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REVIEW ARTICLE

The thermal regime of rivers: a review

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SUMMARY

1. The thermal regime of rivers plays an important role in the overall health of aquatic ecosystems, including water quality issues and the distribution of aquatic species within the river environment. Consequently, for conducting environmental impact assessments as well as for effective fisheries management, it is important to understand the thermal behaviour of rivers and related heat exchange processes.
2. This study reviews the different river thermal processes responsible for water temperature variability on both the temporal (e.g. diel, daily, seasonal) and spatial scales, as well as providing information related to different water temperature models currently found in the literature.
3. Water temperature models are generally classified into three groups: regression, stochastic and deterministic models. Deterministic models employ an energy budget approach to predict river water temperature, whereas regression and stochastic models generally rely on air to water temperature relationships.
4. Water temperature variability can occur naturally or as a result of anthropogenic perturbations, such as thermal pollution, deforestation, flow modification and climate change. Literature information is provided on the thermal regime of rivers in relation to anthropogenic impacts and such information will contribute to the better protection of fish habitat and more efficient fisheries management.

Keywords: aquatic habitat, model, river, water temperature

Introduction

Water temperature has both economic and ecological significance when considering issues such as water quality and biotic conditions in rivers. Water temperature is one of the parameters in stream ecology that determines the overall heath of aquatic ecosystems (Coutant, 1999). It influences the growth rate of aquatic organisms (Markarian, 1980; Jensen, 1990; Elliott & Hurley, 1997) as well as their distribution (Ebersole, Liss & Frissell, 2001). Most aquatic organisms have a specific range of temperatures that they can tolerate (Coutant, 1977). In the case of salmonids, when temperatures exceed this range, it can adversely affect trout (Lee & Rinne, 1980; Bjornin & Reiser, 1991) and salmon populations (Huntsman, 1942; Garside, 1973). Seasonal and daily variations of water temperatures are important determinants for the distribution of aquatic species, as pointed out in the River Continuum Concept (Vannote *et al.*, 1980). As such, it is essential to have a good understanding of the thermal regime of rivers for effective fisheries management as well as for conducting environmental impact assessments.

Water temperature fluctuations can occur naturally or as a result of anthropogenic perturbations such as thermal pollution, deforestation and climate change. For instance, deforestation has been identified as an important source of perturbation to the river thermal regime (Brown, 1970; Brown & Krygier, 1970; Beschta *et al.*, 1987; Johnson & Jones, 2000). Flow reduction and/or flow alteration can also be responsible for

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changes in river water temperature (Morse, 1972; Morin, Nzakimuena & Sochanski, 1994; Sinokrot & Gulliver, 2000). In recent years, climate change has been identified as an important source of disturbance on a large or global scale (Sinokrot *et al.*, 1995; Schindler, 2001). Climate change could significantly modify the distribution of aquatic organisms as water temperature in some systems is already reaching the lethal limit for fish (Eaton *et al.*, 1995).

Early studies of river water temperature focused mainly on observing habitat use (Benson, 1953; Gibson, 1966), the impact of high water temperatures on salmonids (Huntsman, 1946) and on the factors responsible for river thermal processes (Macan, 1958; Ward, 1963). Following these mostly descriptive studies, research then focused on the development of water temperature models (Raphael, 1962; Brown, 1969; Kothandaraman, 1971; Cluis, 1972) that were later classified into three distinct groups, deterministic, regression and stochastic models. Deterministic models employ an energy budget approach to predict river water temperature (Brown, 1969; Morin & Couillard, 1990; Sinokrot & Stefan, 1993), while both regression models (Crisp & Howson, 1982; Jourdonnais *et al.*, 1992; Stefan & Preud'homme, 1993; Mohseni, Stefan & Erickson, 1998) and stochastic models (Cluis, 1972; Marceau, Cluis & Morin, 1986; Caissie, El-Jabi & St-Hilaire, 1998) rely mainly on air temperature data for predicting river water temperatures.

