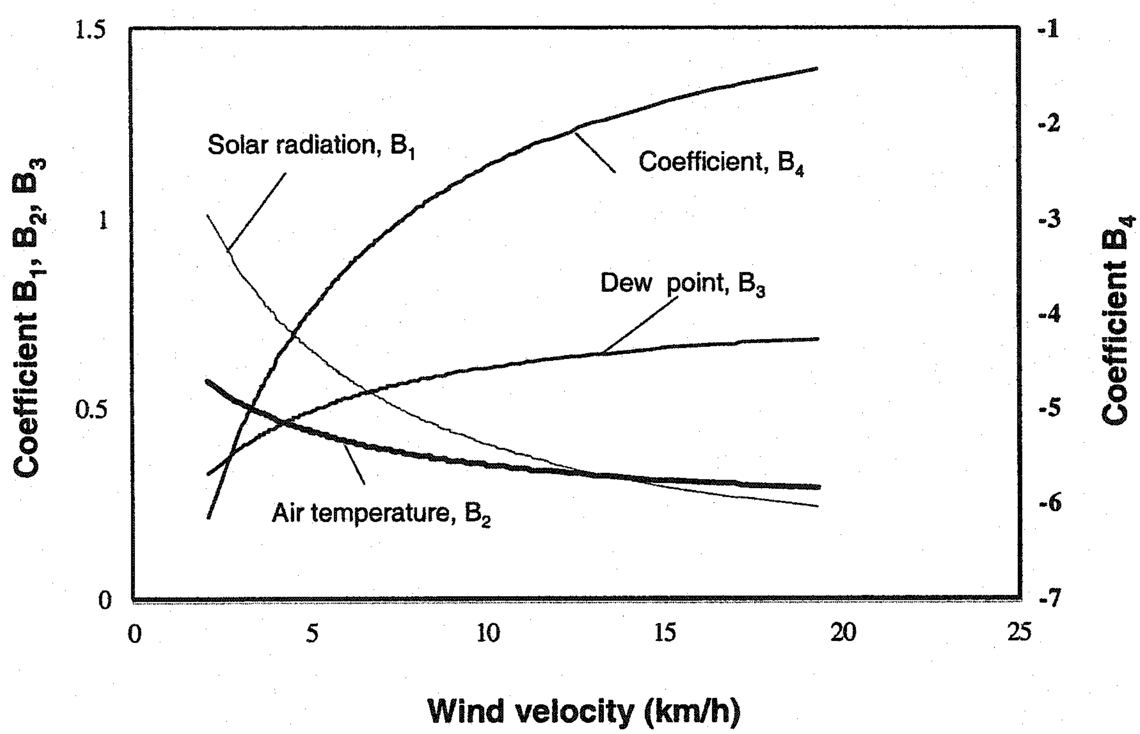

Figure 4.5 Relation between wind velocity and the different coefficients explaining the equilibrium temperature (equation [3.19]).

Given that the equilibrium temperature showed a good linear association with air temperature, the new water temperature model presented in equation [3.25] was tested on data from Catamaran Brook and the Little Southwest Miramichi River. Equation [3.27] was used to represent the equilibrium temperature for both the calibration and validation periods. To carry out the water temperature modelling for both river systems, equation [3.25] required the knowledge of the mean river depth or stream morphology. A power function was used to calculate mean water depth for both Catamaran Brook and the Little Southwest Miramichi River (equation [3.9]) similar to the deterministic model.

Water temperature data for the three calibration years (1992 to 1994) were used to determine the model parameters. The minimum sum of squared residuals was used during the calibration to estimate the model's parameters. For instance, both rivers showed a coefficient a_5 of zero in equation [3.27]. The coefficient b_5 was then calculated at 0.81 for Catamaran Brook and a slightly higher value of 1.05 was calculated for the Little Southwest Miramichi River. Using a constant thermal heat exchange coefficient K' (equation [3.26], which also includes physical properties of the water) for each river, it was possible to model river water temperatures for both Catamaran Brook and the Little Southwest Miramichi River. The thermal exchange coefficient K' for Catamaran Brook was calculated at 0.13, while that of the Little Southwest Miramichi River was estimated at 0.60 during the calibration period (1992-94).

Results of the modelling are presented for Catamaran Brook (Figure 4.7a) and for the Little Southwest Miramichi River (Figure 4.8a). Water temperature residual time series were presented in Figures 4.7b and 4.8b, while the RMSE and Nash coefficients were presented in Table 4.8.

In general, the model based on the equilibrium temperature concept performed very well with a good capture of the peak summer temperatures during both the calibration and validation periods (Figure 4.7a and 4.8a). Intra-annual performance of the model can also be observed. In general, the model showed a better agreement between predicted and observed water temperatures in late summer and autumn compared to predictions in spring. In fact, this particular model performed especially well in autumn during most years, with the exception of 1995 for a short period for the Little Southwest Miramichi River (Figure 4.8a). The model overestimated water temperatures in the Little Southwest Miramichi River in the early spring of 1993, 1995, and 1997. Missing data in the spring prevented a comparison

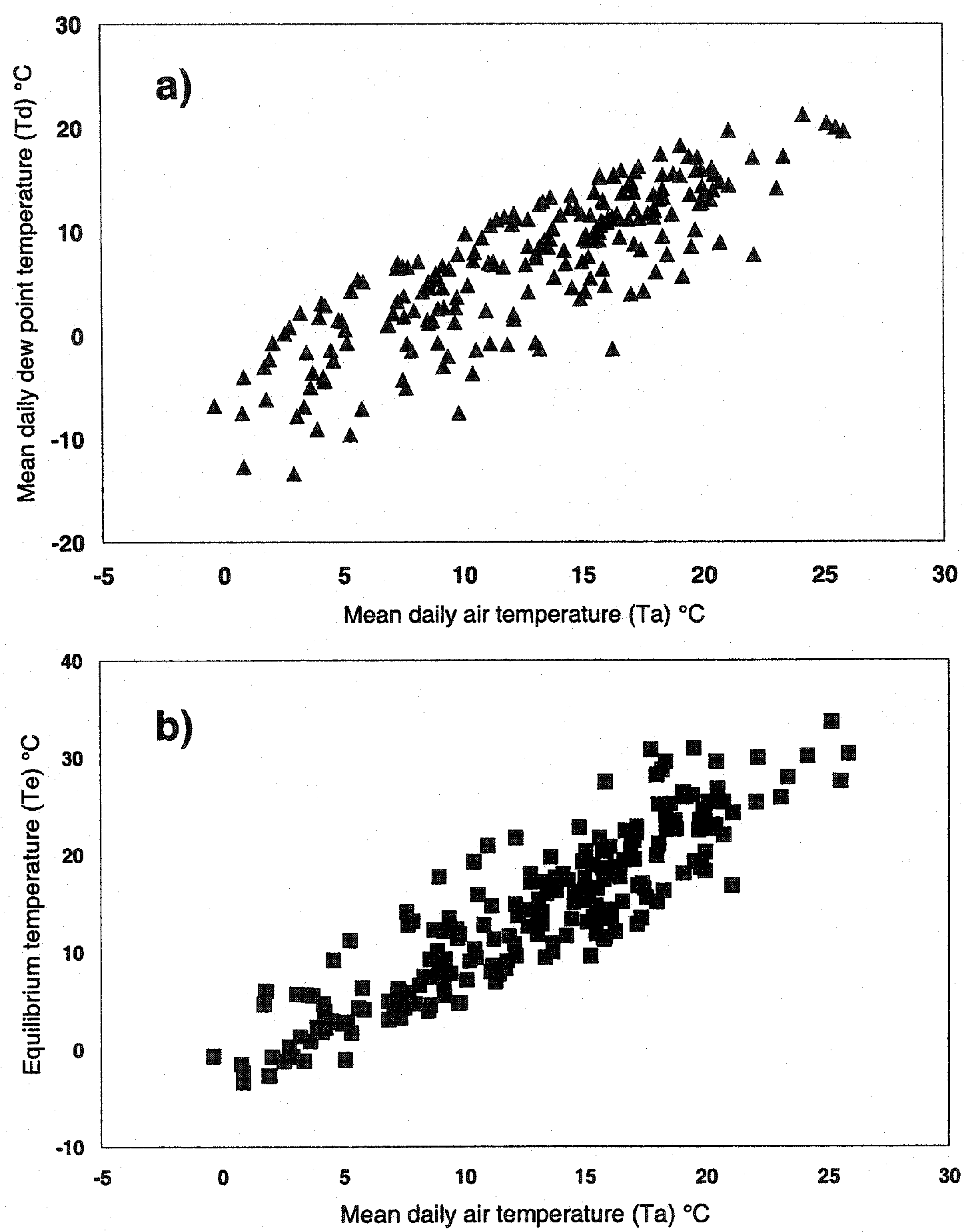

Figure 4.6 Relation between mean daily air temperature and a) mean daily dew point temperature and b) mean daily equilibrium temperature.

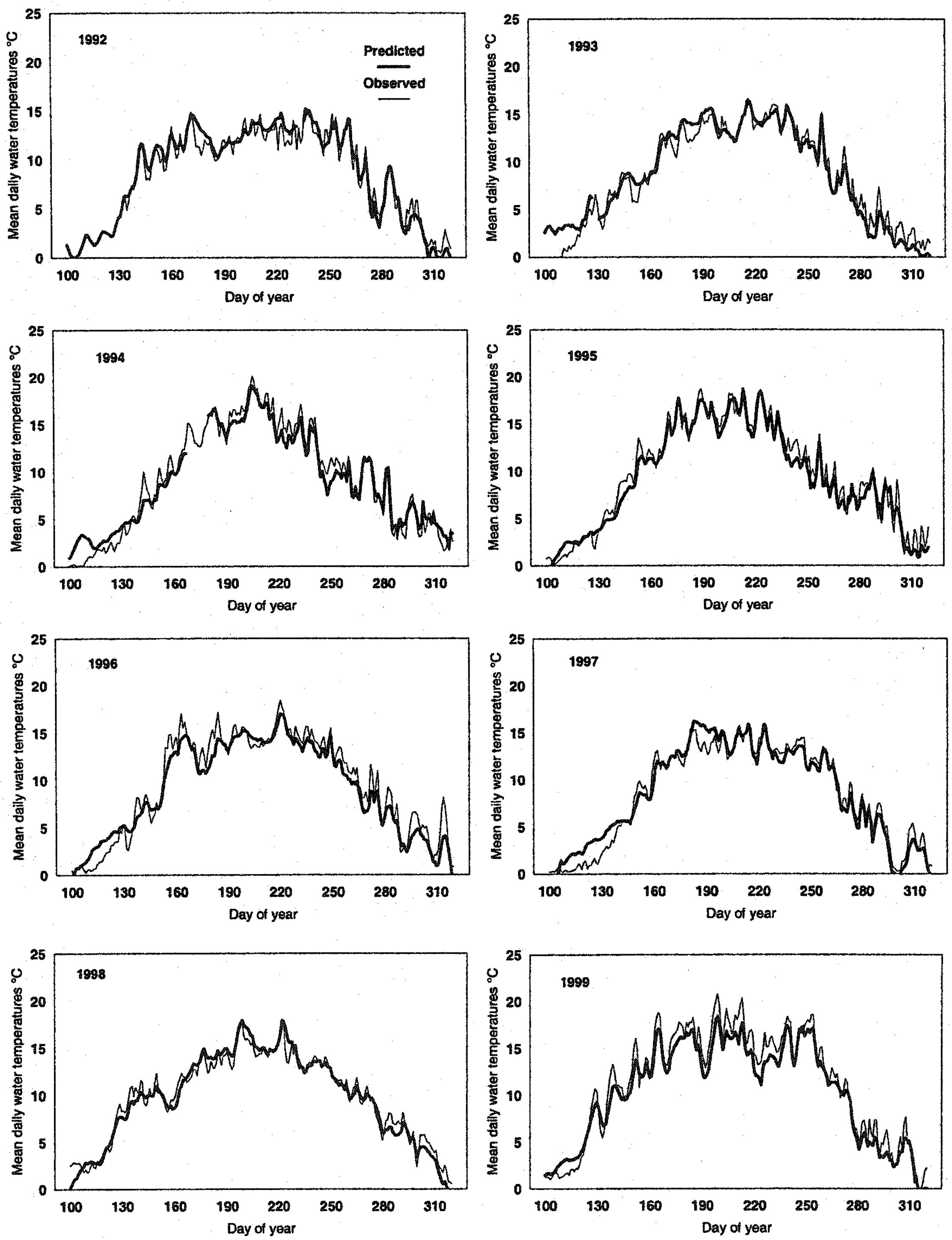

Figure 4.7a Mean daily water temperature modelling at Catamaran Brook (NB) using the equilibrium temperature model. (calibration period = 1992-94; validation period = 1995-99).

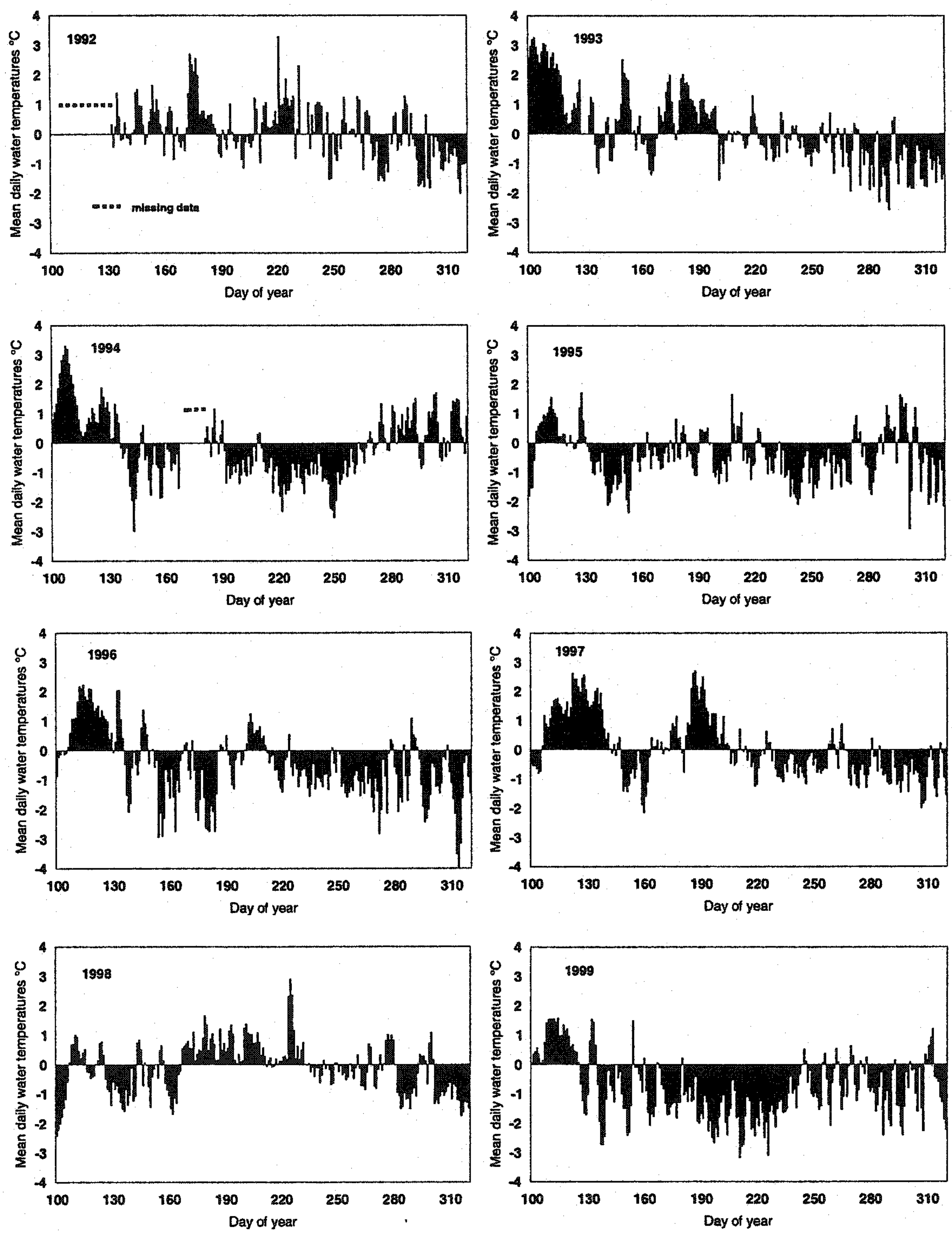

Figure 4.7b Mean daily water temperature residuals at Catamaran Brook (NB) using the equilibrium temperature model. (calibration period = 1992-94; validation period = 1995-99).

Table 4.8 Root-mean-square error (RMSE, °C) and Nash coefficient (NASH) calculated for the equilibrium temperature model using daily mean water temperatures (from 1992 to 1999) at Catamaran Brook and the Little Southwest Miramichi River, New Brunswick.

Year	Catamaran Brook		Little Southwest Miramichi R.	
	RMSE	NASH	RMSE	NASH
1992-94[1]	1.10 °C	0.951	1.45 °C	0.944
1995-99[2]	1.31	0.950	1.55	0.942
1992	0.95	0.958	1.66	0.921
1993	1.20	0.949	1.36	0.957
1994	1.13	0.950	1.35	0.947
1995	1.04	0.967	1.95	0.912
1996	1.33	0.937	1.58	0.930
1997	1.24	0.951	1.50	0.946
1998	1.29	0.945	1.27	0.957
1999	1.38	0.941	1.37	0.960
1992-99	1.26	0.950	1.52	0.943

[1] Calibration period
[2] Validation period

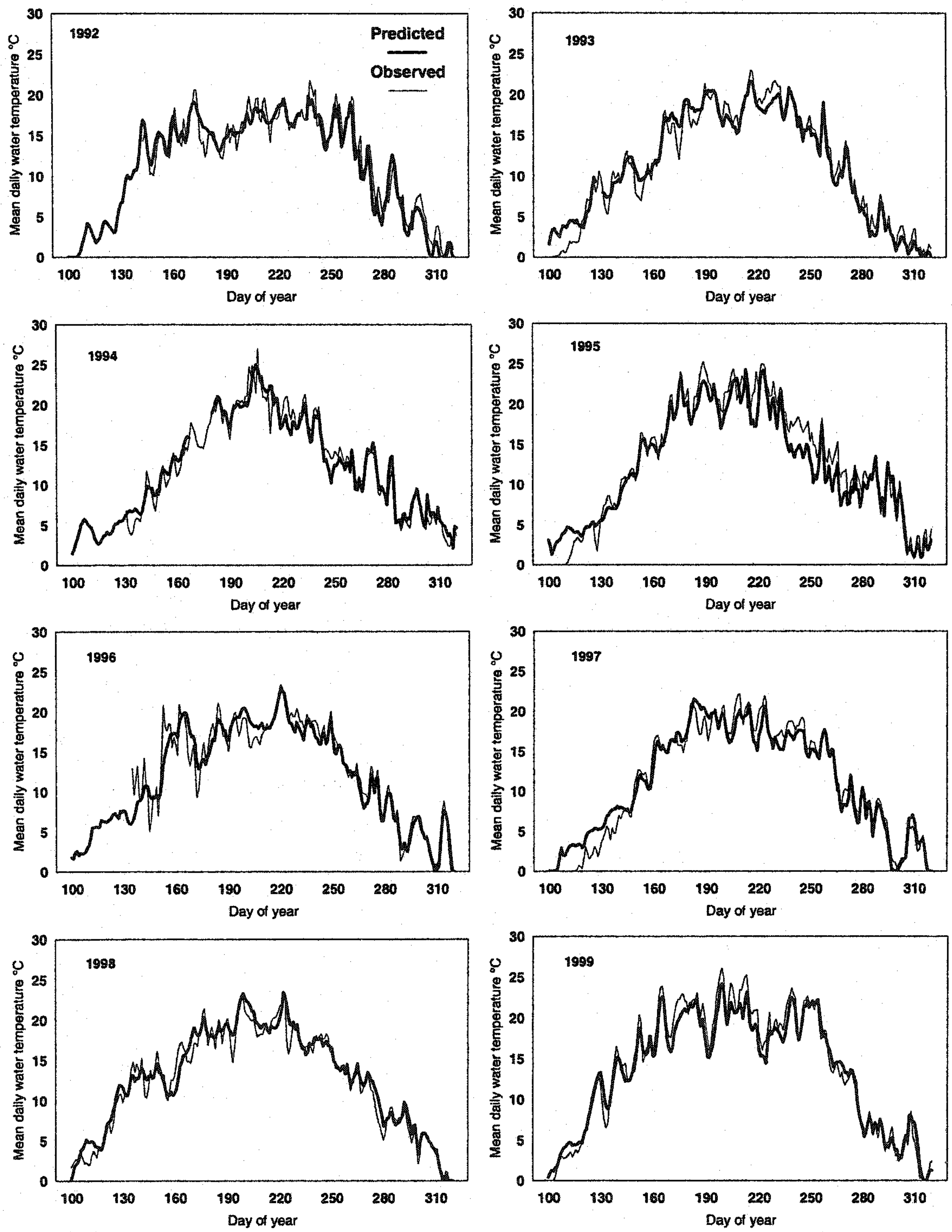

Figure 4.8a Mean daily water temperature modelling at the Little Southwest Miramichi River (NB) using the equilibrium temperature model. (calibration period = 1992-94; validation period = 1995-99).