Some of the earlier studies included that of Macan (1958), who observed that small streams warmed up quickly downstream from their sources and reached equilibrium where average water temperatures were not that different from average air temperatures. While considering factors influencing thermal conditions in rivers, Hynes (1960) showed that water temperature was dependent on many parameters, including the altitude and aspect of the river. Brown & Krygier (1967) were among the first to show that timber harvesting had a significant impact on river thermal conditions, especially for small streams, due to their small thermal capacity. Later, Hopkins (1971) showed that diel fluctuations were not only a function of stream size but also revealed a seasonal component. Smith (1975) showed that peak flows and snowmelt can play a major role in the overall water temperature variability. In the early 1970s, an attempt was made to categorise the thermal regime of rivers using altitude and latitude as the dominant factors (Smith, 1972), although it became apparent that such a classification was fraught with difficultly due to the complex nature of rivers. Since then, such classifications have not been attempted although studies have observed some thermal structure within rivers (e.g. stream order, see Arscott, Tockner & Ward, 2001; Gardner, Sullivan & Lembo, 2003). Over the years many studies have further illustrated the fact that thermal processes are indeed very complex (Smith & Lavis, 1975; Jeppesen & Iversen, 1987) which made any classification difficult. In fact, Ward (1985) showed, by studying many rivers in the Southern Hemisphere that the thermal regime of rivers was dependent on too many factors to have a clear classification, although a pattern emerged when rivers were classified into 'equatorial', 'tropical' and 'temperate', based on their maximum annual temperature and temperature range.

With important implications of water temperature for biotic responses, it became clear that the thermal regime of rivers plays a crucial role in stream productivity and is therefore worthy of study and understanding. Consequently, the present study focuses on a literature review of river thermal processes and anthropogenic impacts in rivers with potential implications for aquatic habitat. The specific objectives are to: (i) describe factors and underlying physical processes related to river thermal conditions; (ii) provide a general overview of water temperature models; and (iii) provide a general review of thermal conditions, anthropogenic impacts and potential implications on aquatic habitat.

The thermal regime of rivers

Factors influencing river temperature

When studying river temperature, many factors are involved which can generally be classified into four different groups: (i) atmospheric conditions; (ii) topography; (iii) stream discharge; and (iv) streambed (Fig. 1). Atmospheric conditions are among the most important factors and are mainly responsible for the heat exchange processes that take place at the water surface, including changes in phase. Topography or geographical setting is also important because it influences atmospheric conditions. Stream discharge, mostly a function of river hydraulics (e.g. inflows and outflows), mainly influences the heating capacity (volume of water) and/or cooling through mixing of

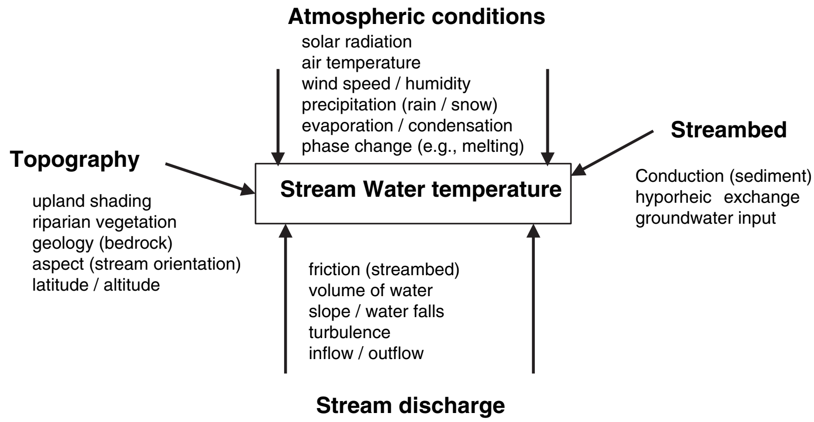

Fig. 1 Factors influencing the thermal regime of rivers.

water from different sources including streambed heat exchanges.