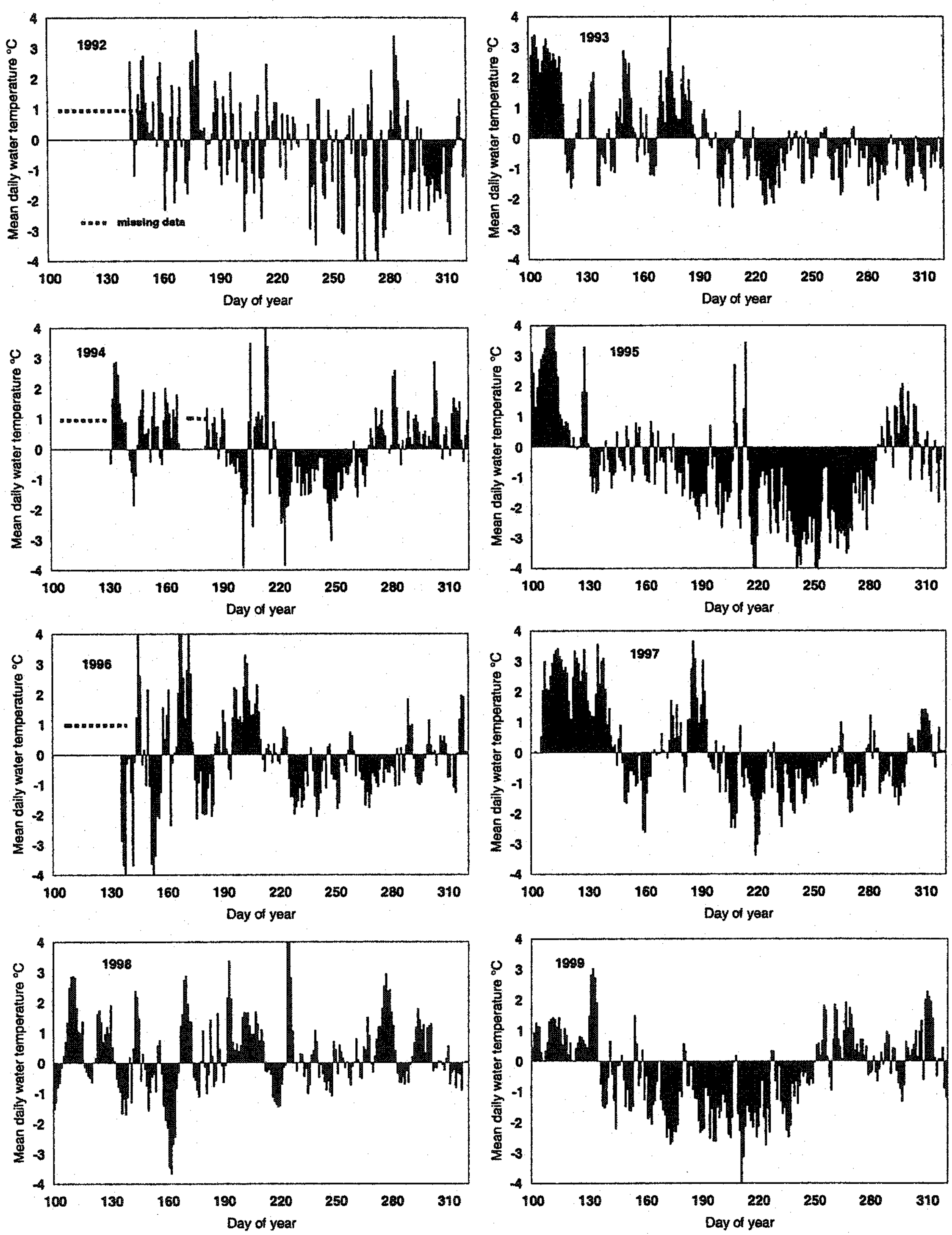

Figure 4.8b Mean daily water temperature residuals at the Little Southwest Miramichi River (NB) using the equilibrium temperature model. (calibration period = 1992-94; validation period = 1995-99).

for some years. Modelled water temperatures at Catamaran Brook showed a similar overestimation of early spring temperatures, i.e. 1993, 1994, and 1997. Peak summer temperatures were relatively well predicted during most years of the calibration and validation periods at both sites, except in 1999 where a slight underestimation was observed for both Catamaran Brook and the Little Southwest Miramichi River.

When looking at the model's performance in terms of RMSE, results showed that during the calibration period (1992-94), the RMSE was calculated at 1.10 °C for Catamaran Brook and at 1.45°C for the Little Southwest Miramichi River (Table 4.8). Nash coefficients (NASH) were 0.95 and 0.94 respectively (Table 4.8). During the validation period of the model (1995-99), the RMSE was slightly higher at 1.31°C for Catamaran Brook compared to a value of 1.55°C for the Little Southwest Miramichi River. Nash coefficients during the validation period were comparable to those of the calibration period (Table 4.8). In general, the equilibrium water temperature model performed slightly better on Catamaran Brook, the smaller stream, than on the Little Southwest Miramichi River, the larger river system. This was reflected by the overall RMSE for Catamaran Brook, which was calculated at 1.26°C (1992-99) compared to 1.52°C (1992-99) for the Little Southwest Miramichi River.

Inter-annual model performance showed that the RMSE ranged from 0.95°C (1992; NASH = 0.96) to 1.38°C (1999; NASH = 0.94) at Catamaran Brook (Table 4.8). This coincided with the coldest summer season of 1992 and the warmest season of 1999 (Figures 4.7a and 4.8a). Therefore, Catamaran Brook showed the extreme model performance during both of these years, although it should be pointed out that 1992 was during the calibration period and 1999 was during the validation period. Slightly higher RMSEs were observed for the Little Southwest Miramichi River, ranging from 1.27°C (1998; NASH = 0.96) to 1.95°C (1995; NASH = 0.91). For the Little Southwest Miramichi River, both the best and worst model performances occurred during the validation period (1998 and 1995; Table 4.8).

Water temperature residuals for the equilibrium temperature model are presented in Figures 4.7b and 4.8b. Water temperature residuals were relatively low in 1992 at Catamaran Brook, also reflective of the good modelling performance during that year (RMSE = 0.95 °C; Table 4.8). Overestimated water temperatures were noticeable in early spring of 1993, 1994, 1996 and 1997 in Catamaran Brook. Also, a few years showed consistent underestimation in summer such as 1996 as well as 1999. In the case of water temperature residuals at the Little Southwest Miramichi River, overestimated temperatures were also evident in spring (1993, 1995 and 1997; Figure 4.8b). Although the RMSE in 1992 at the Little Southwest Miramichi River was relatively high (1.66 °C), it was noted that the residual time series were somewhat random in nature that year, i.e. a mix of over/underestimation. The most severe underestimation in the Little Southwest Miramichi River was observed in 1995, which extended from day 190 (July 9) to 280 (Oct 7) and reaching over 4 °C. This was also reflective by the high RMSE of 1.95°C that year. The year 1999 also experienced a consistent summer underestimation of temperatures at the Little Southwest Miramichi River, but not as important as that observed in 1995.

4.4. Stochastic Model

The application of the stochastic model requires the determination of both the long-term annual component as well as the short-term component in water temperatures. Before calculating the annual component to explain the long-term variation in stream water temperatures, average water temperatures for each day of the year during the study period (1992-1999) were calculated. These averages of daily water temperatures were then fitted using a sine function to represent the long-term water temperature variations (Figure 4.1). The annual component was calculated using equation [3.29], by minimising the sum of squared residuals. The following equations were obtained for each river:

$$TA(t) = 3.1 + 12\ \sin\left((t - 119)\frac{2\pi}{365}\right) \qquad [4.1a]$$

for Catamaran Brook and:

$$TA(t) = 4.2 + 16\ \sin\left((t - 119)\frac{2\pi}{365}\right) \qquad [4.1b]$$

for the Little Southwest Miramichi River, where *TA(t)* represents the long-term stream water temperature at time *t* (day). The highest daily water temperature on the annual component curve was reached on July 30 (day 211) for both rivers, i.e. 15.1°C (Catamaran Brook) and 20.2 °C (Little Southwest Miramichi River; Figure 4.1). The total variation explained by the annual component in the long-term daily water temperature was calculated at 95% for Catamaran Brook and 98% for the Little Southwest Miramichi River.

A similar analysis was carried out for daily air temperatures and the following annual component was calculated:

$$TA(t) = 4.6 + 14\ \sin\left((t - 114)\frac{2\pi}{365}\right) \qquad [4.1c]$$

where parameters have been described previously. The mean daily air temperature reached its maximum on July 25 at 26.6 °C, 5 days earlier than the water temperature annual component of the two river systems. The highest daily air temperature on the annual component was at 18.6 °C.

When the annual component was removed from both air and water temperatures, the resulting short-term component (i.e. departure from annual component) was analysed to link air and water temperatures. The stochastic model was calibrated during the period of 1992 to 1994 for the short-term component while the validation period was from 1995 to 1999, similar to previous models. A calibrated second order Markov process with lag 1 and lag 2 autocorrelation coefficients was used to carry out the water temperature modelling (Cluis, 1972; Caissie et al. 1998). The lag 1 and lag 2 autocorrelation coefficients were calculated at 0.855 and 0.672 respectively for Catamaran Brook. Similarly, the lag 1 and lag 2 autocorrelation coefficients were calculated at 0.855 and 0.656 respectively for the Little Southwest Miramichi River. These autocorrelation coefficients were thereafter used to calculate coefficients A_1' and A_2' of equation [3.30]. A_1' and A_2' for Catamaran Brook were calculated at 1.043 and –0.219 respectively while values of 1.092 and –0.278 were obtained for the Little Southwest Miramichi River. The coefficient K_s, which links air to water temperatures, was obtained by optimisation, using the minimum of the mean sum of squared residuals for the calibration period (1992-94). This coefficient was calculated at 0.130 for Catamaran Brook and at 0.190 for the Little Southwest Miramichi River.

Given the above coefficients, the daily water temperature short-term component (i.e. departure from annual component) at times (t) was calculated using:

$$Rw(t) = 1.043 \ Rw(t-1) - 0.219 \ Rw(t-2) + 0.130 \ Ra(t) \qquad [4.2a]$$

for Catamaran Brook and:

$$Rw(t) = 1.092 \ Rw(t-1) - 0.278 \ Rw(t-2) + 0.190 \ Ra(t) \qquad [4.2b]$$

for the Little Southwest Miramichi River. $Rw(t)$ represents the predicted stream water temperature residual at time t, $Rw(t\text{-}1)$ at time t-1 and $Rw(t\text{-}2)$ at time t-2. The mean daily stream water temperature time series can therefore be reconstructed (prediction of water temperatures) using equation [3.28], knowing *Rw(t)* and by adding the annual component *TA(t)*, i.e. equation [4.1a] and [4.1b].

Using the above stochastic model and daily air temperature short-term component, *Ra(t)*, including equations [4.1], [4.2] and [3.28], the daily stream water temperature time series was predicted for Catamaran Brook and the Little Southwest Miramichi River from 1992 to 1994 (the calibration period). Once that the calibration was done, water temperature predictions were carried out for the validation period, i.e. 1995-99.

Results showed good agreement between predicted and observed water temperatures for both Catamaran Brook and the Little Southwest Miramichi River (Figure 4.9a and 4.10a). Residual time series of the stochastic modelling (difference between predicted vs. observed water temperatures) are presented in Figures 4.9b and 4.10b. The modelling performance as expressed in terms of RMSE and Nash coefficients is presented in Table 4.9. Stochastic modelling results were especially good during the calibration period for both rivers and throughout the summer. Peak summer temperatures were well predicted during the calibration period at both Catamaran Brook and the Little Southwest Miramichi River, especially in 1993 (Figure 4.9a and 4.10a). Similar to other models, a slight overestimation was observed in the spring, especially in 1996 and 1997 at Catamaran Brook as well as in 1997 for the Little Southwest Miramichi River. Peak summer water temperature was better captured during some years (e.g. 1993, 1997, 1998) than others (e.g. 1999). Moreover, peak summer temperatures were better predicted in 1999 for the Little Southwest Miramichi River than for Catamaran Brook.

The stochastic model performed well during the calibration period with a RMSE of only 1.15 °C at Catamaran Brook and a RMSE of 1.35 °C for the Little Southwest Miramichi River (1992-94; Table 4.9). The Nash coefficient was calculated at 0.94 at Catamaran Brook compared to 0.95 for the Little Southwest Miramichi River during the calibration period. During the validation period, RMSEs were slightly higher at 1.31 °C

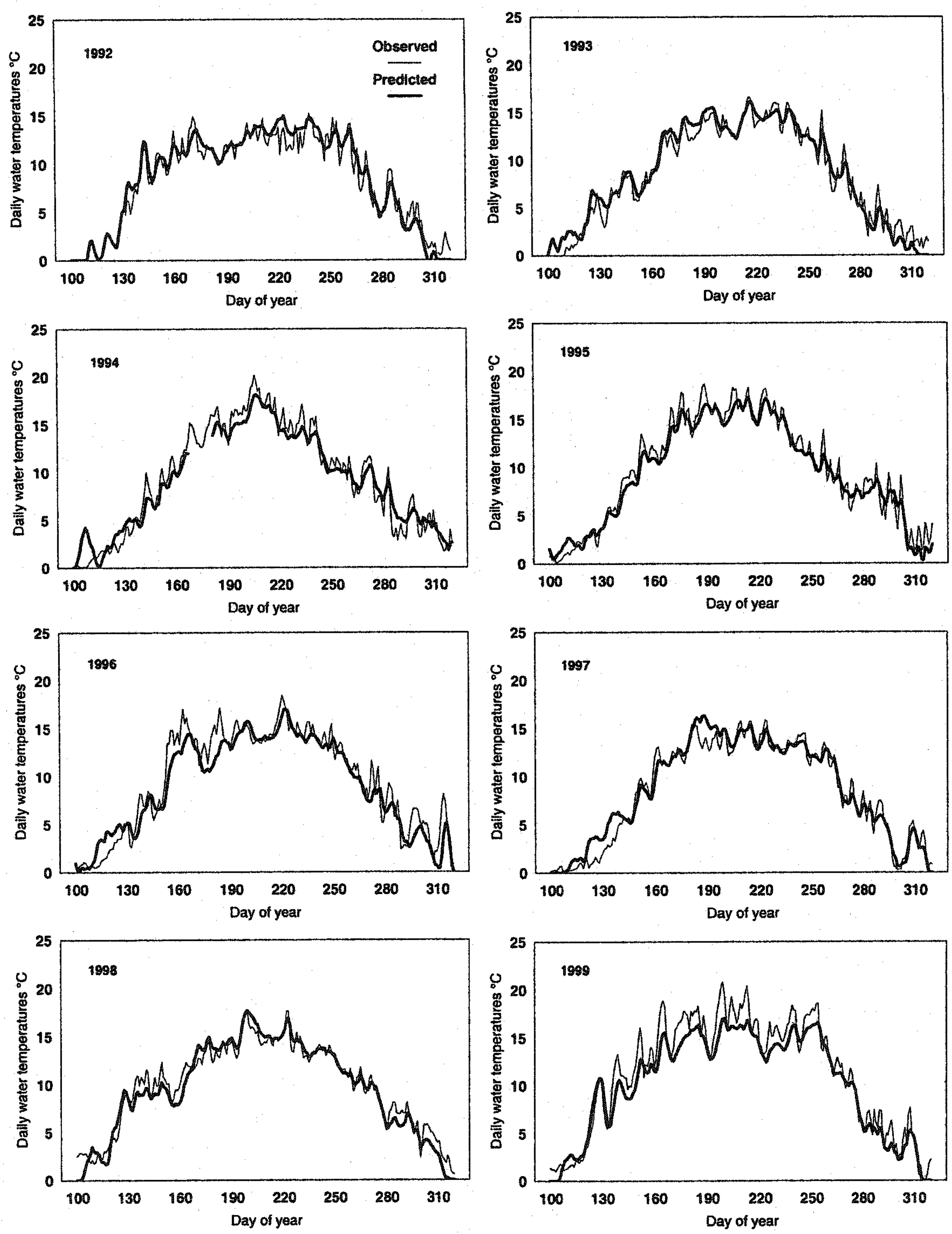

Figure 4.9a Mean daily water temperature modelling at Catamaran Brook (NB) using the stochastic model. (calibration period = 1992-94; validation period = 1995-99).

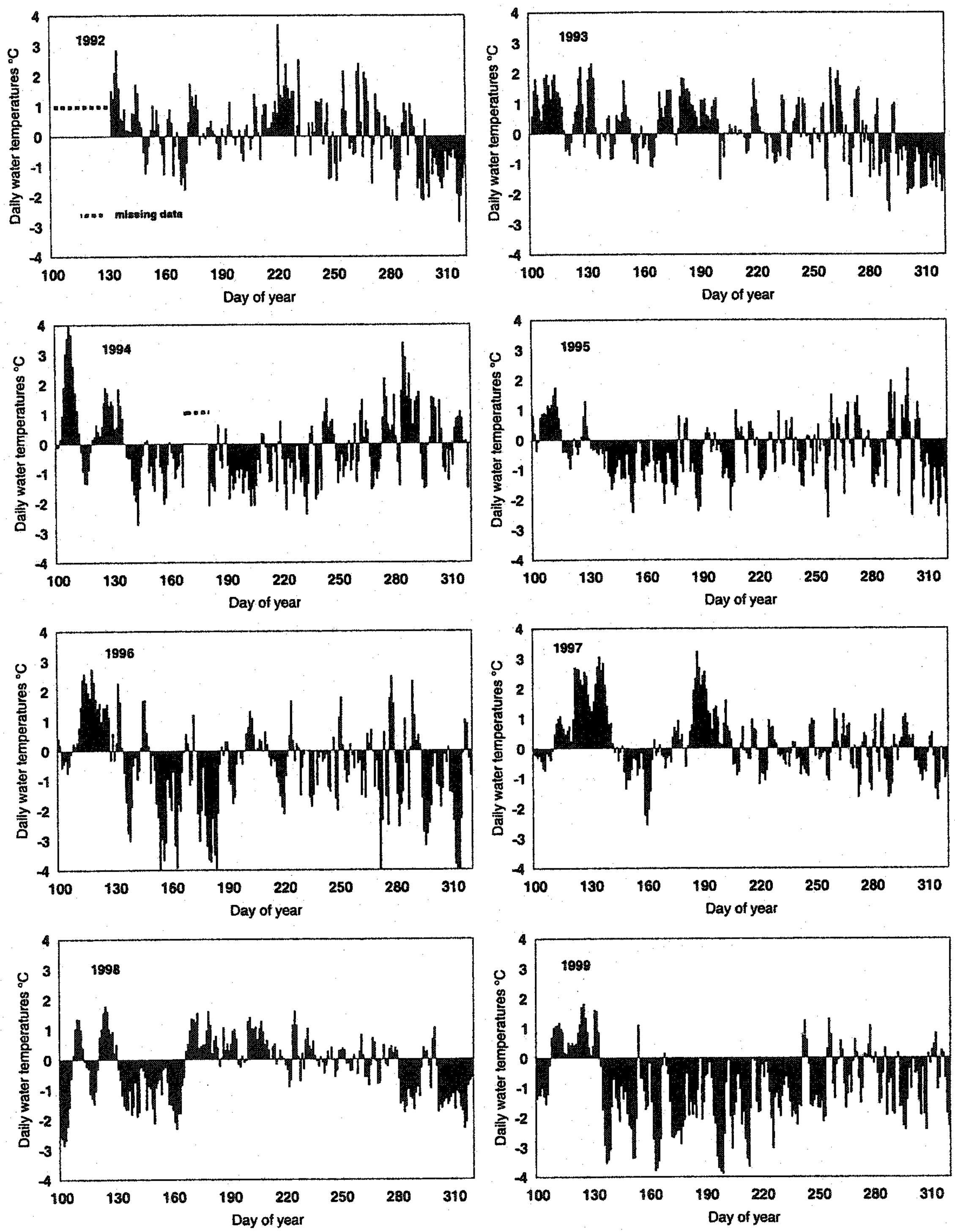

Figure 4.9b. Mean daily water temperature residuals at Catamaran Brook (NB) using the stochastic model. (calibration period = 1992-94; validation period = 1995-99).

Table 4.9 Root-mean-square error (RMSE, °C) and Nash coefficient (NASH) calculated for the stochastic water temperature model using daily mean water temperatures (from 1992 to 1999) at Catamaran Brook and the Little Southwest Miramichi River, New Brunswick.

Year	Catamaran Brook		Little Southwest Miramichi R.	
	RMSE	NASH	RMSE	NASH
1992-94[1]	1.15 °C	0.944	1.35 °C	0.954
1995-99[2]	1.31	0.933	1.74	0.937
1992	1.11	0.936	1.40	0.940
1993	1.06	0.958	1.27	0.966
1994	1.26	0.934	1.39	0.949
1995	1.06	0.957	1.53	0.958
1996	1.61	0.893	2.45	0.835
1997	1.08	0.955	1.51	0.952
1998	1.04	0.953	1.57	0.936
1999	1.63	0.905	1.56	0.958
1992-99	1.26	0.937	1.61	0.942

[1] Calibration period
[2] Validation period

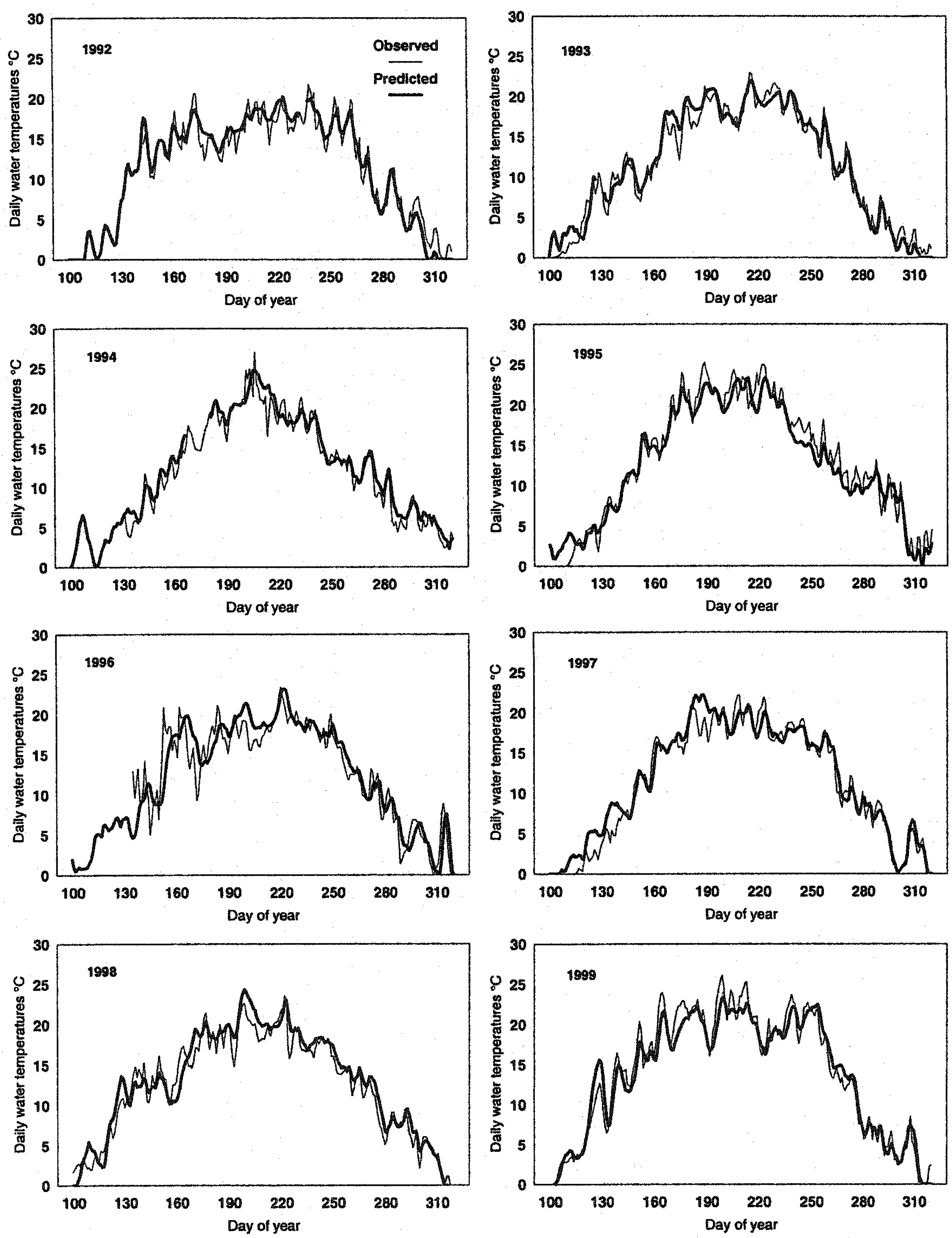

Figure 4.10a Mean daily water temperature modelling at the Little Southwest Miramichi River (NB) using the stochastic model. (calibration period = 1992-94; validation period = 1995-99).