Spatial and temporal variability

The above factors influence the overall thermal conditions of rivers. For instance, it is generally observed that the mean daily water temperature increases in a downstream direction (i.e. as stream order increases; Fig. 2). Water temperature is generally close to the groundwater temperature at the source (e.g. in headwater streams; Benson, 1953) and increases thereafter with distance/stream order. The increase in water temperature is not linear and the rate of increase is greater for small streams than for large rivers. Notably, the rate of increase for small streams has been reported in the literature as being in the order of 0.6 °C km^{-1} (Zwieniecki & Newton, 1999), while larger rivers have shown much lower values

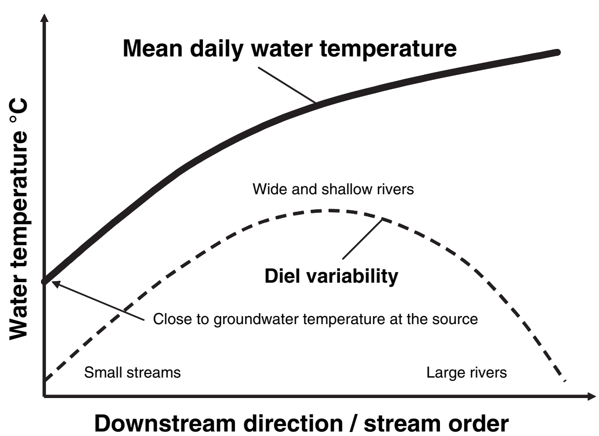

Fig. 2 Mean daily and diel variability of water temperatures as a function of stream order/downstream direction.

(0.09 °C km^{-1}; Torgersen *et al.*, 2001). Intermediate rivers showed rates of increase closer to 0.2 °C km^{-1}, as was noted in Catamaran Brook (New Brunswick; D. Caissie, unpublished data). These represent large-scale variations; however, small spatial scale variability can be observed below the confluence with tributaries (Ebersole, Liss & Frissell, 2003), in seepage area in pools (Matthews *et al.*, 1994) or at microhabitat scales (Clark, Webb & Ladle, 1999). The type of river can also influence thermal regime. For example, Mosley (1983) showed that braided rivers can experience very high water temperature, due to their small and shallow channels which are highly exposed to meteorological conditions.

On the temporal scale, water temperature varies, following both a diel and annual cycle. Diel fluctuations are such that water temperature generally reaches a daily minimum in the early morning (at sunrise) and a maximum in late afternoon to early evening. Also, daily variations (i.e. daily maximum–minimum) are generally small for cold headwater streams and increase for larger streams, as the streams become less dominated by groundwater and more exposed to meteorological conditions. The diel variability often reaches a maximum in wide and shallow rivers (Fig. 2; rivers generally wider than 50 m and <1.5 m deep, approximately stream order 4), while diel fluctuations eventually decrease again further downstream as water depth and river size increases. Associated with this diel variability, rivers also experience an annual temperature cycle, which follows a sinusoidal function (Ward, 1963; Kothandaraman, 1971; Tasker & Burns, 1974; Webb & Walling, 1993a). For colder regions, this annual cycle extends from spring to autumn (Cluis, 1972; Caissie *et al.*,

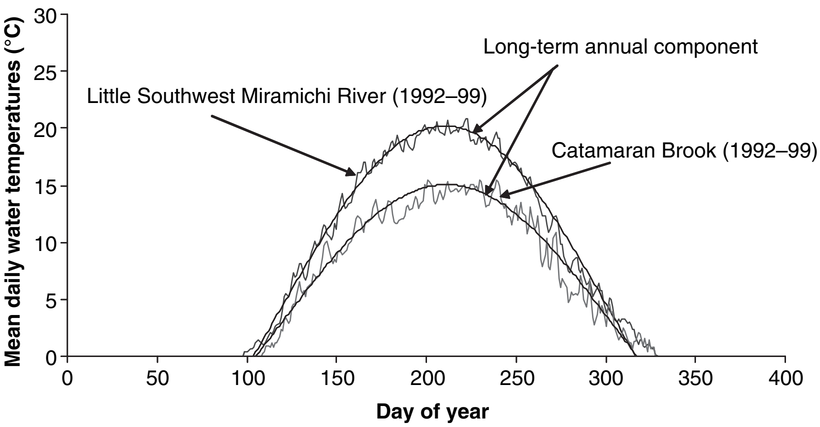

Fig. 3 Long-term annual component (annual cycle) in water temperatures at Catamaran Brook and the Little Southwest Miramichi River (New Brunswick, Canada).

1998), with temperature close to freezing throughout the winter. A comparison of annual cycles for a small and large rivers was made by Caissie, Satish & El-Jabi (2005), using long-term data. Both rivers had similar thermal behaviour in spring and autumn (i.e. similar water temperatures; Fig. 3), whereas the greatest thermal difference occurred at peak summer temperatures (i.e. end of July). At peak summer temperatures, the smaller brook (Catamaran Brook) was 5.1 °C colder than the larger system (Little Southwest Miramichi River). Moreover, it was noted that the long-term annual cycle for both rivers, although different in size, peaked on the same day (July 30; day 211) whereas the long-term annual air temperature cycle had peaked 6 days earlier (July 24; day 205).

River heat exchange processes

The above factors often determine the spatial and temporal variability of water temperature; however, physical forcing or heat exchange processes in the river environment must be taken into account for modelling (Fig. 4). Heat exchange at the air/water surface and at the streambed/water interface are where energy exchange occurs, at least in reaches where inflows/outflows, such as incoming tributaries, thermal effluent and water extractions, are negligible.

The heat flux at the air/surface water interface (H_{surface}; Fig. 4) occurs as a result of energy exchange mainly through: (i) solar radiation or net short-wave radiation; (ii) net long-wave radiation; (iii) evaporative heat flux (evaporation); and (iv) convective heat transfer (flux resulting from temperature differences between the river and the atmosphere). Other components can also be considered, such as precipitation, friction, etc. although their contribution is generally small compared to the above components. Some studies have shown that friction can be important, particularly in autumn and winter (Webb & Zhang, 1997). The equations for each energy component at the air/water interface have been described in previous studies (Raphael, 1962; Marcotte & Duong, 1973;

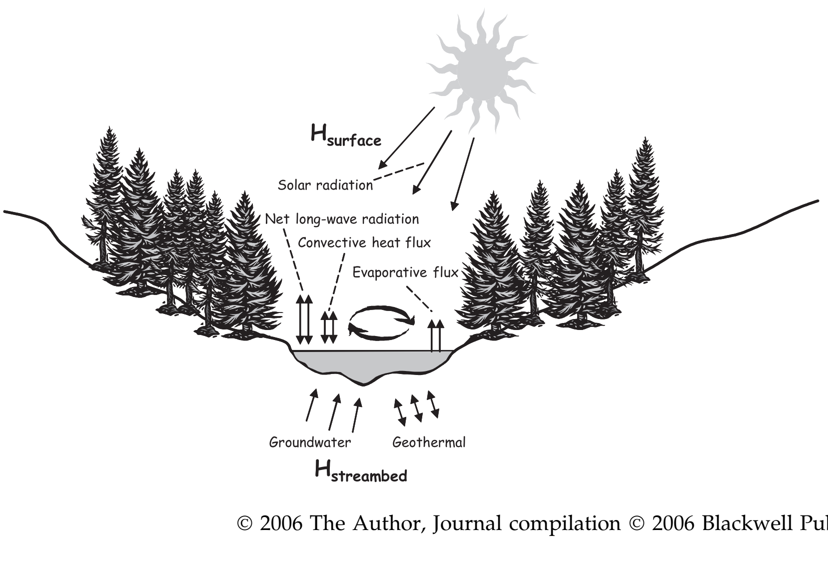

Fig. 4 River heat exchange processes.