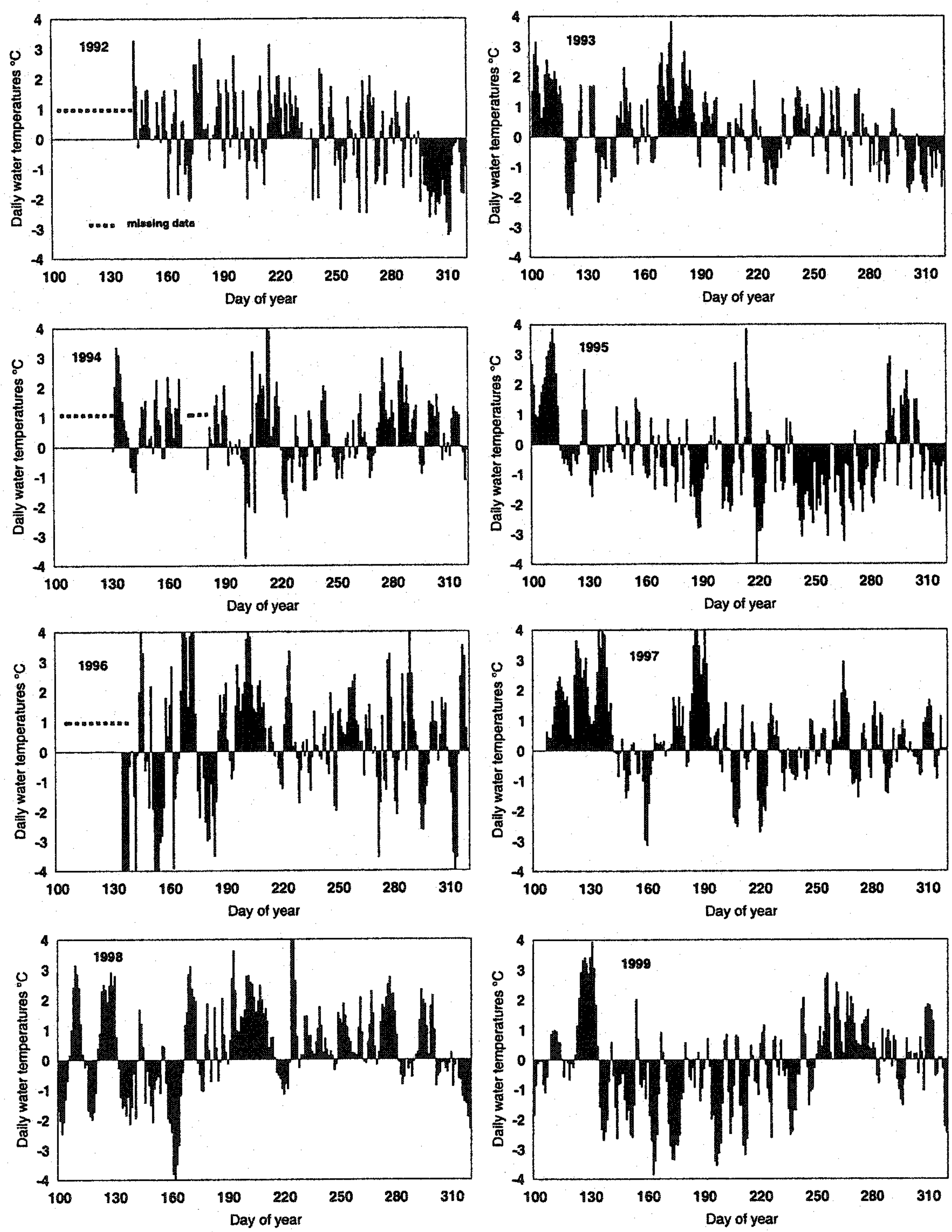

Figure 4.10b Mean daily water temperature residuals at the Little Southwest Miramichi River (NB) using the stochastic model. (calibration period = 1992-94; validation period = 1995-99).

for Catamaran Brook and 1.74 °C for the Little Southwest Miramichi River (1995-99; Table 4.9). Nash coefficients were lower for both rivers (Catamaran Brook, NASH = 0.93; and the Little Southwest Miramichi River, NASH = 0.94). Overall, the stochastic model performed better for Catamaran Brook (RMSE = 1.26 °C; 1992-99) than for the Little Southwest Miramichi River (RMSE = 1.61 °C; 1992-99).

Inter-annual modelling performance showed RMSEs that ranged between 1.06 °C (1993 and 1995; NASH = 0.96) and 1.61 °C (1996; NASH = 0.89) at Catamaran Brook (Table 4.9). Years of good modelling performances at Catamaran Brook included 1993, 1995, 1997 and 1998 with RMSEs less than 1.08 °C and NASHs higher than 0.95. Poorer performances were observed in 1996 and 1999. In the Little Southwest Miramichi River, RMSEs ranged between 1.27 °C (1993; NASH = 0.97) and 2.45 °C (1996; NASH = 0.84). Years with better performances included 1992, 1993 and 1994, which were all during the calibration period. Poorer performances were observed in general during the calibration period (1995-99) with RMSEs higher than 1.50 °C.

The residual time series at both Catamaran Brook and the Little Southwest Miramichi River showed more random errors than the previous models in general (Figure 4.9b and 4.10b). A few periods of consistent over/underestimation were observed for both rivers, similar to previous models. For instance, Catamaran Brook showed consistent negative residuals in later autumn 1992, during the spring of 1998 and in summer of 1999 (Figure 4.9b). Consistent positive residuals (overestimation) were observed in Catamaran Brook in spring of 1996-97 and during a short period in spring of 1994 and summer of 1997. The residual time series at Catamaran Brook consisted of low values, which was also reflective of the model's good performance. Similarly, the residual time series at the Little Southwest Miramichi River showed underestimated temperatures (negative residuals) in autumn of 1992, late summer 1995, spring 1996 and throughout the summer of 1999 (Figure 4.10b). A slight overestimation was observed in the Little Southwest Miramichi River in spring and summer of 1993, spring 1995, 1997 and 199 as well as throughout the summer of 1998.

4.5 Energy Reference Model

The energy reference model makes use of the deterministic model with the long-term energy component, which is a function of the long-term meteorological conditions (i.e. air and water temperatures, solar radiation, wind speed, relative humidity, etc.). The long-term energy component becomes the reference energy (H_{ref}), which is the basis of this new model. To calculate the long-term energy component or reference energy, the annual components of variables, which exhibit annual cycles (air temperature, water temperature and solar radiation) were used. For instance, the annual component for both air and water temperatures was calculated for the stochastic water temperature model (equations [4.1a], [4.1b] and [4.1c]). The annual component for solar radiation can also be expressed using a sine function similar to air and water temperatures. The annual component for solar radiation at the Catamaran Brook meteorological station was calculated and is given by the following equation:

$$SA(t) = 10.87 + 7.63 \ \sin\left((t-89)\frac{2\pi}{365}\right) \qquad [4.3]$$

where *SA(t)* represents the annual component in solar radiation (MJ/m^2) at different times (t) of year. The annual component for solar radiation is shown in Figure 4.11, with corresponding mean daily values for solar radiation (1992-99) used in the development of equation [4.3]. In the case of other variables, which did not exhibit an annual cycle (i.e. wind speed and relative humidity), their respective long-term mean values were used to represent long-term conditions in the energy reference model. For instance, the long-term energy component was calculated using a mean value of 71% for the relative humidity and a long-term wind speed of 3.89 km/h. Once the long-term conditions were established for each variable of the model, the long-term energy component or reference energy was calculated. Each component was then adjusted relative to each other, similarly to the calibration of the deterministic model to best fit predicted and observed water temperatures. Factors in the calibration of energy components varied between 1.2 and 1.9 for the evaporative heat flux while they varied between 4.4 and 6.5 for the convective heat transfer. These higher values for the convective heat transfer presumably reflected the fact that this component needs to play a more dominant role in the overall water temperature variability with the energy reference model. The energy reference model, i.e. equation [3.31] was thereafter applied to calculate daily water temperatures for both Catamaran Brook and the Little Southwest Miramichi River.

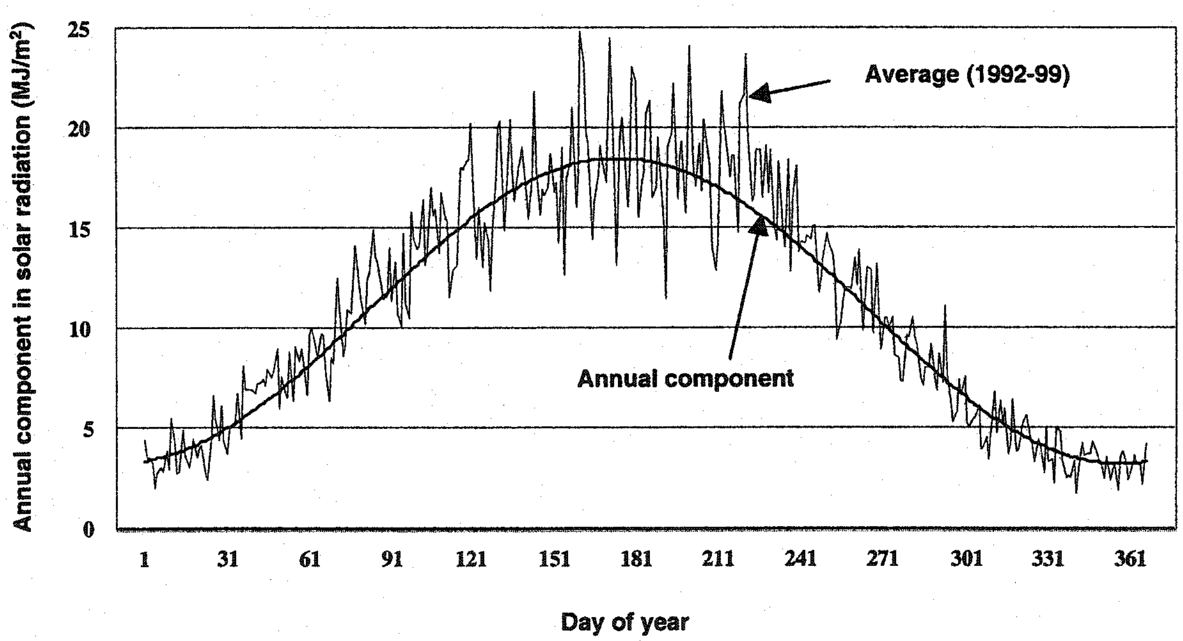

Figure 4.11 Long-term annual component for solar radiation to calculate the long-term energy component.

Results showed relatively good agreement between predicted and observed water temperatures for both Catamaran Brook and the Little Southwest Miramichi River using the energy reference model (Figure 4.12a and 4.13a). The residual time series of this particular modelling are presented in Figure 4.12b and 4.13b. The calculated RMSEs and

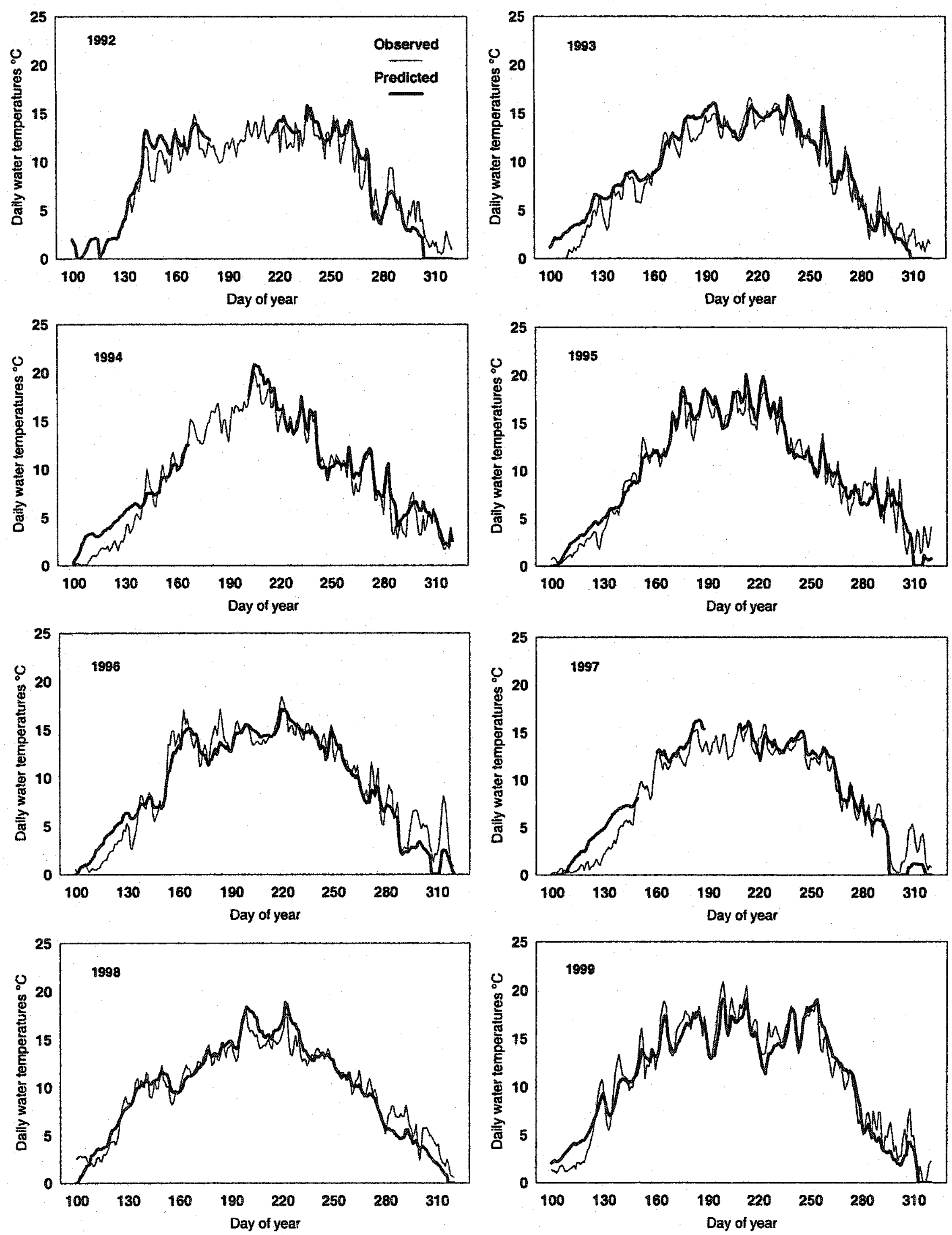

Figure 4.12a Mean daily water temperature modelling at Catamaran Brook (NB) using the energy reference model. (calibration period = 1992-94; validation period = 1995-99).

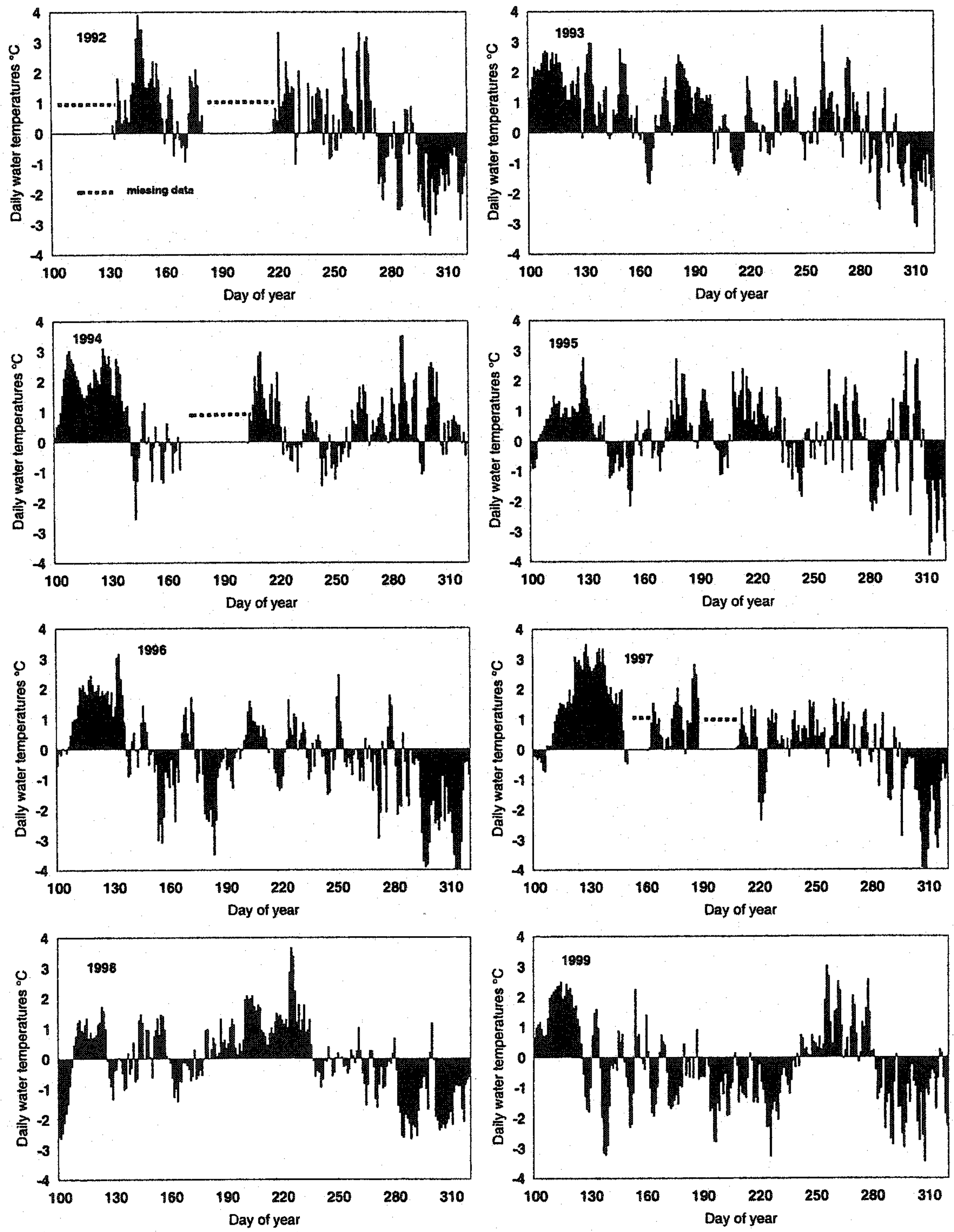

Figure 4.12b Mean daily water temperature residuals at Catamaran Brook (NB) using the energy reference model. (calibration period = 1992-94; validation period = 1995-99).

Table 4.10 Root-mean-square error (RMSE, °C) and Nash coefficient (NASH) calculated for the energy reference water temperature model using daily mean water temperatures (from 1992 to 1999) at Catamaran Brook and the Little Southwest Miramichi River, New Brunswick.

Year	Catamaran Brook		Little Southwest Miramichi R.	
	RMSE	NASH	RMSE	NASH
1992-94[1]	1.41 °C	0.925	1.58 °C	0.945
1995-99[2]	1.39	0.939	1.58	0.951
1992	1.55	0.877	1.63	0.943
1993	1.34	0.937	1.42	0.960
1994	1.37	0.940	1.75	0.921
1995	1.22	0.955	1.37	0.964
1996	1.56	0.921	1.97	0.911
1997	1.47	0.928	1.83	0.935
1998	1.28	0.928	1.53	0.948
1999	1.42	0.947	1.13	0.978
1992-99	1.40	0.935	1.58	0.949

[1] Calibration period
[2] Validation period

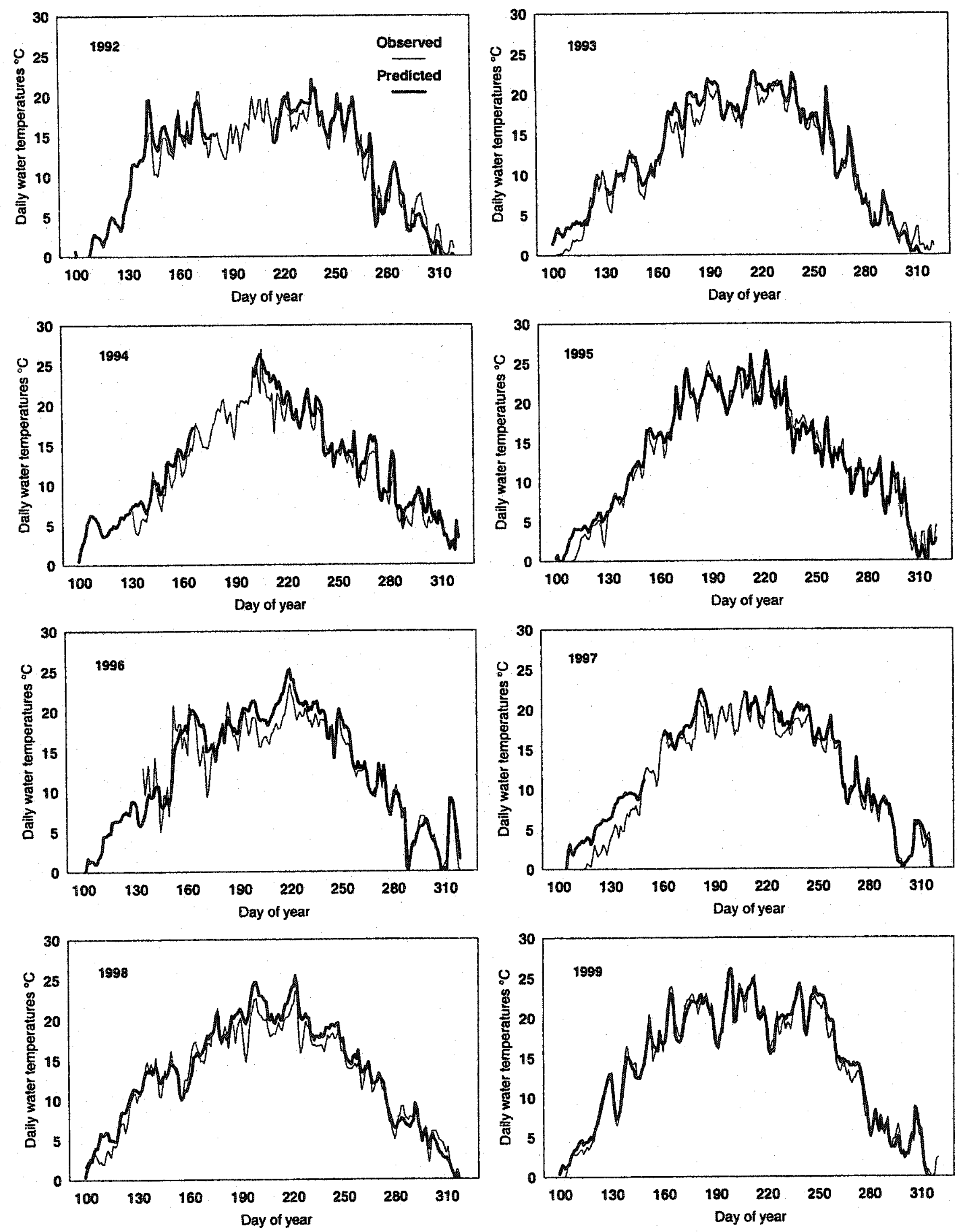

Figure 4.13a Mean daily water temperature modelling at the Little Southwest Miramichi River (NB) using the reference energy model. (calibration period = 1992-94; validation period = 1995-99).

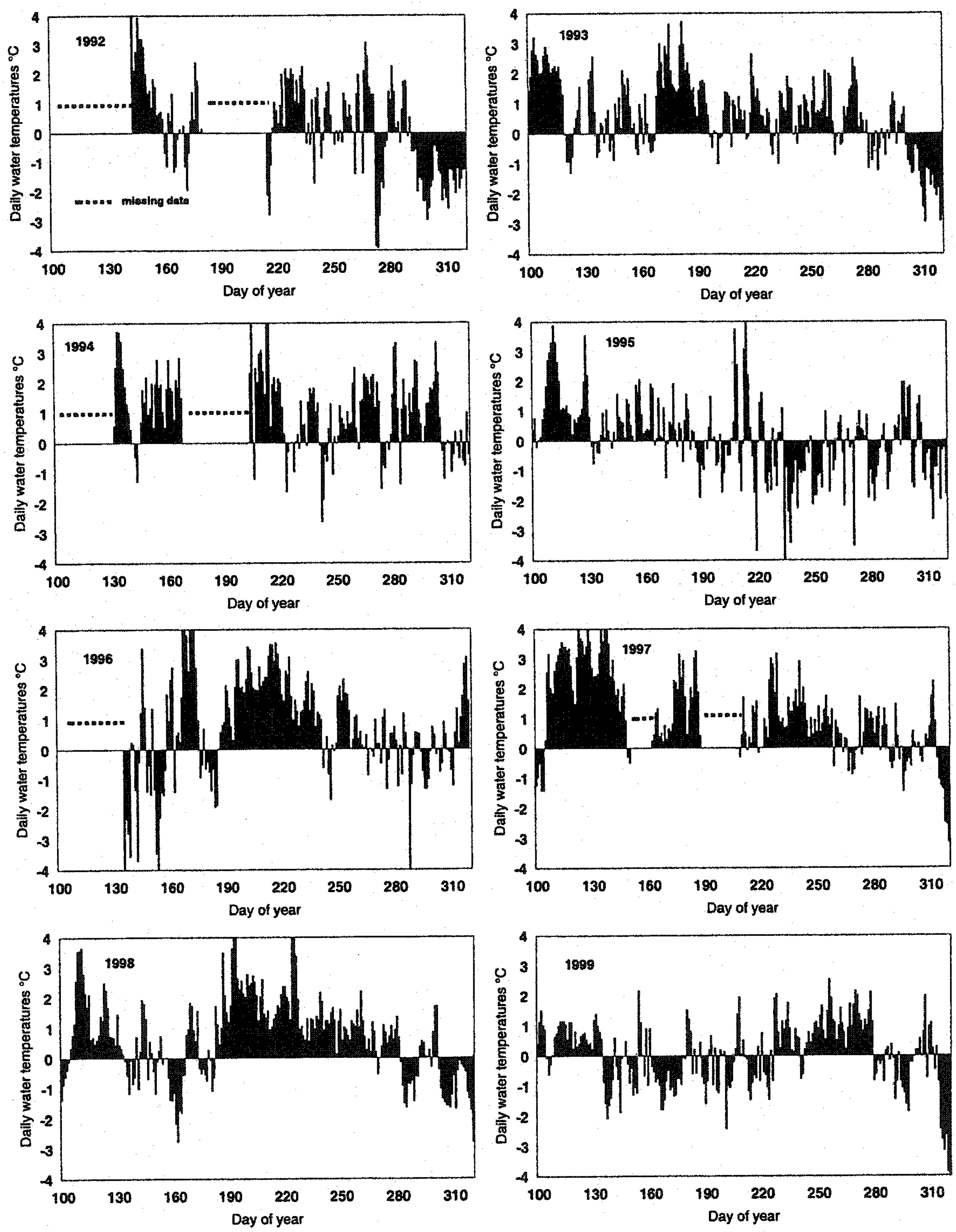

Figure 4.13b Mean daily water temperature residuals at the Little Southwest Miramichi River (NB) using the energy reference model. (calibration period = 1992-94; validation period = 1995-99).

Nash coefficients are presented in Table 4.10. The energy reference water temperature model showed relatively good performances during both the calibration and validation periods for both rivers. Although water temperatures were relatively well predicted for both Catamaran Brook and the Little Southwest Miramichi River, this model did not follow the water temperature variability as well during certain periods (e.g. spring and early summer of 1993, 1996 for Catamaran Brook; Figure 4.12a). The water temperature variability was better predicted for the Little Southwest Miramichi River, especially later in the season (e.g. 1993, 1995, and 1999 after day 220; Figure 4.13a). Similarly to other models, an overestimation was observed in the spring for both rivers. With the energy reference model, the spring overestimation was more pronounced in Catamaran Brook in 1994, 1996 and 1997, and in the Little Southwest Miramichi River in 1997. Peak summer water temperatures were better captured in Little Southwest Miramichi River (e.g. 1993, 1995 and 1999) than in Catamaran Brook (Figure 4.12a and 4.13a).

The performance of the energy reference model during the calibration period was slightly better at Catamaran Brook (RMSE = 1.41 °C) than for the Little Southwest Miramichi River (RMSE = 1.58 °C, 1992-94; Table 4.10). The Nash coefficient was calculated at 0.93 during the calibration period at Catamaran Brook compared to 0.95 for the Little Southwest Miramichi River. During the validation period, the energy reference model also performed better at Catamaran Brook (RMSE = 1.39 °C and NASH 0.94) than at the Little Southwest Miramichi River (RMSE = 1.58 °C and NASH = 0.95, 1995-99; Table 4.10). Although the modelling at the Little Southwest Miramichi River seemed to have better captured the water temperature variability and peak summer temperatures, the overall RMSE was lower at Catamaran Brook (1992-99, RMSE = 1.40 °C) than at the Little Southwest Miramichi River (RMSE = 1.58 °C, 1992-99).

The residual time series at both Catamaran Brook and the Little Southwest Miramichi River showed consistent over/underestimation during specific time periods (Figure 4.12b and 4.13b). For instance, spring overestimated temperatures were observed in Catamaran Brook during most years except for 1998 which was not as pronounced. Similar results were observed in the Little Southwest Miramichi River in 1993, 1995, 1997 and 1998. Results during the spring of other years could not be compared due to missing data. Consistent positive residuals were observed in mid-summer at Catamaran Brook in 1998, while negative residuals were observed during the similar period the following year 1999. The residual time series at the Little Southwest Miramichi River showed significant overestimation (positive residuals) in the summers of 1996 and 1998. In general, the autumn residuals were low in the Little Southwest Miramichi River, which reflected the good performance of the model that time of year. The residual time series also showed low values in 1995 in general for this river. Autumn results at Catamaran Brook generally showed negative residuals for 6 years (i.e., 1992, 1993 and 1996-99), which was reflective of a consistent autumn underestimation of water temperatures.

CHAPTER 5

DISCUSSION

5.1 River thermal characteristics

Studies have shown that water temperature variations in streams can depend on many factors including climate, location (altitude, latitude), stream size, streamside vegetation, river geomorphology, basin topography, and others (Ward 1985). The thermal regime of rivers can also depend on factors such as bedrock predominance (Brown 1969), streambed friction (Vugts 1974), and groundwater contribution (Smith 1975), among others. The thermal capacity (or thermal inertia) of a river is a function of the volume of water or river depth, and therefore can influence diurnal fluctuations in water temperatures (Webb and Walling 1986). Surface and subsurface water exchange (or hyporheic exchange) as well as streambed temperature gradient have also been observed to influence the thermal conditions in rivers (Alexander and Caissie 2003; Hondzo and Stefan 1994). In general, these factors will influence the stream water temperature as well as modelling results. These factors influencing river water temperatures will also impact on the overall aquatic ecosystem (Vannote et al. 1980; Coutant 1999). Water temperature has been known to impact aquatic biota not only within the water column but also within the stream substrate.

Studies dealing with the modelling of water temperatures have ranged from simple regression type models (Crisp and Howson 1982, Jourdonnais et al. 1992, Erickson and Stefan 2000) to full energy budget or deterministic models (Raphael 1962, Morin and Couillard 1990, Sinokrot and Stefan 1993). The present study provides information related to four different types of modelling approaches, namely a deterministic model, a simplified water temperature model based on the equilibrium temperature concept, a stochastic model as well as an energy reference model.

Unlike previous stream water temperature modelling studies, which were carried out over a few seasons (Sinokot and Stefan 1994) to a few years (Marceau et al. 1986), the present study was conducted using 8 years of data. With so many years of data, it was possible to study river water temperature models under varied meteorological conditions. The present study also provided water temperature modelling results on two thermally different river systems, i.e. Catamaran Brook and the Little Southwest Miramichi River within a similar meteorological area. A comparison of different thermal characteristics was possible through a study of long-term data on monthly water temperatures as well as the annual component (cycle) for both rivers.

Monthly air temperatures, collected at the Catamaran Brook meteorological station, showed a mean air temperature of 10.3 °C (1992-99; Table 4.1). It was noted that during the 8 years of study, a significant range of annual air temperatures was observed. The coldest year was monitored in 1992 at 9.4 °C, while the warmest was in 1999 at 11.9°C, a difference of 2.5 °C. Air temperature resulted in a mean water temperature at Catamaran Brook of 8.8 °C (1992-99; Table 4.2), whereas the Little Southwest Miramichi River mean water temperature was calculated at 11.2 °C (Table 4.3). Interestingly, the Little Southwest Miramichi River mean water temperature was 0.9 °C higher than the air temperature within the same period (i.e., 1992-99; Table 4.1 and 4.3). This was also noted for the peak summer temperatures of the annual component (maximum of 18.6 °C air temperature [equation 4.1b] and 20.2 °C for the Little Southwest Miramichi River [equation 4.1c]). This phenomenon of water temperatures being higher than air temperature could not be found elsewhere in the literature and it has important implications to river thermal exchange processes. This warmer water can be attributed to the solar radiation input to the river, in which water temperature already approaches air temperature (due to efficient heat exchange processes). As reported in previous studies (Morin and Couillard 1990; Sinokrot and Stefan

1993; Sinokrot and Stefan 1994), solar input is the major component of the total energy flux, and this component could have resulted in higher water temperature in Little Southwest Miramichi River. Moreover, it has been observed that rivers tend to heat more efficiently during the daytime, whereas nighttime cooling may not be as dominant. This can be attributed to lower wind speed at night, as observed by Brosofske et al. (1997).

The coldest summer (Apr. to Nov.) was observed in 1992, while the warmest summer occurred in 1999 (Table 4.1). Mean summer water temperature was not available in 1992 for either Catamaran Brook or Little Southwest Miramichi River due to missing data. However, the highest mean summer water temperatures were observed in 1999 for both rivers (10.3 °C and 12.8 °C; Table 4.2 and 4.3), which was consistent with highest annual air temperatures (Table 4.1). This reflects a relatively high level of association between air and water temperature on an annual basis.

On a monthly basis, highest monthly water temperatures were generally observed in July and August (Table 4.2 and Table 4.3) as was noted in previous studies (Langan et al. 2001). The highest monthly air temperature (during the study period, 1992-99) was observed in July of 1994 at 20.0 °C, although other months were close, such as July 1995 at 19.9 °C (Table 4.1). Although highest monthly air temperature was observed in July 1994, highest monthly water temperature was not observed during that month. In fact, highest water temperature at Catamaran Brook was monitored in July of 1999 at 17.2 °C. River discharge was observed to be an important factor influencing water temperatures. For instance, it was noted that the stream discharge at Catamaran Brook was slightly lower in July of 1999 compared to July of 1994 (Table 4.4). In the Little Southwest Miramichi River, the highest monthly water temperature was monitored in July 1995 (22.0 °C) and July 1999 (21.9 °C) and discharge was significantly lower than in 1994 (Table 4.5). River discharge in July of 1994 for the Little Southwest Miramichi River was approximately 75% higher than in 1995 and 1999, thus resulting in lower water temperature during the month of maximum air temperature. These results show that although monthly air/water temperatures are related, stream discharge (and thermal inertia) plays an important role on maximum monthly water temperatures. Higher discharge ultimately resulted in lower water temperatures for similar meteorological conditions and vice versa. Other studies have also shown the importance of river discharge on water temperatures (Gu et al. 1998; Sinokrot and Gulliver 2000). Years with low flow periods coupled with high air temperature will ultimately result in higher water temperatures. Although stream discharge is important in explaining water temperatures, air temperature remains a dominant factor (Langan et al. 2001).

Mean annual water temperature at the Little Southwest Miramichi River was higher than mean annual air temperature (see above). This was also observed on a monthly basis (at the Little Southwest Miramichi River) from the month of June and extending into autumn (Table 4.1 and 4.3). As mentioned previously, this was most likely due to solar radiation inputs reaching the river as well as the close relationship between air and water temperature in this river.

Studies have shown that the annual component can be represented by a sine function or a Fourier series (Ward 1963; Kothandaraman 1971; Kothandaraman 1972; Caissie et al. 1998). However, no studies could be found in the literature where the annual component of thermally different rivers (in a similar climatic area) was compared. The present study showed that the annual component for both Catamaran Brook and the Little Southwest Miramichi River can be represented by a sine function calculated using mean daily water temperatures (Figure 4.1). These mid-latitude rivers, which experienced near freezing temperatures throughout the winter period, showed that the thermal regime in the spring was very similar between the small and large river systems. In fact, water temperature for both rivers departed from 0°C at approximately the same time in the spring (April 13 or day 103; Figure 4.1) based on long-term data. These results suggest that in early spring, snowmelt is potentially a dominant factor in keeping rivers thermally similar at near freezing temperatures. Although important for ecological purposes, it has been recognized in the literature that there is lack of information related to the thermal condition of rivers this time of year (Prowse and Culp 2003). For both river systems to become thermally active at the same time also suggests that such influences (e.g. snowmelt) would affect rivers on a regional rather than local basis. Snowmelt as a factor has been observed to impact the river thermal regime in only a few studies (Smith 1972). For instance, Smith (1972) discussed the fact that heat balance and water temperature relationships change during the snowmelt period. Other studies have reported a non-linear behaviour in air/water relations at low air temperatures (Crisp and Howson 1982; Mohseni and Stefan 1999).

The warming period or the rising portion of the annual component extended until the end of July for both river systems, with the Little Southwest Miramichi River experiencing a greater increase in water temperatures. The maximum long-term water temperature for the Little Southwest Miramichi River was 20.2 °C compared to 15.1 °C for Catamaran Brook, and both rivers experienced their long-term peak temperatures on the same day, i.e. July 30 (day 211). When comparing the annual component from other rivers in the literature, it can be observed that the timing of peak summer temperatures was very similar regardless of location throughout the world. For instance, Ward (1963) showed that the annual component peaked on July 25, whereas Cluis (1972) showed peak summer temperatures occurring on July 26. These dates are very close to those observed in the present study. Marceau (1984) also showed peak summer temperatures at the end of July (approximately July 28). The annual component of rivers in a milder climate, such as those experiencing above freezing temperatures throughout winter, also show peak summer temperatures at the end of July (Webb and Walling 1993a).

The present study showed that for thermally different rivers under similar meteorological conditions, the greatest difference in water temperatures between the two systems was observed at long-term peak water temperatures, i.e. end of July. For Catamaran Brook and the Little Southwest Miramichi River, this difference represented 5.1 °C. This implies that although the larger and more exposed system heated more (i.e., higher radiative fluxes), the long-term heating and cooling processes of these two rivers were similar, with their long-term maximum occurring on the same date. Following the peak summer water temperatures, a cooling period was observed that extended into late autumn when water temperatures decreased to near freezing again. It was noticed that this cooling period was not identical between the two rivers and that the Little Southwest Miramichi River cooled at a slightly faster rate during the end of the season (after day 250, September 7). During this period, long-term mean water temperatures for the Little Southwest Miramichi River showed values slightly below the annual component (Figure 4.1). This faster cooling of the Little Southwest Miramichi River temperature was especially noticeable in some years, such as in 1993 (Figure 5.1).

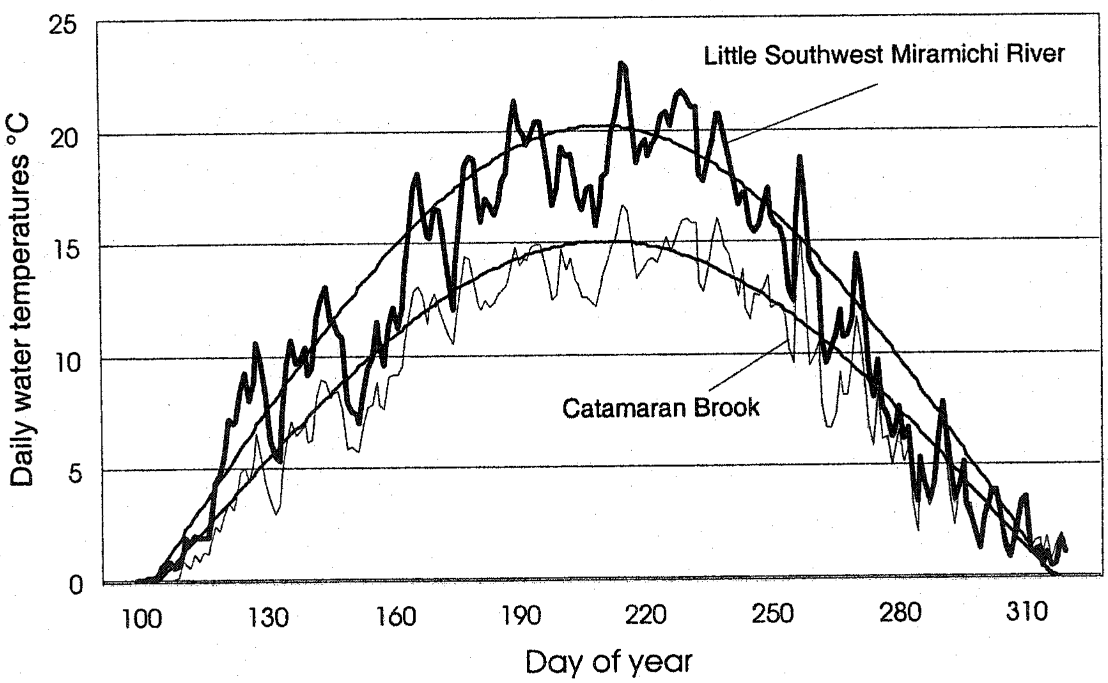

Figure 5.1 Water temperatures in 1993 at Catamaran Brook and the Little Southwest Miramichi River, and showing the slightly faster rate of cooling at the Little Southwest Miramichi River (after day 250) in relation to their respective annual components.

For instance in autumn 1993, water temperatures in the Little Southwest Miramichi River reached those of Catamaran Brook (after day 280; Figure 5.1). Autumn was the only time of year where water temperatures in the Little Southwest Miramichi River have been observed to be colder than Catamaran Brook temperatures (D. Caissie, pers. obser.). This faster cooling of the Little Southwest Miramichi River is most likely the result of this river being more exposed to meteorological conditions, having proportionally less groundwater input and experiencing relatively low discharge at this time of year. In fact, Catamaran Brook has been observed to have proportionally higher groundwater inputs based on observations of the ice cover formation (D. Caissie, pers. obser.). It has been observed that the ice cover forms slightly later in the Middle Reach of Catamaran Brook and also opens earlier in the spring due to groundwater inputs. Quantifying such microclimatic influences on the river thermal regime is still at the research stage; however, studies have clearly shown significant differences between microclimatic conditions at the stream level compared to upland conditions (Dong et al. 1998; Brosofske et al. 1997) as well as between forested vs. clearcut areas (Chen et al. 1995). These microclimatic conditions could have an important influence on the heat exchange processes at the water surface interface.