Morin & Couillard, 1990; Sinokrot & Stefan, 1993; Caissie *et al*., 2005) and can easily be calculated using weather station meteorological data. River thermal processes and physical forcing responsible for the variability in river water temperature are highly related to these energy components. For example, when comparing energy components, research has shown that solar radiation is the dominant component of the total energy flux, followed by the net long-wave radiation and the evaporative heat flux (the last two components usually being comparable in magnitude) (Morin & Couillard, 1990). The smallest component of the total energy flux is generally the convective heat transfer, although this component is not negligible. Research has quantified these fluxes to explain the thermal conditions in rivers. Notably, Webb & Zhang (1997) showed that net radiation (solar radiation and net long-wave radiation) was the most important component in both heat gain and heat loss in the River Exe, U.K. The net radiation accounted for 56% of the total heat gain and 49% of heat loss. Similar findings were reported by Webb & Zhang (1999) for two other rivers in the U.K. They showed that net radiation accounted for close to 85% of the total energy gained and 27% of losses. In their study, the most significant energy loss component was through evaporative heat flux, which was estimated at 40%. These studies showed the importance of radiation and, by extension, riparian vegetation, the latter protecting streams against excessive heating.

The heat exchange at the streambed/water interface ($H_{\text{streambed}}$; Fig. 4) has received less attention, particularly from a modelling perspective. The streambed heat flux is mainly a function of geothermal heating through conduction and of advective heat transfer through groundwater contribution and hyporheic exchange (Lapham, 1989; Fig. 4). Although many modelling studies have neglected streambed heat fluxes, some have collected valuable data, which can be used to explain important thermal processes and associated fish habitat implications. For instance, Comer & Grenney (1977), Sinokrot & Stefan (1993) and Hondzo & Stefan (1994) all measured water temperature within the gravel bed and Alexander & Caissie (2003) measured streambed temperature and related it to groundwater discharges. Intragravel water temperature data revealed that rivers are generally cooled in summer through streambed heat fluxes whereas heat is released throughout the winter (Shepherd, Hartman & Wilson, 1986; Caissie & Giberson, 2003). Streambed heat fluxes can be especially important in autumn prior to winter freezing, due to a significant thermal gradient (important differences in intragravel temperature as a function of depth) resulting from summer residual heat accumulated within the ground (Alexander *et al*., 2003).

Of the studies that have looked at the different energy components, few have compared the heat exchange at the air/water interface to that of the streambed/water interface. However, Evans, McGregor & Petts (1998) did calculate and compare the total heat fluxes at both interfaces. They found that 82% of the energy exchange occurred at the air/water interface with approximately 15% at the streambed/water interface and the remaining 3% of energy accounted for by other processes. Using a sensitivity analysis, Sinokrot & Stefan (1994) showed similar results, in which streambed fluxes accounted for less than −0.12 to +0.15 °C in terms of water temperature variability. These few data suggest that heat exchange occurs mainly at the air/water interface. However, much uncertainty remains pertaining to the streambed heat fluxes on very small streams (<3 m), where sheltering and shading is very high. For larger channels, it is fair to assume that heat exchange at the air/water surface interface dominates over streambed fluxes mainly due to high solar radiation input and exposure to wind (less shading and sheltering by riparian vegetation). As streamside vegetation becomes more important (as in headwater streams), however, both of these parameters (solar radiation and wind speed) have been shown to be significantly reduced (Dong *et al*., 1998). This would reduce the air/water surface heat fluxes and increase the relative importance of streambed heat flux. More data are required on small streams to quantify these components effectively.