5.2 Deterministic model

Similar to the study of river thermal characteristics, the present study permitted a comparison of different modelling approaches on two different river systems. A deterministic model was calibrated by adjusting energy components relative to each other, as was the case in previous studies (e.g., Morin and Couillard 1990; Sinokrot and Stefan 1993). To adjust the relative contribution of each energy component, calibration parameters were used for solar radiation, latent (evaporative) and sensible heat fluxes. The net incoming solar radiation was calibrated using a shading factor (*SF*), which quantifies the amount of sunlight directly reaching the river. In the case of Catamaran Brook the shading factor was calculated at 0.55, while the shading factor for the Little

Southwest Miramichi River was calculated at 0.08. These shading factors were well within the values observed in the literature (e.g. Marcotte and Duong 1973, SF = 0.05-0.40; Sinokrot and Stefan 1993, SF = 0.0-0.70; St-Hilaire et al. 2000, SF = 0.6). It should be noted that the study by St-Hilaire et al. (2000) was also conducted at Catamaran Brook, using the CEQUEAU model. The value at the Little Southwest Miramichi River reflects that this river is highly exposed to climatic conditions, whereas Catamaran Brook is more sheltered by riparian vegetation.

The present study also permitted a comparison of the relative contribution of each energy component for both rivers, as they were subject to similar meteorological conditions. For instance, solar radiation has been noted to dominate the energy fluxes in most studies (Morin and Couillard 1990; Sinokrot and Stefan 1993; Webb and Zhang 1997). This was also the case for Catamaran Brook and the Little Southwest Miramichi River. The net short-wave radiation (solar radiation) showed a mean value of 5.56 MJ m^2 d^{-1} at Catamaran Brook, while a mean value of 11.38 MJ m^2 d^{-1} was calculated for the Little Southwest Miramichi River (Table 4.4). The higher contribution of solar radiation in the Little Southwest Miramichi River was reflective of this river being more exposed to direct sunlight, with a shading factor of only 0.08. Long-wave radiation and energy lost by evaporation have been reported in the literature as being somewhat similar in magnitude (Marcotte and Duong 1973; Morin and Couillard 1990). For instance, values of -6.8 MJ m^2 d^{-1} (long-wave radiation) and -8.2 MJ m^{-2} d^{-1} (evaporative heat flux) were reported for the Chaudiere River in Quebec (Marcotte and Duong 1973). In the present study, the mean long-wave radiation (H_l) was calculated at -3.61 MJ m^{-2} d^{-1} for Catamaran Brook and was highly comparable to the mean evaporative heat flux (H_e) at -3.58 MJ m^{-2} d^{-1}. The mean long-wave radiation was slightly higher for the Little Southwest Miramichi River at -4.66 MJ m^{-2} d^{-1} but highly comparable to the mean evaporative heart flux (H_e) at -5.33 MJ m^{-2} d^{-1} (Table 4.4). The slightly higher long-wave radiation values for the Little Southwest Miramichi River compared to Catamaran Brook can be attributed to the higher water temperatures in the Little Southwest

Miramichi River Similarly, the higher value of H_e for the Little Southwest Miramichi River can also be attributed to higher water temperatures resulting in a higher saturated vapour pressure (e_s). It should be noted that values of H_l and H_e for the Little Southwest Miramichi River were closer to those of the Quebec rivers (i.e. similar size) than to Catamaran Brook. Webb and Zhang (1997) showed that the evaporative heat flux was a significant component of the deterministic model, especially during periods of relatively low humidity and high wind speed. Other studies have also shown that the evaporative heat flux can be particularly important during very warm weather, and therefore can contribute to the cooling of rivers (Mohseni and Stefan 1999). This process, also known as evaporative cooling, can prevent excessive water temperatures in rivers. Evaporative cooling would have been important at both Catamaran Brook and the Little Southwest Miramichi River in 1995 and especially in 1999, with higher values of the evaporative heat flux (Table 4.6). Highest values in evaporative heat flux were consistent with the warmest summer of 1999. As pointed out in the literature, the calculated evaporative flux can be a function of the equation used. For instance, Dake (1972) showed a difference of 7-15% in the evaporative flux depending on the equation used to calculate evaporation.

The smallest energy component was the convective heat transfer (or sensible heat), calculated at 1.42 MJ m^2 d^{-1} for Catamaran Brook and -0.65 MJ m^{-2} d^{-1} for the Little Southwest Miramichi River. Morin and Couillard (1990) also reported an overall small mean value of sensible heat (e.g. -0.5 MJ m^{-2} d^{-1}) for rivers in Quebec based on data from Marcotte and Duong (1973). Other studies showed that sensible heat can account for less than 13% of the energy contribution (Webb and Zhang 1997). Although this energy component is small on average, it is not negligible because it is often responsible for most variations in water temperatures as it alternates between a positive and negative energy flux (unlike the other fluxes, which show more consistently positive or negative values). This is because the convective heat transfer is a function of the difference between the air and water temperatures. For instance, as water temperatures in Catamaran Brook were on average lower than air temperatures, the convective heat flux was on average positive (Table 4.4). Conversely, as water temperatures in the Little Southwest Miramichi River were on average higher than air temperatures, the convective heat flux was on average negative.

The present study showed that it was possible to achieve good calibration of the deterministic water temperatures model with only 3 years of data (1992-94). During the validation period (1995-99), independent data were used based on parameters established during the calibration period. Predicted vs. observed water temperatures at Catamaran Brook (Figure 4.3a) and the Little Southwest Miramichi River (Figure 4.4a) using the deterministic model showed relatively good agreement with RMSE of 1.58°C and 1.53°C respectively (1992-99; Table 4.5a). The Nash coefficient was slightly higher for the Little Southwest Miramichi River at 0.94 (1992-99) than for Catamaran Brook at 0.92 (1992-99). The calibration period showed slightly lower RMSE than the validation period in both rivers (1.51 °C vs. 1.61 °C, Catamaran Brook; 1.49 °C vs. 1.55 °C, Little Southwest Miramichi River), which is to be expected. This model showed slightly better results for the Little Southwest Miramichi River than for Catamaran Brook, presumably due to the fact that the former river was more exposed and therefore susceptible to meteorological conditions. In Catamaran Brook, sheltering effects by riparian vegetation could have introduced slightly more variability and uncertainty in parameter estimation, thus resulting in slightly higher RMSEs. Deterministic models have been shown to be applicable under varying physical and meteorological conditions (Sinokrot and Stefan 1993) as well as varying riparian conditions (Rutherford et al. 1997). Also, modelling uncertainties can be introduced due to the variability of meteorological conditions at the stream level compared to upland conditions where the meteorological data were collected. This aspect of at-river microclimatic conditions has not been subject to much research in the application of water temperature models. However, forestry related studies have clearly shown that microclimatic conditions can be very different between open areas, interior forest, and at the stream level (Brosofske et al. 1997; Chen et al. 1995). For instance, Chen et al. (1995) showed a transition zone of meteorological conditions from the edge of the forest which can reach into the interior forest up to 240 m. Among those studies that have looked at meteorological conditions at the stream level, Rutherford et al. (1997) showed that conditions can vary and that maximum measured shade was the required value in the model to most closely represent the actual sunlight reaching the stream. Another related study showed that after timber harvesting (with riparian buffer zones), meteorological conditions at the stream were modified and air temperatures were 2-4°C higher (Dong et al. 1998). The forest edge effect could be important in water temperature modelling, and Catamaran Brook is most likely more influenced by forest microclimatic conditions than the Little Southwest Miramichi River.

The deterministic model performance (inter and intra annual) was studied during both the calibration and validation periods at Catamaran Brook and the Little Southwest Miramichi River (Figure 4.3a and 4.4a). This model did not perform as well in early autumn in Catamaran Brook during some years, where the model significantly underestimated water temperatures (e.g. after day 270; Figure 4.3a). This was also reflected by a consistent negative residual time series (Figure 4.3b). Such was the case in autumn of 1992 as well as in 1996-99. In contrast, the deterministic model performed among the best for the Little Southwest Miramichi River during the same period in autumn (Figure 4.4a and 4.4b). It is believed that groundwater contribution in Catamaran Brook played an important role in thermal condition in early autumn and thus resulted in higher observed water temperatures. Catamaran Brook is proportionally richer in groundwater than the Little Southwest Miramichi River. Discharge and/or precipitation were most likely not a significant contributing factor, because flows in October 1992 and 1993 were very similar in Catamaran Brook (Table 4.4) while the modelling performance was very different (Figure 4.3a and 4.3b). Other factors that could have contributed to these higher than predicted water temperatures most likely include residual summer soil heating (energy transferred through shallow groundwater). Little information is available in the literature about such transfer of heat by shallow groundwater; however some investigations are presently being carried out at Catamaran Brook to address this issue

(Alexander et al. 2003). Groundwater contribution has been observed to modify the thermal regime in rivers as reported in other studies (Smith 1972; Mackey and Berrie 1991; Clark et al. 1999). Heat flux at the sediment water interface has also been shown to be a contributing factor (Comer and Grenney 1977; Hondzo and Stefan 1994).

Low water conditions in both Catamaran Brook and the Little Southwest Miramichi River are usually observed in August and September (Table 4.4 and 4.5). Under these conditions, the deterministic model showed very good performances for both rivers. Spring water temperatures showed good agreement between predicted and observed temperatures in Catamaran Brook, however, values in the Little Southwest Miramichi River showed a slight overestimation in 1993 and 1995 and more so in 1997 (Figures 4.4a and 4.4b). Higher predicted water temperatures in the spring at the Little Southwest Miramichi River can be attributed to snowmelt influences as well as to higher stream discharges (i.e., greater thermal inertia). In fact during the month of May, the discharge in the Little Southwest Miramichi River was much greater than in Catamaran Brook (100.1 m^3/s vs. 1.84 m^3/s). These two main factors (snowmelt and high discharge) can influence the overall performance of the deterministic model, especially during early vs. late spring. This was especially noticeable when comparing water temperatures during the spring of 1997 to those of 1999 (late vs. early spring). For instance, the spring of 1997 was late with below normal air temperature in April (1.5 °C), which resulted in the highest May discharge for both rivers (Catamaran Brook = 3.06 m^3/s; Little Southwest Miramichi River = 166 m^3/s; Table 4.4 and 4.5). Spring peak flows were also late and occurred in mid-May (i.e., May 14-17) that year. In contrast, the year 1999 had an early spring with above normal air temperature in April. Spring peak flows occurred close to April 27, with much lower flow in May (Catamaran Brook = 1.13 m^3/s; Little Southwest Miramichi River = 76.2 m^3/s; Table 4.4 and 4.5). The relatively better modelling performance in the spring at Catamaran Brook suggests that colder and smaller tributaries may be less affected by spring conditions. The influence of snowmelt on water temperatures and a lack of association to air temperatures during spring conditions have been observed in other studies (Smith 1975; Jeppesen and Iversen 1987). Overall the deterministic model performed relatively well during cold summers (e.g. 1992) and also during warm summers (e.g. 1999; Figure 4.3a and 4.3b). In fact, this modelling approach performed surprisingly well during the summer of 1999, which experienced its highest summer air temperatures in over 40 years of record (Caissie 2000).

Peak summer water temperatures were better predicted during some years than others for both rivers (Figure 4.3a and 4.4a). The better performance during some years was somewhat random in nature and could not be attributed to low or high discharge conditions or air temperature events. For instance, the summer of 1996 showed relatively high discharge (e.g., July and August), while the summer 1999 showed the opposite (Table 4.4) although water temperature predictions were similar.

Due to relative humidity sensor malfunction during some years (e.g. 1992, part of 1993, 1995-96), data from the Miramichi Airport were used as well as using a mean value of relative humidity (Table 4.5b). Results showed generally higher RMSEs when using a mean value of relative humidity (i.e. average conditions), although the added uncertainty in predicted water temperatures was low. In fact, the added uncertainty was calculated at only 0.08 °C in Catamaran Brook and 0.09 °C at the Little Southwest Miramichi River (i.e., based on improvements in the RMSEs). In a study by Sinokrot and Stefan (1994), it was shown that water temperatures are sensitive to relative humidity, however air temperatures and solar radiation remained the most dominant factors. This can explain the fact that water temperatures in both rivers could be modelled relatively well using a mean value for relative humidity. When using relative humidity data from the Miramichi Airport, modelling results provided almost identical performances for both rivers compared to Catamaran Brook data (Table 4.5b). These results suggest that on a daily basis the relative humidity at the Miramichi Airport (at approximately 76 km from the Catamaran Brook meteorological station) was reflective of the study area meteorological conditions (Figure 4.2).

5.3 Equilibrium temperature model

Previous studies have used the equilibrium temperature concept to study the thermal conditions in rivers (Edinger et al. 1968; Boutin et al. 1981; Mohseni and Stefan 1999), however no study could be found in the literature where water temperature was actually modelled using this approach. In the present study, a new model [equation, 3.19] was presented to express the equilibrium temperature as a function of the most relevant meteorological parameters. This equation showed that the equilibrium temperature was mainly a function of solar radiation, air and dew point temperature with coefficients that were largely a function of wind velocity (see equations [3.20] to [3.24]). The coefficients within the equilibrium temperature model provided valuable insight into factors influencing river water temperatures. When plotted against wind velocity, it was noted that as wind speed decreased the solar radiation coefficient (B_1) increased (Figure 4.6). This means that T_e will be predominantly influenced by solar radiation (H_{si}) at very low wind velocity. However, for more general wind speed conditions, the air and dew point temperature dominated the equilibrium temperature, which was thereafter the basis of developing an equation relating the equilibrium temperature to air temperature.

Previous studies have shown that for temperate regions, there is a relatively good linear association between air and dew point temperature as a function of relative humidity (Mohseni and Stefan 1999). The present study showed that under these conditions, the equilibrium temperature is highly correlated with air temperature (Figure 4.5). Therefore, a simplified function of air temperature was used to represent the equilibrium temperature, which constituted the basis of this modelling approach. With the equilibrium temperature, it was possible to model water temperatures with as few as 3 years of calibration data, similar to the deterministic model. Previous studies have shown that the thermal heat exchange coefficient K' is generally a function of many meteorological parameters (Edinger et al. 1968; Mohseni and Stefan 1999). In this study, it was demonstrated that it was possible to consider the thermal heat exchange coefficient as a constant, and modelling results show very good agreement between predicted and observed water temperatures.

Because the equilibrium temperature is mainly a function of air temperature, dew point temperature and solar radiation, when relating the equilibrium temperature to air temperature only, the air temperature alone has to represent the total energy flux. For instance, Catamaran Brook showed a coefficient (b_5) of 0.81 due to the sheltering nature of the brook from meteorological conditions. The Little Southwest Miramichi River showed a higher coefficient at 1.05, which is reflective of the fact that this river is more exposed to meteorological conditions. A coefficient higher than one suggests that the bulk energy component (as indexed by air temperature) for this river is higher than the measured air temperature, to account for solar radiation and other meteorological factors.

When looking at the overall performance of this model, results showed RMSE of 1.26 °C for Catamaran Brook compared to 1.52 °C for the Little Southwest Miramichi River (1992-99; Table 4.6). The Nash coefficient was slightly higher for Catamaran Brook (0.95; 1992-99) than for the Little Southwest Miramichi River (0.94), but these reflected similar results to the deterministic model. Similar to the deterministic model, slightly lower RMSEs were observed during the calibration period compared to the validation period (1.10 °C vs. 1.31 °C, Catamaran Brook; and 1.45 °C vs. 1.55 °C, Little Southwest Miramichi River, Table 4.6). Again, this was expected given that the validation period constituted an independent data set from the calibration period.

Intra annual modelling results showed that this model performed generally better in late summer and autumn than in spring for both Catamaran Brook and the Little Southwest Miramichi River (Figure 4.7a and 4.8a). These periods also showed lower residual time series (Figure 4.7b and 4.8b), which was generally less than ± 3°C. This was due to predominantly low water level in late summer and autumn, which resulted in a more efficient thermal exchange. The predicted late autumn water temperatures for both rivers were better predicted with the equilibrium temperature model than the deterministic model (e.g., see 1992 for both models). This could be attributed to the fact that this model has fewer calibration parameters, therefore less uncertainty related to parameter estimation. Also, the total heat flux was estimated by the equilibrium temperature, which potentially represented better the actual energy fluxes. Studies have shown that simplified water temperature models can be effective in modelling water temperature (Jeppesen and Iversen 1987). Water temperatures in the spring were not captured as well with the equilibrium temperature model compared to the deterministic model for Catamaran Brook (Figure 4.3a and 4.7a). Moreover, predicted spring water temperatures were slightly overestimated and comparable to those of the deterministic model for the Little Southwest Miramichi River (Figure 4.4a and 4.8a). The poorer model performance in early spring can be attributable to the presence of snowmelt conditions and higher water levels including late vs. early spring, as discussed for the deterministic model. Comparable to the deterministic model, the equilibrium temperature model captured the peak summer temperatures better in some years, especially in 1995 and 1998 in Catamaran Brook as well as in 1998 for the Little Southwest Miramichi River (Figure 4.7a and 4.8a). River discharge and air temperature during these summers did not seem to have played an important role in better capturing the peak summer water temperatures.

5.4 Stochastic model

Similar to previous models, the stochastic model was calibrated using 3 years of data (1992-94) and validated using the following 5 years (1995-99). The long-term annual component of air and water temperature was calculated for both rivers, as described in section 4.4. Following the removal of the annual component for both air and water temperatures, the resulting short-term component was used to link air and water temperatures. A calibrated second order Markov process was used with lag 1 and lag 2 autocorrelation coefficients to carry out the water temperature modelling (Cluis, 1972; Caissie et al. 1998). Lag 1 and lag 2 autocorrelation coefficients of daily water temperatures (i.e., short-term component) were calculated at 0.855 and 0.672 respectively for Catamaran Brook. Similarly, lag 1 and lag 2 autocorrelation coefficients of 0.855 and 0.656 were calculated for the Little Southwest Miramichi River. The autocorrelation coefficients of the short-term component of the present study were comparable to those reported in the literature (e.g. Cluis 1972; Marceau 1984; Marceau et al. 1986). For instance, Cluis (1972) reported autocorrelation coefficients of 0.92 (lag 1) and 0.74 (lag 2) for the rivière du Nord (Quebec). Marceau et al. (1986) reported values of 0.71 and 0.50 for lag 1 and lag 2 autocorrelation coefficients, which were slightly lower than those observed in the present study. It should also be noted that Cluis (1972) hypothesised that rivers within similar meteorological conditions should also have similar autocorrelation coefficients. Results from the present study suggest that is the case, with almost identical autocorrelation coefficients calculated for Catamaran Brook and the Little Southwest Miramichi River (see above).

The autocorrelation coefficients were thereafter used to calculate second order Markov model coefficients A_1' and A_2' (equation [3.30]). The coefficient K_s of the stochastic model, which relates the air temperature to water temperature, is reflective of the efficiency of thermal exchange. Specific to each river, this coefficient can be influenced by factors such as stream cover (shade), depth of water, groundwater inputs, and others. The coefficient (K_s) was calculated at 0.130 for Catamaran Brook and at 0.190 for the Little Southwest Miramichi River. A higher K_s coefficient means that there was a stronger association between air and water temperatures (short-term component) for the Little Southwest Miramichi River than for Catamaran Brook.

Predicted vs. observed water temperatures at Catamaran Brook and the Little Southwest Miramichi River using the stochastic model showed similar results to previous models with RMSEs of 1.26°C and 1.61°C respectively (1992-99; Table 4.9). Nash coefficients were 0.94 (Catamaran Brook; 1992-99) and 0.94 (Little Southwest Miramichi River). Lower RMSEs were observed during the calibration period than the validation period for both rivers (1.15 °C vs. 1.31 °C, Catamaran Brook; 1.35 °C vs. 1.74 °C, Little Southwest Miramicih River). The overall modelling performance was identical to the equilibrium temperature model for Catamaran Brook and better than the deterministic model. For the Little Southwest Miramichi River, RMSEs were slightly higher at 1.61 °C, nonetheless similar to deterministic and equilibrium temperature models.

Results of the present study showed that the RMSEs using the stochastic model were comparable to results from other studies (Marceau et al. 1986; Caissie et al. 1998). For instance, the RMSEs calculated by Marceau et al. (1986) were between 1.10°C and 2.52°C. Results of the present study showed RMSEs of 1.04-1.63 °C at Catamaran Brook and 1.27-2.45 °C for Little Southwest Miramichi River annually. Modelling results of the present study can also be compared to those of three different stochastic models applied in Catamaran Brook for the years 1992 to 1995 (i.e., using the same data as in the present study; Caissie et al. 1998; Table 5.1). However, in their study they used only one year to calibrate the stochastic models (i.e. 1993). The three stochastic models used included: 1) a multiple regression model, 2) a second-order Markov process model, and 3) a Box-Jenkins type model (see Caissie et al. 1998, for details). Among the 1992-95 results of the present study, RMSEs were consistent with the study of Caissie et al. (1998), showing the best performance year in 1993, while the worst was in the following year in 1994.

Inter and intra water temperature predictions using the stochastic model were similar to previous water temperature models. A slight overestimation was observed in the spring with generally better performance in later summer and autumn (Figures 4.9a and 4.10a). Water temperature residual time series were generally less than ± 3 °C (Figures 4.9b and 4.10b). The spring overestimation was consistent with results from other models as well. Peak summer water temperatures were better captured during some years (e.g. 1993, 1997, 1998) than others (e.g. 1999). Peak summer temperatures were better predicted in 1999 at the Little Southwest Miramichi River than in Catamaran Brook, which showed a consistent underestimation.

Table 5.1 Root-mean-square error (RMSE, °C) obtained by Caissie et al. (1998) from 1992 to 1995 at Catamaran Brook using a stochastic model. For comparison with the results of the present study.

	Stochastic modelling (Caissie et al. 1998)		
Year	*multiple regression*	*second-order Markov process*	*Box-Jenkins approach*
1992	1.50	1.28	1.45
1993	0.87	0.96	0.89
1994	1.66	1.57	1.68
1995	1.30	1.24	1.23

5.5 Energy reference model

The energy reference model makes use of the long-term components in meteorological parameters to predict stream water temperatures. This new approach in the modelling of stream water temperatures showed relatively good agreement between predicted and observed water temperatures for both Catamaran Brook and the Little Southwest Miramichi River (Figures 4.12a and 4.13a). The energy reference water temperature model performed especially well in late summer and early autumn, similar to previous models. The better performance of this model at this time of year is likely due to the lower discharge which resulted in a more efficient modelling, as was noticed for previous models.

The overall modelling performance was good for both rivers, with a RMSE of 1.40 °C at Catamaran Brook (1992-99; Table 4.10) and a RMSE of 1.58 °C for the Little Southwest Miramichi River (1992-99; Table 4.10). The overall Nash coefficient was calculated at 0.94 at Catamaran Brook compared to 0.95 for the Little Southwest Miramichi River (1992-99), which was also comparable to previous models. Rather than showing an improvement between the calibration and validation period, as was observed for previous models, the energy reference model showed almost identical performances (e.g, 1.41 °C vs. 1.39 °C in Catamaran Brook and 1.58 °C vs. 1.58 °C in the Little Southwest Miramichi River; Table 4.10). This suggests that the energy reference model may lack some flexibility in fitting water temperature data (i.e., calibration period), but when calibrated the model can predict water temperatures equally well using an independent data set.

Water temperature predictions were generally good for both Catamaran Brook and the Little Southwest Miramichi River; however this model did not capture the water temperature variability as well during certain periods, particularly at Catamaran Brook (e.g. early summer of 1993, 1996 and 1998; Figure 4.12a). Water temperature variability was better captured at the Little Southwest Miramichi River in early summers, especially in 1995, and 1999 (Figure 4.13a). The difficulty of the energy reference model to reproduce stream water temperature variability also resulted in consistent over/underestimation of water temperatures (Figures 4.12b and 4.13b), especially at Catamaran Brook. The difficulty to capture the water temperature variability suggests that the energy reference model was dominated by the annual component over the short-term component. Similar to other models, the energy reference model showed an overestimation in the spring, potentially due to late vs. early spring or other factors as mentioned for previous models. With this modelling approach, the spring overestimation was equally important in both Catamaran Brook and the Little Southwest Miramichi River (e.g. spring of 1994 and 1997 in Catamaran Brook, Figure 4.12a; and spring of 1997 in the Little Southwest Miramichi River, Figure 4.13a). The spring overestimation was especially noticeable in 1997, whereas 1999 showed very good temperature predictions. The energy reference model showed good evidence of potential spring snowmelt influences at the Little Southwest Miramichi River when comparing these years. During the late spring of 1997 water temperature predictions were significantly higher than measured temperatures (Figure 4.13a). In contrast, during the early spring of 1999 water temperatures in Little Southwest Miramichi River showed among the best predictions starting very early in the season (Figure 4.13a).

Peak summer water temperatures were captured during some years in both Catamaran Brook (1993 and 1995; Figure 4.12a) and the Little Southwest Miramichi River (1995 and 1999; Figure 4.12a). Incidentally, both Catamaran Brook and the Little Southwest Miramichi River experienced below normal summer discharge in these years (Table 4.4 and Table 4.5).

5.6 Comparison of modelling approaches

Results from the 4 different models were somewhat similar with RMSEs ranging from 1.26 °C to 1.61 °C (all years, 1992-99; Figure 5.2). Therefore, all of the considered models were effective in predicting stream water temperatures of the two thermally different watercourses. However, a slight difference was noted among modelling approaches and potential explanation will be provided within this section. For instance, the deterministic model showed the highest RMSE among all models at Catamaran Brook (all years, 1.58 °C; Figure 5.2a), while the overall RMSE for the Little Southwest Miramichi River was among the better performance (all years, 1.53 °C; Figure 5.2b). Higher RMSE at Catamaran Brook with the deterministic model can potentially be attributed to heat exchange processes, which may not have been captured as well in this river. This is probably due to the sheltering effects of riparian vegetation on Catamaran Brook as mentioned previously. In addition, although neglected in all models, groundwater contributions and/or heat flux at the water / sediment interface would most likely have had a greater influence in Catamaran Brook than

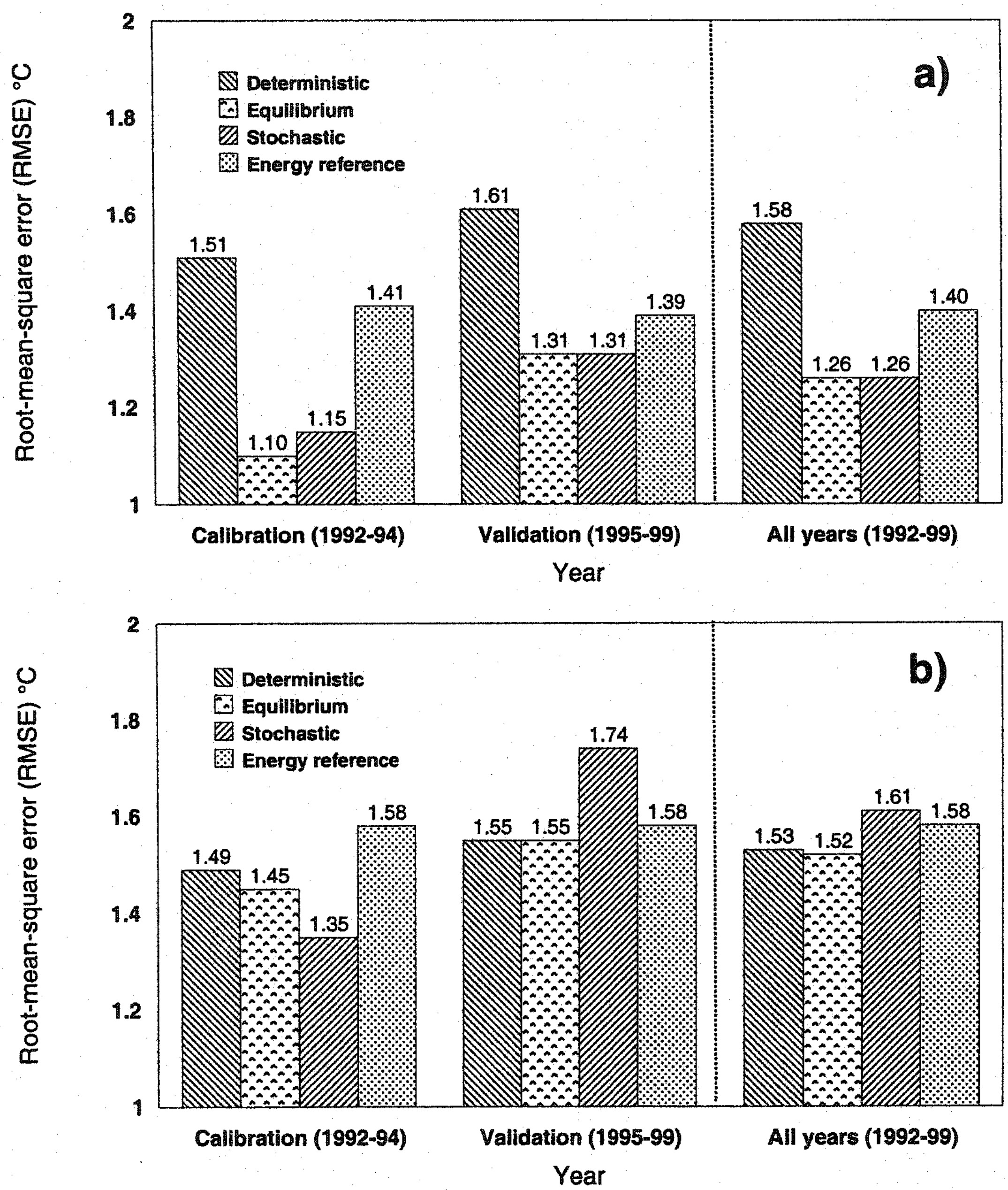

Figure 5.2 Modelling performance (RMSE) by the different modelling approaches for the calibration period (1992-94), the validation period (1995-99) and during all years of the study, i.e. 1992-99. a) Catamaran Brook and b) Little Southwest Miramichi River.

in the Little Southwest Miramichi River. Conversely, the relatively good performance of the deterministic model in the Little Southwest Miramichi River compared to other models can be attributed to the fact that this river was more exposed to meteorological conditions and therefore the heat exchange was best represented by this model. It should be noted that the deterministic model was the only model where the Little Southwest Miramichi River outperformed Catamaran Brook (lower RMSEs for all years, Figure 5.2). For both rivers, RMSEs during the calibration period were slightly lower than those during the validation period, however the added uncertainty between these two periods was low (0.1 °C at Catamaran Brook and 0.06 at the Little Southwest Miramichi River; Figure 5.2).

The equilibrium temperature model showed overall (1992-99) best results at Catamaran Brook (all years, 1.26 °C; Figure 5.2a), with a slightly higher RMSE at Little Southwest Miramichi River (all years, 1.52 °C; Figure 5.2b). Nonetheless, this model showed the overall best results among all models. This is most likely attributable to the fact that the equilibrium temperature represented the heat exchange processes of these two thermally different rivers well. Fewer uncertainties related to parameter estimation may also have contributed to the good performance of this model. It was noted that this model showed the best results, lowest RMSE, during the calibration period among all models (Catamaran Brook, calibration, 1.10 °C; Figure 5.2a). However, the added uncertainties between the calibration and validation period were higher for the equilibrium temperature model at Catamaran Brook (0.21°C) than for other models.

The stochastic model performed especially well at Catamaran Brook (all years, 1.26 °C, 1992-99; Figure 5.2), while showing poorer performance in the Little Southwest Miramichi River (all years, 1.61 °C; 1992-99). Results of the stochastic model were similar to those of the equilibrium temperature model, but different than the deterministic model at Catamaran Brook. The stochastic model may lack some generality (i.e. robustness). This was most noticeable at the Little Southwest Miramichi River where the RMSE was 1.35 °C during the calibration period to 1.74 °C during the validation period, i.e. an added uncertainty of 0.39 °C and the highest among models. In fact, this model showed the best modelling performance during the calibration to the worst modelling performance during the validation period for the Little Southwest Miramichi River (Figure 5.2b). Stochastic models consider few parameters in the modelling, and this may result in an overall good fit during the calibration period, which could not be reproduced during the validation period.

The energy reference model showed better results at Catamaran Brook (all years, 1.40 °C; Figure 5.2a) than for the Little Southwest Miramichi River (all years, 1.58 °C; Figure 5.2b), although comparable. These RMSEs are close to the average RMSEs of other models for each river. The energy reference model showed practically no improvement between the calibration and the validation periods, which suggests that this model has very little flexibility in fitting the water temperature time series (i.e., being too "rigid"). The energy reference model seemed to be in opposition with stochastic models in term of generalisation. For instance, while the stochastic model seemed to lack generalization (reflected by the difference in RMSE between the calibration and validation period), the energy reference model seemed to be too "rigid" in term of modelling water temperatures.

Results from the present study suggest that robustness of water temperature models is most likely linked to their nature (e.g. deterministic, stochastic, etc). For instance, stochastic and equilibrium temperature models may tend to fit data very well during the calibration period; however, their relative performance during the validation period was not as good. Alternatively, deterministic models may not be as efficient in fitting data during the calibration period; however, their predictions during the validation period remained equally good as during the calibration period. The energy reference model may be too "rigid" and it is potentially dominated by the annual component, therefore showed practically no difference in RMSEs between the calibration and validation periods.

When comparing the Nash coefficient among the different models, results showed that the NTDs were generally higher for the Little Southwest Miramichi River, even when

RMSEs were very close between the two river systems (Tables 4.7 to 4.10). This is reflective of the fact that the Nash coefficient is a function of the mean water temperatures and for similar RMSEs, the Nash coefficient will be slightly higher for warmer rivers. This was the case at the Little Southwest Miramichi River where temperatures were higher than those of Catamaran Brook. This was most evident for the deterministic model where RMSEs were very similar among rivers (1.58 °C Catamaran Brook vs. 1.53 °C Little Southwest Miramichi River; Table 4.7a) and yet the Nash coefficient was higher for the Little Southwest Miramichi River (0.944 vs. 0.918). As such and because the Nash coefficient is influenced by the overall average water temperature, it informs about the relative performance of the model while the RMSE is more of an absolute index.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RESEARCH RECOMENDATIONS

6.1 Summary

Although river water temperatures are highly dependant on many factors (e.g., climate, location, stream size, streamside vegetation, etc.), many of the current water temperature models are based on an air / water temperature relationship or they use an energy budget approach for modelling purposes. In addition, in a particular study, the choice of a water temperature model may also be dependent on data availability, the cost of model development and the type of problem under investigation, rather than strictly on modelling performances. The present study showed that it was possible to effectively model river water temperatures for two thermally different river systems, namely Catamaran Brook and the Little Southwest Miramichi River, within a similar meteorological area. This was done through the application of four different types of water temperature models with varying complexity, approaches and data requirements. These models included: 1) a deterministic model, 2) a water temperature model based on the equilibrium temperature, 3) a stochastic model, and 4) an energy reference model. All models performed relatively well with predicted water temperatures differing by less than 1.5 °C of actual measurements on a daily basis. Unlike previous modelling studies, which were mostly carried out over a few seasons to a few years, the present study used 8 years of data, of which 3 years were used for model calibration and 5 years were used for model validation (i.e., as an independent data set).

6.2 Conclusions

Based on the present investigation, it was concluded that all 4 models performed relatively well in the modelling of river water temperatures with overall RMSEs ranging from 1.26 °C to 1.61 °C. However, differences were noted in the modelling approaches based on data requirement, model concept, as well as modelling performance under different hydrometeorological conditions. Long-term data on water temperatures showed that the heat flux at the water surface was most likely dependent on at-river climatic conditions, of which solar radiation played an important role. This was most noticeable in the Little Southwest Miramichi River, where long-term water temperatures were higher than corresponding long-term air temperatures. On a monthly basis, peak water temperatures in both Catamaran Brook and the Little Southwest Miramichi River were found to be influenced not only by meteorological conditions but also by discharge. It was concluded based on long-term data, that the greatest difference in water temperatures between the two studied rivers was observed at peak summer water temperatures, i.e., end of July during maximum temperatures of the annual cycle (i.e., annual component). For Catamaran Brook and the Little Southwest Miramichi River, this difference represented 5.1 °C during summer peak water temperatures, while practically no difference existed between them in early spring and late autumn.

Slightly higher RMSE's were calculated for Catamaran Brook using the deterministic model compared to other models. Conversely, the Little Southwest Miramichi River showed among the lowest RMSE using the deterministic model. The deterministic model should provide more accurate modelling results than other models because it is physically based. It was concluded that the poorer performance of the deterministic model at Catamaran Brook was partially attributable to a less effective representation of the total heat flux, as this river was more sheltered by upland slopes and riparian vegetation. These geomorphologic conditions arguably resulted in different microclimatic conditions at the stream level than those observed upland at the meteorological station. Other sources of uncertainty could include the influence of groundwater thermal effects, estimates of solar radiation reaching the stream and other local factors. Alternatively, it was concluded that the relatively good performance of the deterministic model in the Little Southwest Miramichi River was attributable to this river being more exposed to ambient meteorological conditions and therefore the total heat flux was better captured by considering energy components.

As noted in previous studies, the net incoming solar radiation dominated the heat flux component of the deterministic model. Other heat fluxes, such as the net long-wave radiation and the evaporative heat flux, were relatively similar in magnitude and comparable to other studies as well. The sensible heat component (convective heat transfer) was the smallest component on average; however, as pointed out in other studies, it remains very important in the overall temperature variability. This study looked at the impact of using different sources of relative humidity data on the overall modelling of water temperatures. Although the relative humidity is an important variable in deterministic models, it was concluded based on present results that the increased RMSE when using other sources of data (e.g., mean value for relative humidity and/or Miramichi Airport data) was low and generally less than 0.09 °C for both rivers.

A newly developed equation to express the equilibrium temperature (T_e) showed that this variable was mainly a function of solar radiation, air temperature and dew point temperature. It was concluded that T_e was predominantly influenced by solar radiation (H_{si}) at very low wind velocity and that for more general wind speed conditions, the air and dew point temperatures dominated the equilibrium temperature. This constituted the basis of the equilibrium temperature model, wherein the equilibrium temperature was simplified as a function of air temperature. The equilibrium temperature was then used in the modelling of river water temperatures for both Catamaran Brook and the Little Southwest Miramichi River.

The equilibrium temperature model showed the overall best results among all the models studied. This was most likely attributable to the fact that the equilibrium temperature model is a relatively simple model with fewer input parameters than the deterministic model (i.e., fewer uncertainties related to the estimation of parameters) comprising deterministically based equations. The overall good performance of this model for both rivers suggests that the total heat flux was well represented by the equilibrium temperature.

In the application of the stochastic model, previous studies had hypothesised that rivers within similar meteorological conditions should also have similar autocorrelation coefficients. The calculated autocorrelation coefficients of the short-term components were almost identical between Catamaran Brook and the Little Southwest Miramichi River, which confirms these previous observations. Also, present results showed that the RMSEs using the stochastic model were in the range of 1.2 - 1.6 °C, comparable to values reported in the literature. The stochastic model performed well at Catamaran Brook, however this model showed slightly poorer performance in the Little Southwest Miramichi River, especially during the validation period. For instance, the RMSE in the Little Southwest Miramichi River was the lowest (best) for all models during the calibration period, whereas the RMSE was the highest (worst) during the validation period. It was concluded from these results that stochastic models can lack some generality (i.e. robustness) because they consider only air temperature as the input parameter. This lack of generality in modelling tends to result in a better overall fit of data during the calibration period and a worse fit of data during the validation period compared to other models.

The energy reference model showed overall comparable results to other models in the present study. However, the energy reference model showed practically no improvement between the calibration and the validation period, which suggests that this model may be too "rigid" in fitting water temperatures. Another aspect which suggests that this model may be too "rigid" is the fact that it did not reproduce the water temperature variability as well as other models, particularly in Catamaran Brook. This difficulty in capturing the water temperature variability by the energy reference model suggests that it was dominated by the annual component over the short-term component.

When looking at inter and intra annual performances, a few patterns emerge from the application of the different water temperature models. For instance, early spring water temperatures tended to be slightly overestimated with most models, more so during some years than others. It was concluded that this overestimation of water temperatures in early spring was attributable to snowmelt influences as well as higher stream discharge (i.e., greater thermal inertia). For instance, these factors (snowmelt and high discharge) were present during the spring of 1997, which was a late spring year. In contrast, the spring of 1999 was earlier than normal, and all models performed generally better during that spring. It was also concluded that late summer water temperature predictions were consistently among the best for all models, presumably due to low water conditions and a more efficient thermal exchange during that time of year.

This study showed that the Nash coefficient (NTD) was generally higher for the Little Southwest Miramichi River, even when RMSEs were very similar for the two river systems. This was attributed to the fact that the Nash coefficient is a function of the mean water temperature and that warmer rivers will ultimately result in slightly higher NTD. As such, it was concluded that the Nash coefficient is a better indicator of the relative performance of models for a specific river. Alternatively, the RMSE, which is only a function of water temperature errors, is better adapted as an absolute index and in the comparison of modelling performances among different rivers.

Finally, results of the present study suggest that robustness and performances of water temperature models was most likely linked to their nature (e.g. statistical vs. deterministic). For instance, the stochastic model tended to fit data very well during the calibration period; however, its performance during validation period generally resulted in higher RMSEs. Alternatively, the deterministic model performed better on the river more exposed to meteorological conditions (e.g., the Little Southwest Miramichi River), which suggests that the climate station data may have been more representative of at river conditions for this river. The energy reference model showed some evidence of being too "rigid" and potentially dominated by the annual component. The equilibrium temperature model provided the best overall results for the study area due to the equilibrium temperature which accurately represented the bulk energy at the water surface.

The advantages and disadvantages of each of the four models tested in the present investigation are summarised in Table 6.1. Input data requirements for each model are also listed in Table 6.1, which should be helpful in choosing a particular model for a specific application. In general, the choice of a particular model is a function of the modelling objectives and data requirement. For instance, the deterministic model is best adapted for the quantification of energy components and their relative contribution and impact on the thermal regime of rivers. This modelling approach is also the most suitable for impact studies dealing with the mixing of waters of different temperatures (e.g., thermal effluent, impact of tributaries, etc.). Alternatively, the equilibrium temperature model may be better adapted in water temperature studies where river discharge is an important parameter and where air temperature is the only weather data available for the study. Stochastic model are most useful in studies where air temperature data are the only data available for the modelling of water temperatures. The energy reference model would be most useful in rivers where most meteorological data are available and where this model would perform better than other models.

6.3 Research recommendations

Based on results of the present study and available literature information, the following research recommendations are suggested for future investigations of water temperature models. The first research recommendation pertains to the predictions of water

Table 6.1 Comparison of advantages, disadvantages and data requirement of the four different types of water temperature models applied in the present study.

Type of Model	Advantages	Disadvantages	Data Requirements
Deterministic Model	- Adapted to impact studies - Quantification of energy components - Conceptual model	- Numerous input parameters - Costly in development and application	- High
Equilibrium Temperature Model	- Simple model - Conceptually based - Few input parameters	- Semi-empirical - Not well adapted to impact studies	- Low
Stochastic Model	- Simple in application - Requires only air temperature as the input parameter - Consideration of the annual component	- Not well adapted to impact studies - Based on statistics rather than physical processes	- Low
Energy Reference Model	- Conceptually based - Consideration of the annual component	- Too "rigid", not reproducing water temperature variability as well - Highly dominated by the annual component	- High

temperature during early spring conditions where discharge is relatively high and snowmelt may still be an important factor in determining river thermal condition. Further research should be conducted at this time of year to determine important factors in the water temperature variability, and which energy component dominates the total heat flux. To conduct such an analysis, good snowmelt data would be needed as well as at-river solar input. At-river solar radiation monitoring would be especially important this time of year because the forest cover is generally not fully developed. Moreover, as the forest cover develops in May, this additional data would provide valuable information on changes over time in the amount of net incoming solar radiation reaching the stream. Changes over time in solar radiation could be especially significant in smaller streams.

The second research recommendation pertains to at-river meteorological conditions (or microclimatic data) vs. those collected from upland meteorological stations. It is clear from the literature dealing with forest harvesting and its impact on the thermal regime of rivers, that streamside riparian vegetation plays an important role in the amount of total net short-wave radiation (i.e., solar radiation) reaching the stream. In particular, most studies attribute increases in river water temperatures to the increase in solar radiation received. However, what remains largely unclear in the literature is the role that microclimatic conditions (at-steam conditions) play on the overall thermal exchange. For instance, studies have shown that microclimatic conditions are very different at the stream level compared to the interior forest or within clearcut areas (Brosofske et al. 1997; Dong et al. 1998). It is expected that at-stream microclimatic conditions would not be as different from those at an upland meteorological station in a larger system (e.g. Little Southwest Miramichi River) because they are more open and exposed to atmospheric conditions. Therefore, for larger rivers, upland meteorological conditions (such as those used in most modelling studies including the present study) would accurately represent at-stream conditions. Alternatively, when streams become smaller, it is postulated that microclimatic conditions or influences may be different than those experienced at an upland meteorological station. These at-river conditions may play an important role in the river thermal regime and heat exchange processes. For instance, most forestry related studies have shown that at-stream solar radiation and wind speed is highly reduced in small streams compared to more exposed conditions. More recent studies are showing that other parameters such as air temperature and relative humidity could also be very different from upland conditions (Brosofske et al. 1997). To effectively address these microclimatic issues, the collection of good at-stream meteorological data for different sizes of river in addition to that from a proximate upland meteorological station would be required.

The third research recommendation pertains to the quantification of heat exchange at the air / water surface interface vs. the sediment / water interface. Most models neglect the heat flux at the sediment / water interface (streambed heat flux) because for large rivers the heat flux at the air / water surface interface tends to dominate over the streambed heat flux. The streambed heat flux is largely a function of diffusive heat from the streambed and advective heat transfer through groundwater input. A few studies have addressed streambed heat flux (Comer and Grenney 1977; Hondzo and Stefan 1994), however much uncertainty remains relative to the significance of its contribution as either a function of stream size or modelling time scale (hourly, daily, etc). For instance, studies have shown that the streambed heat flux can usually be neglected when conducting modelling studies on a daily or longer time step (Sinokrot and Stefan 1994). However, wind speed and solar radiation are those parameters, which are most significantly reduced in small and well sheltered streams. Moreover, it is accepted that small streams are generally proportionally richer in groundwater, therefore potentially important fluxes could be coming from the streambed. Under these small stream conditions, it can be hypothesised that the heat flux at the surface may not dominate over that from the streambed. To address this, the heat flux at both the air / water surface interface and at water / sediment interface should be quantified and compared. To effectively quantify the streambed heat flux, groundwater input would need to be monitored using seepage meters (Lee and Cherry 1978), and water temperature gradients within the streambed (temperatures at different depths) would also needed to be measured.

In summary, these few research recommendations would help address current shortcomings in water temperatures modelling as well as provide a better understanding of physical processes responsible for the thermal exchange in rivers. In conclusion, much has been learned about the thermal exchange of larger river systems and their modelling. Future research should also focus on small streams as they also constitute an important component of the river ecosystem.

REFERENCES

Alderdice, D.F., and F.P.J. Velsen. 1978. ***Relation between temperature and incubation time for eggs of Chinook salmon (Oncorhynchus tshawytscha).*** Journal of the Fisheries Research Board of Canada 35: 69-75.

Alexander, M.D., and D. Caissie. 2003. ***Variability and comparison of hyporheic water temperatures and seepage fluxes in a small Atlantic salmon stream***. Ground Water 41(1): 72-82.

Alexander, M.D., K.T.B. MacQuarrie, D. Caissie and K.E. Butler. 2003. ***The thermal regime of shallow groundwater and a small Atlantic salmon stream bordering a clearcut with a forested streamside buffer***. *In:* Annual Conference of the Canadian Society for Civil Eningeering, Moncton, NB, June 4-7, 2003, GCL-343, 10p.

American Society of Civil Engineers. 1990. ***Evaporation and irrigation water requirements***. M.E. Jensen, R.D. Burman and R.G. Allen [ed.], ASCE Manuals and Reports on Engineering Practice No. 70, 332p.

Arscott, D.B., K. Tockner and J.V. Ward. 2001. ***Thermal heterogeneity along a braided floodplain river (Tagliamento River, northeastern Italy).*** Canadian Journal of Fisheries and Aquatic Sciences 58: 2359-2373.

Bartholow, J.M. 1989. ***Stream temperature investigations: field and analytic methods***. Instream Flow Information Paper No. 13, U.S. Fish Wildl. Serv. Biol. Rep. 89 (17). 139p.

Bartholow, J.M. 1991. ***A modeling assessment of the thermal regime for an urban sport fishery***. Environmental Management 15 (6): 833-845.

Bartholow, J.M. 2000. ***Estimating cumulative effects of clearcutting on stream temperatures***. Rivers 7 (4): 284-297.

Beer, W.N., and J.J. Anderson. 2001. ***Effect of spawning day and temperature on salmon emergence: interpretations of a growth model for Methow River chinook.*** Canadian Journal of Fisheries and Aquatic Sciences 58: 953-949.

Beschta, R.L., R.E. Bilby, G.W. Brown, L.B. Holtby and T.D. Hofstra. 1987. ***Stream temperature and aquatic habitat: fisheries and forestry interactions***. *In:* E.O. Salo and T.W. Cundy [ed.], Streamside management: Forestry and fishery interactions. University of Washington, Institute of Forest Resources, Contribution No. 57, pp.191-232.

Beschta, R.L., and R.L. Taylor. 1988. ***Stream temperature increases and land use in a forested Oregon watershed.*** Water Resources Bulletin 24 (1): 19-25.

Beschta, R.L. 1997. ***Riparian shade and stream temperature: an alternative perspective***. Rangelands 19: 25-28.

Bjornin, J.R. and Reiser, D.W. 1991. ***Habitat Requirements of Salmonids in Streams***. *In:* W.R. Meehan [ed.], Influence of Forest and Rangeland Management on Salmonids Fishes and Habitats, American Fisheries Society, Special Publication 19: 83-138.

Bormans, M., and I.T. Webster. 1998. ***Dynamics of temperature stratification in lowland rivers***. ASCE, Journal of Hydraulic Engineering 124(10): 1059-1063.

Boutin, C., J.P. Albignat and H. Isaka. 1981. ***Sur l'utilisation de la température d'équilibre pour l'établissement du bilan thermique d'un plan d'eau***. Hydrological Sciences Bulletin 26 (2): 159-171.

Bowen, I.S. 1926. ***The ratio of heat losses by conduction and by evaporation for any water surface***. Phys. Rev. 27: 316-355.

Box, G.E.P., and G.M. Jenkins. 1976. ***Time series analysis, forecasting and control.*** Enders Robinson, Holden-Day Inc., San Francisco, Calif.

Bradley, A.A., R.J. Jr. Holly, W.K. Walker and S.A. Wright. 1998. ***Estimation of water temperature exceedance probabilities using thermo-hydrodynamic modeling***. Journal of the American Water Resources Association 34 (3): 467-480.

Bravo, H.R., W.F. Krajewski, F.M. Holly. 1993. ***State space model for river temperature prediction***. Water Resources Research 29 (5): 1457-1466.

Brocard, D.N. and D.R.F. Harleman. 1976. ***One-dimensional temperature predictions in unsteady flows***. ASCE, Journal of the Hydraulics Division HY3: 227-240.

Brosofske, K.D., J. Chen, R.J. Naiman and J.F. Franklin. 1997. ***Harvesting effects on microclimatic gradients from small streams to uplands in western Washington***. Ecological Application 7 (4): 1188-1200.

Brown, G.W. 1969. ***Predicting temperatures of small streams.*** Water Resources Research 5 (1): 68-75.

Brown, G.W. 1970. ***Predicting the effect of clearcutting on stream temperature***. Journal of Soil and Water Conservation, Jan-Feb, pp.11-13.

Brown R.T., and A. Huber. 1998. ***Hourly water temperature modeling of the Guadalupe River, California***. *In*: Proceedings of the 1998 International Water Resources Engineering Conference. Part 1. ASCE, Reston, VA, USA, pp.684-689.

Brown, G.W., and J.T. Krygier. 1967. ***Changing water temperatures in small mountain streams.*** Journal of Soil and Water Conservation 22: 242-244.

Brown, G.W., and J.T. Krygier. 1970. ***Effects of clear-cutting on stream temperature***. Water Resources Research 6 (4):1133-1139.

Burton, T.M. and G.E. Likens. 1973. ***The effects of stripe cutting on stream temperatures in the Hubbard Brook Experimental Forest, New Hampshire.*** BioScience 23: 433-435.

Caissie, D. and N. El-Jabi. 1995. ***Hydrology of the Miramichi River drainage basin***. p.83-93. *In* E.M.P. Chadwick [ed.] Water, science, and the public: the Miramichi ecosystem. Can. Spec. Publ. Fish. Aquat. Sci. 123.

Caissie, D., N. El-Jabi and A. St-Hilaire. 1998. ***Stochastic Modelling of Water Temperature in a Small Stream Using Air to Water Relations***. Canadian Journal of Civil Engineering 25: 250-260.

Caissie, D. 2000. ***Hydrological Conditions for Atlantic Salmon Rivers in 1999.*** Canadian Stock Assessment Secretariat, Research Document 2000/011, 29p.

Caissie, D., N. El-Jabi and M.G. Satish. 2001. ***Modelling of maximum daily water temperatures in a small stream using air temperatures***. Journal of Hydrology 251: 14-28.

Caissie, D., T.L. Pollock and R.A. Cunjak. 1996. ***Variation in stream water chemistry and hydrograph separation in a small drainage basin***. Journal of Hydrology 178: 137-157.

Caissie, D. and M.G. Satish. 2001. ***Modelling water temperatures at depths within the stream substrate of Catamaran Brook (NB): potential implication of climate change***. Canadian Technical Report of Fisheries and Aquatic Sciences 2365: 27p.

Caissie, D., A. St-Hilaire, N. El-Jabi and G. Morin. 1997. ***Water temperature modelling: comparison between stochastic and deterministic approaches***. In: Annual Conference of the Canadian Society for Civil Engineering, Sherbrooke, Québec, May 27-30, 1997, pp.119-128.

Chaudhry, M.H., D.E. Cass and J.E. Edinger. 1983. ***Modeling of unstready-flow water temperatures***. ASCE, Journal of Hydraulic Engineering 109 (5): 657-669.

Chen, J., J.F. Frankin and T.A. Spies. 1995. ***Growing-season microclimatic gradients from clearcut edges into old-growth Douglas-fir forests***. Ecological Applications 5 (1): 74-86.

Chen, Y.D., R.F. Carsel, S.C. McCutcheon and W.L. Nutter. 1998a. ***Stream temperature simulation of forested riparian areas: 1. Watershed-scale model development.*** ASCE, Journal of Environmental Engineering 124 (4): 304-315.

Chen, Y.D., S.C. McCutcheon D.J. Norton and W.L. Nutter. 1998b. ***Stream temperature simulation of forested riparian areas: 2. Model application***. ASCE, Journal of Environmental Engineering 124 (4): 316-328.

Chiu, C.-L. and E.O. Isu. 1978. ***Stream temperature estimation using Kalman filter***. ASCE, Journal of the Hydraulics Division 104 (HY9): 1257-1268.

Chow, V.T., D.R. Maidment and L.W. Mays. 1988. ***Applied hydrology***. McGraw-Hill, 572p.

Clark, E., B.W. Webb and M. Ladle. 1999. ***Microthermal gradients and ecological implications in Dorset rivers***. Hydrological Processes 13: 423-438.

Cluis, D.A. 1972. ***Relationship between stream water temperature and ambient air temperature - A simple autoregressive model for mean daily stream water temperature fluctuations***. Nordic Hydrology, 3 (2):65-71.

Combs, B.D. 1965. ***Effect of temperature on the development of salmon eggs***. Prog. Fish-Cult. 27: 134-137.

Combs, B.D., and R.E. Burrows. 1957. ***Threshold temperatures for the normal development of Chinook salmon eggs***. Prog. Fish-Cult. 19: 3-6

Comer, L.E., and W.J. Grenney. 1977. ***Heat transfer processes in the bed of a small stream.*** Wat. Res. 11: 743-744.

Cooter, E.J., and W.S. Cooter. 1990. ***Impacts of greenhouse warming on water temperature and water quality in the southern United States***. Climate Res. 1: 1-12.

Coutant. C.C. 1977. ***Compilation of temperature preference data***. Journal of the Fisheries Research Board of Canada 34: 739-745.

Coutant, C.C. 1999. ***Persprective on temperature in the Pacific Northwest's fresh water***. Environmental Scienes Division, Publication No. 4849, Oak Rige National Laboratory, ORNL/TM-1999/44, 109p.

Cox, T.J., and J.C. Rutherford. 2000a. ***Thermal tolerances of two stream invertebrates exposed to diurnally varying temperature***. New Zealand Journal of Marine and Freshwater Research 34: 203-208.

Cox, T.J. and J.C. Rutherford. 2000b. ***Predicting the effects of time-varying temperatures on stream invertebrates mortality***. New Zealand Journal of Marine and Freshwater Research 34: 209-215.

Crisp, D.T., and G. Howson. 1982. ***Effect of air temperature upon mean water temperature in streams in the north Pennines and English Lake District***. Freshwater Biology 12: 359-367.

Crisp, D.T. 1990a. ***Water temperature in a stream gravel bed and implication for salmonid incubation***, Freshwater Biology 23: 601-612.

Crisp. D.T. 1990b. ***Simplified methods of estimating daily mean stream water temperature***. Freshwater Biology 23: 457-462.

Cunjak, R.A., D. Caissie and N. El-Jabi, 1990. ***The Catamaran Brook Habitat Research Project: description and general design of study***. Canadian Technical Report of Fisheries and Aquatic Sciences 1751: 14p.

Cunjak, R.A., D. Caissie, N. El-Jabi, P. Hardie, J.H. Conlon, T.L. Pollock, D.J. Giberson and S. Komadina-Douthwright. 1993. ***The Catamaran Brook (New Brunswick) Habitat Research Project: Biological, Physical and Chemical Conditions (1990-1992).*** Canadian Technical Report of Fisheries and Aquatic Sciences 1914: 81 p.

Cunjak, R.A., and G. Power, 1986. ***Winter habitat utilization by stream resident brook trout (Salvelinus fontinalis) and brown trout (Salmo trutta)***, Canadian Journal of Fisheries and Aquatic Sciences 43: 1970-1981.

Cunjak, R.A. 1988. ***Behaviour and microhabitat of young Atlantic salmon (salmo salar) during winter***, Canadian Journal of Fisheries and Aquatic Sciences 45: 2156-2160.

Dake, J.M.K. 1972. ***Evaporative cooling of a body of water***. Water Resources Research 8 (4): 1087-1091.

Dingman, S.L. 1972. ***Equilibrium temperatures of water surfaces as related to air temperature and solar radiation***. Water Resources Research 8 (1): 42-49.

Dingman, S.L. 2002. ***Physical Hydrology***. Prentice-Hall Inc. Upper Saddle, New Jersey, 646p.

Dong, J., J. Chen, K.D. Brosofske and R.J. Naiman. 1998. ***Modelling air temperature gradients across managed small streams in western Washington***. Journal of Environmental Management 53 (4): 309-321.

Duttweiler, D.W. 1963. ***A mathematical model of stream temperature***. Ph.D. thesis, John Hopkins University, Baltimore, Maryland, 139p.

Dymond, J. 1984. ***Water temperature change caused by abstraction***. ASCE, Journal of hydraulic engineering 110 (7): 987-991.

Eaton, J.G., J.H. McCormick, H.G. Stefan and M. Hondzo. 1995. ***Extreme value analysis of a fish/temperature field database***, Ecological Engineering, 4 (4): 289-305.

Ebersole, J.L., W.J. Liss, and C.A. Frissell. 2001. ***Relationship between stream temperature, thermal refugia and rainbow trout Oncorhynchus mykiss abundance in arid-land streams in the northwestern United States***. Ecology of Freshwater Fish 10 (1): 1-10.

Edinger, J.E., D.W. Duttweiler and J.C. Geyer. 1968. ***The reponse of water temperatures to meteorological conditions***. Water Resources Reserarch 4 (5): 1137-1143.

Edwards, R.W., J.W. Densen and P.A. Russell. 1979. ***An assessment of the importance of temperature as a factor controlling the growth rate of brown trout in streams***, Journal of Animal Ecology 48: 501-507.

El-Jabi, N., G. El-Kourdahi and D. Caissie. 1995. ***Modélisation stochastique de la température de l'eau en rivière***. Revue des sciences de l'eau 8: 77-95.

Elliott, J. M., and M. A. Hurley. 1997. ***A functional model for maximum growth of Atlantic salmon parr, Salmo salar, from two populations in northwest England***. Functional Ecology 11:592-603.

Erickson, T.R., and H.G. Stefan. 2000. ***Linear air/water temperature correlations for streams during open water periods***, ASCE, Journal of Hydrologic Engineering 5 (3): 317-321.

Evans, E.C., M.T. Greenwood and G.E. Petts. 1995. ***Short communication thermal profiles within river beds***. Hydrological Processes 9: 19-25.

Feller, M.C., 1981. ***Effects of clearcutting and slashburning on stream chemistry in southwestern British Columbia.*** Water Resources Bulletin 17: 863-867.

Foreman, M.G.G., C.B. James, M.C. Quick, P. Hollemans and E. Wiebe. 1997. ***Flow and temperature models for the Fraser and Thompson Rivers***. Atmosphere-Ocean 35 (1): 109-134.

Foreman, M.G.G., D.K. Lee, J. Morrison, S. MacDonald, D. Barnes and I.V. Williams. 2001. ***Simulation and retrospective analyses of Fraser watershed flows and temperatures***. Atmosphere-Oceans 39 (2): 89-105.

Garside, E.T. 1969. ***The upper lethal temperature and thermal resistance of parr of Atlantic salmon (Salmo salar L) in Terra Nova National Park, Newfoundland.*** Canadian Wildlife Service, Ottawa, Canada,10p.

Garside, E.T. 1973. ***Ultimate upper lethal temperature of Atlantic salmon (Salmo salar L.)***, Canadian Journal of Zoology 51: 898-900.

Gilbert, A., R. Gras and D. Roult. 1986. ***Numerical computation of natural river temperatures***. *In*: Internation Conference on Water Quality Modelling in the Inland Natural Environment, Bournemouth, England, 10-13 June 1986, pp. 457-471.

Gillett, B.E., and L.L. Long. 1974. ***Statistical analysis of water temperature residuals.*** Water Resources Research 10 (6): 1127-1132.

Grant, P.J. 1977. ***Water temperatures of the Ngaruroro River at three stations***. Journal of Hydrology (New Zealand). 16 (2) : 148-157.

Gray, J.R.A. and J.M. Edington. 1969. ***Effect of woodland clearance on stream temperature***. Journal of the Fisheries Research Board of Canada 26: 399-403.

Gu, R., S. Montgomery and T. Al Austin. 1998. ***Quantifying the effects of stream discharge on summer river Temperature***, Hydrological Sciences Journal 43 (6): 885-904.

Hammar, L., and H.T. Shen. 1995. ***Frazil evolution in channels***. Journal of Hydraulic Research 33 (3): 291-306.

Hartman, G.F., and R.M. Leahy. 1983. ***Some temperature characteristics of stream and intra-gravel water in Carnation Creek, British Columbia***. Can. Man. Rep. Fish. Aquati. Sci. 1731: 36p.

Hawkins, C.P., J.N. Nogue, L.M. Decker and J.W. Feminella. 1997. ***Channel morphology, water temperature, and assemblage structure of stream insects***. Journal of the North American Benthological Society 16 (4): 728-749.

Hembre, B., J.V. Arnekleiv and J.H. L'Abée-Lund. 2001. ***Effects of water discharge and temperature on the seaward migration of anadromous brown trout, Salmo trutta, smotls***. Ecology of Freshwater Fish 10: 61-64.

Hewlett, J.D., and J.C. Fortson. 1982. ***Stream temperature under an inadequate buffer strip in the southeast Piedmont.*** Water Resources Bulletin 18 (6): 983-988.

Hills, R.G., and R. Viskanta. 1976. ***Modeling of unsteady temperature distribution in rivers with thermal discharges***. Water Resources Research 12 (4) : 712-722.

Hockey, J.B., I.F. Owens and N.J. Tapper. 1982. ***Empirical and theoretical models to isolate the effect of discharge on summer water temperatures in the Hurunui River***. Journal of Hydrology (New Zealand) 21: 1-12.

Hoff, C. 1983. ***A practical guide to Box-Jenkins forecasting***. Wadsworth Inc., Lifetime Learning Publication, Belmont, California.

Holtby, L.B. 1988a. ***The effects of logging on stream temperatures at Carnation Creek***. In: Applying 15 years of Carnation Creek results. T.W. Chamberlin [ed], Nanaimo, BC, pp.118-122.

Holtby, L.B. 1988b. ***Effects of logging on stream temperature in Carnation Creek, British Columbia, and associated impacts on the coho salmon (Oncorhynchus kisutch).*** Canadian Journal of Fisheries and Aquatic Sciences 45: 502-515.

Holtby, B., and C.P. Newcombe. 1982. ***A preliminary analysis of logging-related temperature changes in Carnation Creek, British Columbia***. In: Proceedings of the Carnation Creek Workshop, A 10 year Review, G. Hartman [ed], Nanaimo, BC, February 24-26, 1982, pp.81-99.

Hondzo, M., and H.G. Stefan. 1994. ***Riverbed heat conduction prediction***. Water Resources Research. 30 (5): 1503-1513.

Hopkins, C.L. 1971. ***The annual temperature regime of a small stream in New Zealand.*** Hydrobiologia 37 (3-4): 397-408

Hostetler. S.W. 1991. ***Analysis and modeling of long-term stream temperatures on the Steamboat Creek basin, Oregon: Implication for land use and fish habitat***. Water Resources Bulletin, 27 (4): 637-647.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, and D. Xiaosu. 2001. ***Climate Change 2001: The Scientific Basis***. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK.

Huntsman, A.G. 1942. ***Death of salmon and trout with high temperature***. Journal of the Fisheries Research Board of Canada 5 (5): 485-501.

Janssen, P.H.M., and P.S.C. Heuberger. 1995. ***Calibration of process-oriented models***, Ecological Modelling 83: 55-66.

Jensen, A. J., N. A. Hvidsten and B. O. Johnsen. 1998. ***Effects of temperature and flow on the upstream migration of adult salmon in two Norwegian Rivers.*** Pages 45-54 *in:* M. Jungwirth, S. Schmutz, and S. Weiss, [ed]. Fish migration and fish bypasses. Fishing News Books, Oxford.

Jeppesen, E., and T.M. Iversen. 1987. ***Two simple models for estimating daily mean water temperatures and diel variations in a Danish low gradient stream***. Oikos 49: 149-155.

Jobson, H.E. 1977. ***Bed conduction computation for thermal models***. ASCE, Journal of the Hydraulics Division 103 (HY10): 1213-1217.

Johnson, F.A., 1971. ***Stream temperatures in an alpine area***, Journal of Hydrology 14: 322-336.

Johnson, S.L., and J.A. Jones. 2000. ***Stream temperature response to forest harvest and debris flows in western Cascades, Oregon***. Canadian Journal of Fisheries and Aquatic Sciences 57 (suppl. 2): 30-39.

Johnston, T.A. 1997. ***Downstream movement of young-of-the-year fishes in Catamaran Brook and the Little Southwest Miramichi River, New Brunswick.*** Journal of Fish Biology 51: 1047-1062.

Jourdonnais, J.H, R.P. Walsh, F. Pickett and D. Goodman. 1992. ***Structure and calibration strategy for a water temperature model of the lower Madison River, Montana***. Rivers 3 (3): 153-169.

Kim, K.S. 1993. ***Development, application and analysis of the physical aspect of a water-quality modeling framework for highly transient streams***. Ph.D. thesis, University of Colorado, Boulder, Colorado, 187p.

Kim, K.S., and S.C. Chapra. 1997. ***Temperature model for highly transient shallow streams.*** ASCE, Journal of Hydraulic Engineering 123 (1): 30-40.

Kothandaraman, V. 1971. ***Analysis of Water Temperature Variations in Large Rivers***. ASCE, Journal of the Sanitary Engineering Division 97 (SA1): 19-31.

Kothandaraman, V. 1972. ***Air-Water Temperature Relationship in Illinois River***. Water Resources Bulletin 8 (1): 38-45.

Krajewski, W., A. Kraszewski and W. Grenney. 1982. ***A graphical technique for river water temperature predictions***. Ecological Modeling 17: 209-224.

Langan, S.J., L. Johnston, M.J. Donaghy, A.F. Youngson, D.W. Hay, and C. Soulsby. 2001. ***Variation in river water temperatures in an upland stream over a 30-year period***. The Science of the Total Environment 265: 195-207.

Lapham, W.W. 1989. ***Use of temperature profiles beneath streams to determine rates of vertical ground-water flow and vertical hydraulic conductivity.*** US Geological Survey Water-Supply Paper 2337, 35p.

Larson, L.L., and S.E. Larson. 1996. ***Riparian shade and stream temperature: a perspective***. Rangelands 18: 149-152.

LeBlanc, R.T., and R.D. Brown. 2000. ***The use of ripirian vegetation in stream-temperature modification***. Journal of the Chartered Institution of Water and Environmental Management 14, Aug. pp.297-303.

LeBlanc, R.T., R.D. Brown and J.E. FitzGibbon. 1997. ***Modeling the effects of land use change on the water temperature unregulated urban streams***. Journal of Environmental Management 49 (4): 445-469.

LeBosquet, M. 1946. ***Cooling water benefits from increased river flow***. J. N. England Wat. Wks. Assoc. 60: 111-116.

Lee, D.R., and J.A. Cherry. 1978. ***A field exercice on groundwater flow using seepage meters and mini-piezometers***. J. Geol. Educ. 27: 6-10.

Lee, R.M., and J.N. Rinne. 1980. ***Critical Thermal Maximum of Five Trout Species in the Southwestern United States***. Transaction of the American Fisheries Society 109 (6): 632-635.

Leopold, L.B., Wolman, M.G., Miller, J.P., 1964. ***Fluvial processes in geomorphology***. San Francisco, California, W.H. Freeman and Company, 522p.

Lowney, C.L. 2000. ***Stream temperature variation in regulated rivers: Evidence for a spatial pattern in daily minimum and maximum magnitudes***. Water Resources Research 36 (10): 2947-2955.

Lund, S.G., D. Caissie, R.A. Cunjak, M.M. Vijayan and B.L. Tufts. 2002. ***The effects of environmental heat stress on heat-shock mRNA and protein expression in Miramichi Atlantic salmon (Salmo salar) parr***. Canadian Journal of Fisheries and Aquatic Sciences 59: 1553-1562.

Lynch, J.A., G.A. Rishel and E.S. Corbett. 1984. ***Thermal alteration of streams draining clearcut watersheds: quantification and biological implications***. Hydrobiologia 111: 161-169.

Macan, T.T. 1958. ***The temperature of a small stony stream***. Hydrobiologia 12: 89-106.

Mackey, A.P., A.D. Berrie. 1991. ***The prediction of water temperatures in chalk streams from air temperatures***. Hydrobiologia 210: 183-189.

Malatre, K, and P. Gosse. 1995. ***Is it possible to influence water temperature and quality in the River Seine upstream of Paris in summer by managing the upstream reservoir?*** Water Science and Technology 31 (8): 67-77.

Marceau, P. 1984. ***Modèle stochastique de température de l'eau en rivière et comparaison avec un modèle déterministe***. Mémoire de maîtrise ès en sciences (eau), Institut national de la recherche scientifique, INRS-Eau, Université du Québec, 113p.

Marceau, P., D. Cluis and G. Morin. 1986. ***Comparaison des performances relatives à un modèle déterministe et à un modèle stochastique de température de l'eau en rivière***, Canadian Journal of Civil Engineering 13 (3): 352-364.

Marcotte, N., and V.-L. Duong. 1973. ***Le calcul de la température de l'eau des rivières.*** Journal of Hydrology 18: 273-287.

Markarian, R.K. 1980. ***A study of the relationship between aquatic insect growth and water temperature in a small stream***. Hydrobiologia 75: 81-95.

Marsh, P. 1990. ***Modelling water temperature beneath river ice covers***. Canadian Journal of Civil Engineering 17 (1): 36-44.

Meisner, J.D., J.S. Rosenfeld and H.A. Regier. 1988. ***The role of groundwater in the impact of climate warming on stream salmonies***. Fisheries 13 (3): 2-8.

Meisner, J.D. 1990a. ***Effect of climatic warming on the Southern margins of the native range of brook trout, Salvelinus fontinalis***. Canadian Journal of Fisheries and Aquatic Sciences 47: 1065-1070.

Meisner, JD. 1990b. ***Potential loss of thermal habitat for brook trout, due to climatic warming, in two southern Ontario streams***. Transaction of the American Fisheries Society 119: 282-291.

Minns, C.K., R.G. Randall, E.M.P. Chadwick, J.E. Moore, and R. Green. 1995. ***Potential impact of climate change on the habitat and production dynamics of juvenile Atlantic salmon (Salmo salar) in eastern Canada***. *In:* R.J. Beamish [ed.], Climate change and northern fish population, Can. Spec. Publ. Fish. Aquat. Sci. 121: 699-708.

Mitchell, S. 1999. ***A simple model for estimating mean monthly stream temperatures after riparian canopy removal***. Environmental Management 24 (1): 77-83.

Mitchell, C., C.B. James and J.E. Edinger. 1995. ***Analyses of flow modification on water quality in Nechako River***. Journal of Energy Engineering 121 (2): 73-80.

Mohseni, O., H.G. Stefan and T.R. Erickson. 1998. ***A nonlinear regression model for weekly stream temperatures***. Water Resources Research 34 (10): 2685-2692.

Mohseni, O., T.R. Erickson and H.G. Stefan. 1999. ***Sensitivity of stream temperatures in the United States to air temperatures projected under a global warming scenario***. Water Resources Research 35 (12): 3723-3733.

Mohseni, O., and H.G. Stefan. 1999. ***Stream temperature/air temperature relationship: a physical interpretation.*** Journal of Hydrology 218: 128-141.

Mohseni, O., and H.G. Stefan. 2001. ***Water budgets of two watersheds in different climatic zones under projected climate warming***. Climate Change 49 (1-2): 77-104.

Moore, M.V., M.L. Pace, J.R. Mather, P.S. Murdoch, R.W. Howarth, C.L. Flot, C.Y. Chen, H.F. Hemon, P.A. Flebbe and C.T. Driscoll. 1997. ***Potential effects of climate change on freshwater ecosystems of the New England / Mid-Atlantic Region***. Hydrological Processes 11 (8): 925-947.

Morin, G., D. Cluis, D. Couillard, H.G. Jones and J.M. Gauthier. 1983. ***Modélisation de la température à l'aide du modèle quantité-qualité CEQUEAU***. Rapport scientifique no 153. INRS-EAU, 103p.

Morin, G., D. Couillard, D. Cluis, H.G. Jones and J.-M. Gauthier. 1987. ***Prévision des températures de l'eau en rivière à l'aide d'un modèle conceptuel***. Journal of Hydrological Sciences 32: 31-41.

Morin, G., and D. Couillard. 1990. ***Predicting river temperatures with a hydrological model***, Chapter 5, Encyclopedia of Fluid Mechanic, Surface and Groundwater Flow Phenomena, Gulf Publishing Company, Houston, Texas, Vol. 10, pp.171-209.

Morin, G., T.-J. Nzakimuena and W. Sochanski. 1994. ***Prévision des températures de l'eau en rivières à l'aide d'un modèle conceptuel: le cas de la rivière Moisie***, Canadian Journal of Civil Engineering 21 (1):63-75.

Morrison, J., M.C. Quick and M.G.G. Foreman. 2002. ***Climate change in the Fraser River watershed: flow and temperature projections***. Journal of Hydrology 263: 230-244.

Morse , W. 1970. ***Stream Temperature Prediction Model***. Water Resource Research 6: 290-302.

Morse, W.L. 1972. ***Stream temperature prediction under reduced flow***. ASCE, Journal of the Hydraulics Division 98 (HY6): 1031-1047.

Morse, W.L. 1978. ***The dishonest method in stream temperature modeling***. Water Research Research 14 (1): 45-51.

Mosley, M.P. 1983. ***Variability of water temperatures in the braided Ashley and Rakaia rivers***. New Zealand Journal of Marine and Freshwater Research 17: 331-342.

Murray, G.L.D., R.L. Edmonds and J.L. Marra. 2000. ***Influence of partial harvesting on stream temperatures, chemistry, and turbidity in forests on the western Olympic Peninsula, Washington***. Northwest Science 74 (2): 151-164.

Myrick, C.A., and J.J. Cech. 2000. ***Swimming performances of four California stream fishes: temperature effects***. Environmental Biology of Fishes 58: 289-295.

Nash, J.E., and J.V. Sutcliffe. 1970. ***River flow forecasting through conceptual models part I – a discussion of principles***. Journal of Hydrology 10: 282-290.

Noble, R.D., and A.P. Jackman. 1979. ***Predicting the natural water temperature profile throughout a river basin***. J. Envrionmental System 9 (4): 361-381.

Novotny, V., and P.A. Krenkel. 1973. ***Simplified mathematical model of temperature changes in rivers***. Journal WPCF, 45 (2): 240-248.

Paily, P.P., and E.O. Macagno. 1976. ***Numerical prediction of thermal-regime of rivers***. ASCE, Journal of the Hydraulics Division 102 (HY3): 255-274.

Parks Canada. 1999. ***Climate change scenario, summer and winter temperatures***, 2090. Air Issues Bulletin No. 100, Air Quality, Climate Change and Canada's National Parks. Ottawa, Natural Resources Branch, Parks Canada.

Peterson, R.H., H.C. Spinney and A. Sreedharan. 1977. ***Development of Atlantic salmon (Salmo salar) eggs and alevins under varied temperature regimes***. Journal of the Fisheries Research Board of Canada 34: 31-43.

Pilgrim, J.M., X. Fang and H.G. Stefan. 1998. ***Stream temperature correlations with air temperature in Minnesota: implications for climatic warming***. Journal of the American Water Resources Association 34 (5): 1109-1121.

Poole, G.C., and C.H. Berman. 2001. ***An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation.*** Environmental Management 27 (6): 787-802.

Postel, S.L., G.C. Daily and P.R. Ehrlich. 1996. ***Human appropriation of renewable fresh water***. Science 271: 785-788.

Prowse, T.D., and J.M. Culp. 2003. ***Ice breakup: a neglected factor in river ecology***. Canadian Journal of Civil Engineering 30: 128-144.

Raphael, J.M. 1962. ***Prediction of Temperature in Rivers and Reservoirs***. ASCE, Journal of the Power Division 88 (PO2): 157-181.

Rinaldi, S., R. Soncini-Sessa, H. Stehfest and H. Tamura. 1979. ***Modeling and control of river quality***, McGraw-Hill Series in Water Resources and Environmental Engineering, 380p.

Ringler, N.H., and J.D. Hall. 1975. ***Effects of logging on water temperature and dissolved oxygen in spawning beds***. Transaction of the American Fisheries Society 104: 111-121.

Rishel, G.B., J.A. Lynch and E.S. Corbett. 1982. ***Seasonal stream temperature changes following forest harvesting***. Journal of Environmental Quality 11: 112-116.

Robinson, A.T., and M.R. Childs. 2001. ***Juvenile growth of native fishes in the Little Colorado River and in a thermally modified portion of the Colorado River***. North American Journal of Fisheries Management 21: 809-815.

Rutherford, J.C., S. Blackett, C. Blackett, L. Saito and R.J. Davies-Colley. 1997. ***Predicting the effects of shade on water temperature in small streams.*** New Zealand Journal of Marine and Freshwater Research 31 (5): 707-721.

Sado, K., 1983. ***Fundamental study on heat balance of river water***. Transactions of JSCE 15: 240-242.

Salas, J.D., J.W. Delleur, V. Yevjevich and E.L. Lane. 1980. ***Applied modelling of hydrological time series***. Water Resources Publication, Colorado, 484p.

Schindler, D.W. 2001. ***The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium***. Canadian Journal of Fisheries and Aquatic Sciences 58: 18-29.

Scrivener, J.C., and B.C. Andersen. 1984. ***Logging impacts and some mechanisms that determine the size of spring and summer population of coho salmon fry (Oncorhynchus kisutch) in Carnation Creek, British Columbia***. Canadian Journal of Fisheries and Aquatic Sciences 41: 1097-1105.

Shanley, J.B., and N.E. Peters. 1988. ***Preliminary observations of streamflow generation during storms in a forested piedmont watershed using temperature as a tracer***. Journal of Contaminant Hydrology 3: 349-365.

Shen, H.T., D.S. Wang and A.M. Wasantha Lal. 1995. ***Numerical simulation of river ice processes***. Journal of Cold Regions Engineering, ASCE, 9 (3): 107-118.

Shepherd, B.G., G.F. Hartman and W.J. Wilson. 1986. ***Relationships between stream and intragravel temperatures in coastal drainages, and some implications for fisheries workers***, Canadian Journal of Fisheries and Aquatic Sciences 43: 1818-1822.

Sinokrot, B.A., and H.G. Stefan. 1993. ***Stream temperature dynamics: Measurements and modeling***. Water Resources Research 29 (7): 2299-2312.

Sinokrot, B.A., and H.G. Stefan. 1994. ***Stream water temperature sensitivity to weather and bed parameters.*** ASCE, Journal of Hydraulic Engineering 120 (6): 722-736.

Sinokrot, B.A., H.G. Stefan, J.H. McCormick and J.G. Eaton. 1995. ***Modeling of climate change effects on stream temperatures and fish habitats below dams and near groundwater inputs***. Climatic Change 30 (2): 181-200.

Sinokrot, B.A., J.S. Gulliver and R. Gu. 1997. ***Impacts of instream flow requirements upon water temperature in the central Platte River.*** *In*: Proceedings of the International Conference on Hydropower – Waterpower, vol. 1 1997, ASCE, New York, NY, USA, pp.1-9.

Sinokrot, B.A., and J.S. Gulliver. 2000. ***In-stream flow impact on river water temperatures***. Journal of Hydraulic Research 38 (5): 339-349.

Smith, K. 1972. ***River water temperatures: an environmental review***. Scottish Geographical Magazine 88: 211-220.

Smith, K., M.E. Lavis. 1975. ***Environmental influences on the temperature of a small upland stream***. Oikos 26: 228-236.

Smith, K. 1975. ***Water temperature variations within a major river system***, Nordic Hydrology 6: 155-169.

Smith, K. 1981. ***The prediction of river water temperatures***, Hydrol. Sci. Bull.26: 19-32.

Smith, R.L., and W.J. Carswell Jr. 1984. ***Average annual fulfillment of instream uses***. Journal of Water Resources Planning and Management 110 (4): 497-510.

Song. C.C.S., A.F. Pabst and C.E. Bowers. 1973. ***Stochastic analysis of air and water temperatures***. J. Environ. Eng. Div. Am. Soc. Civ. Eng. 99: 785-800.

Song, C.C.S., and C.-Y. Chien. 1977. ***Stochastic properties of daily temperature in rivers***. ASCE, Journal of the Environmental Engineering Division 103 (2): 217-231.

Stefan, H.G., and E.B. Preud'homme. 1993. ***Stream temperature estimation from air temperature***. Water Resources Bulletin 29: 27-45.

Stefan, H.G., X. Fang and J.G. Eaton. 2001. ***Simulated fish habitat changes in North American lakes in response to projected climate warming***. Transactions of the American Fisheries Society 130 (3): 459-477.

St-Hilaire, A, G. Morin, N. El-Jabi and D. Caissie. 2000. ***Water temperature modelling in a small forested stream: implication of forest canopy and soil temperature***. Canadian Journal of Civil Engineering 27: 1095-1108.

Swansburg, E.O., G. Chaput, D. Moore, D. Caissie, N. El-Jabi. 2002. ***Size variability of juvenile Atlantic salmon: links to environmental conditions***. Journal of Fish Biology 61: 661-683.

Swift, L.W., and J.B. Messer. 1971. ***Forest cuttings raise temperatures of small streams in the southern Appalachians.*** J. Soil Water Conserv. 26: 111-116.

Tasker, G.D. and A.W. Burns. 1974. ***Mathematical generalization of stream temperature in central New England***. Water Resources Bulletin 10 (6): 1133-1142.

Theurer, F.D., K.A. Voos and W.J. Miller. 1984. ***Instream water temperature model.*** Instream Flow Information Paper 16, FWS/OBS-84/15. Fort Collins, Colorado, United States Fish and Wildlife Service.

Theurer, F.D., I. Lines and T. Nelson. 1985. ***Interaction between riparian vegetation, water temperature and salmonid habitat in the Tucannon River***. Water Resources Bulletin 21: 53-64.

Thomas, R.E., J.A. Gharrett, M.G. Carls, S.D. Rice, A. Moles and S. Korn. 1986 ***Effects of fluctuating temperature on mortality, stress, and energy reserves of juvenile coho salmon.*** Transaction of the American Fisheries Society 115: 52-59.

Torgersen, C.E., D.M. Price, H.W. Li and B.A McIntosh. 1999. ***Multiscale thermal refugia and stream habitat associations of Chinook salmon in Northeastern Oregon***. Ecological Applications 9 (1): 301-319.

Torgersen, C.E., R.N. Faux, B.A. McIntosh, N.J. Poage, D.J. Norton. 2001. ***Airborne thermal sensing for water temperature assessment in rivers and streams***. Remote Sensing of Environment 76: 386-398.

Troxler, R.W., and E.L. Thackston. 1977. ***Predicting the rate of warming of rivers below hydro-electric installations***. Journal of the Water Pollution Control Federation (August) pp.1902-1912.

Tsang, G. 1982. ***Frazil and anchor ice: a monograph***. National Research Council of Canada, Associate Committee on Hydrology, Subcommittee on Hydraulics of Ice Covered Rivers, 90p.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell and C.E. Cushing. 1980. ***The river continuum concept.*** Canadian Journal of Fisheries and Aquatic Sciences 37:130-137.

Vannote, R.L. and B.W. Sweeney. 1980. ***Geographic analysis of thermal equilibria: A conceptual model for evaluating the effects of natural and modified thermal regimes on aquatic insect communities***. American Naturalist 115 (5): 667-695.

Vugts, H.F. 1974. ***Calculation of temperature variations of small mountain streams***. Journal of Hydrology 23: 267-278.

Ward, J. 1963. ***Annual Variation of Stream Water Temperature***. ASCE, Journal of the Sanitary Engineering Division, 89 (SA6): 3710-3732.

Ward, J.V. 1985. ***Thermal characteristics of running waters***. Hydrobiologia 125: 31-46.

Webb, B.W. 1996. ***Trends in stream and water temperatures***. Hydrological Processes 10: 205-226.

Webb, B.W., and F. Nobilis. 1997. ***A long-term perspective on the nature of the air-water temperature relationship: a case study***. Hydrological Processes 11 (2): 137-147.

Webb, B.W., and D.E. Walling. 1986. ***Spatial variation of water temperature characteristics and behaviour in Devon river systems***. Freshwater Biology 16: 585-608.

Webb. B.W., and D.E. Walling. 1993a. ***Longer-term water temperature behaviour in an upland stream.*** Hydrological Processes 7 (1): 19-32.

Webb, B.W., and D.E. Walling. 1993b. ***Temporal variability in the impact of river regulation on thermal regime and some biological implications***. Freshwater Biology 29: 167-182.

Webb, B.W., and D.E. Walling. 1996. ***Long-term variability in the thermal impact of river impoundment and regulation***. Applied Geography 16 (3): 211-227.

Webb, B.W., and D.E. Walling. 1997. ***Complex summer water temperature behaviour below a UK regulating reservoir***. Regulated Rivers: Research & Management 13: 463-477.

Webb, B.W., and Y. Zhang. 1997. ***Spatial and seasonal variability in the components of the river heat budget***. Hydrological Processes 11: 79-101.

Webb, B.W., and Y. Zang. 1999. ***Water temperatures and heat budgets in Dorset chalk water courses***. Hydrological Processes 13: 309-321.

Wichert, G.A., and P. Lin. 1996. ***A species tolerance index of maximum water temperature.*** Water Qual. Res. J. Canada 31 (4): 875-893.

Wright, S.A., F.M.Jr. Holly, A.A. Bradley and W. Krajewski. 1999. ***Long-term simulation of thermal regime of Missouri River***. ASCE, Journal of Hydraulic Engineeging 125 (3): 242-252.

Younus, M., M. Hondzo and B.A. Engel. 2000. ***Stream temperature dynamics in upland agricultural watershed***. Journal of Environmental Engineering 126 (6): 518-526.

Zwieniecki, M.A., and M. Newton. 1999. ***Influence of streamside cover and stream features on temperature trends in forested streams of Western Oregon***. Western Journal of Applied Forestry 14: 106-113.