River water temperature models

There are many options for modelling water temperature although most models can be classified into one of three groups: (i) regression models; (ii) stochastic models; and (iii) deterministic models. Regression models, consisting of simple linear regression, multiple regression or logistic regression, have been applied in many studies. Simple linear regression models have been used to predict water temperature using only air temperature as the input parameter and such models have been applied using mostly weekly and/or monthly data (Johnson, 1971; Smith, 1981; Crisp & Howson, 1982; Mackey & Berrie, 1991; Webb & Nobilis, 1997). At such time scales (e.g. weekly/monthly), the water temperature is not generally autocorrelated within the time series and therefore linear regression models are quite effective. For example, Crisp & Howson (1982) developed a water temperature model based on a 5-day and 7-day mean water temperature and they showed that such a model explained 86–96% of the water temperature variability. This model was subsequently used to predict growth rate of brown trout (*Salmo trutta* Linnaeus) where they found good agreement between calculated growth from simulated and observed water temperature data. When using simple regression models, it is important to realise that different time scales will yield different air to water temperature relationships (i.e. different slopes and intercepts). Studies have shown that as the time scale increases (daily, weekly, monthly and annually), the slope of the regression line of water on air temperature generally increases with a decreasing intercept (Stefan & Preud'homme, 1993; Pilgrim, Fang & Stefan, 1998; Erickson & Stefan, 2000; Webb, Clack & Walling, 2003; Caissie, St-Hilaire & El-Jabi, 2004). The slope and intercept of the water to air temperature relationship is not only a function of time scale, but also of the stream type. For instance, non-groundwater-dominated streams tend to have steeper slopes with intercepts closer to the origin (e.g. 0 °C) whereas groundwater-dominated streams tend to have shallower slopes with relatively high intercepts (Fig. 5). As an example, Erickson & Stefan (2000) calculated an average slope of 1.06 with a mean intercept of 0.90 °C for Minnesota streams (monthly data), which are very close to values observed by Caissie *et al.*, (2004) (slope = 1.06, intercept = 0.12 °C) for the Little Southwest Miramichi River (New Brunswick). In contrast, Mackey & Berrie (1991) studied groundwater-dominated streams in England and calculated a mean overall slope of 0.61 with a corresponding intercept of 4.8 °C. Similar results were also observed by Smith (1981) who studied both groundwater and non-groundwater-dominated streams. Such differences in linear regression models for both groundwater and non-groundwater streams are illustrated on Fig. 5.

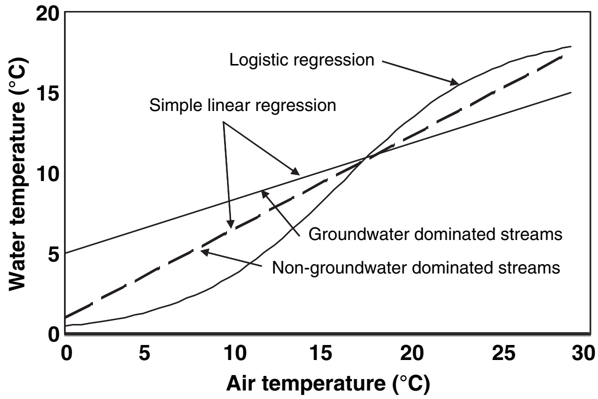

Fig. 5 Simple regression water temperature model (groundwater and non-groundwater streams) and logistic regression model.

Rather than using simple regression models, multiple regression models have also been used to predict river water temperatures (Jeppesen & Iversen, 1987; Jourdonnais *et al.*, 1992). When using such models, explanatory variables other than air temperature, such as river discharge, time lag data, etc. are often included. For example, Jourdonnais *et al.* (1992) included a suite of parameters in their modelling, such as maximum, minimum and mean air temperatures on the present and preceding day, as well as discharge. In the case of Jeppesen & Iversen (1987), they included air temperature, solar radiation and depth of water in the model as input data.

The last type of regression model found in the literature is the logistic regression model given by the following equation:

$$T_{\mathrm{w}} = \frac{\alpha}{1 + \mathrm{e}^{\gamma(\beta - T_{\mathrm{a}})}}, \quad (1)$$

where T_{a} and T_{w} represent air and water temperatures, α is a coefficient which estimates the highest water temperature, β represents the air temperature at the inflection point and γ represents the steepest slope (see Mohseni *et al.*, 1998 for further details). Studies have used the logistic regression rather than linear regression model on the basis that the air/water temperature relationships are not necessarily linear. This can be due to influences by groundwater at low air temperature and due to evaporative cooling at high air temperature. For instance, evaporative cooling can reduce the increase in water temperature at high air temperature and, therefore, the logistic regression can capture this non-linearity better in some rivers (Fig. 5). Such non-linear air/water temperature relationships have been observed for weekly data of many U.S. Rivers (Mohseni *et al*., 1998; Mohseni & Stefan, 1999; Mohseni, Stefan & Eaton, 2003), although other studies have shown that logistic regression performed poorly when studying daily water temperature time series (Caissie, El-Jabi & Satish, 2001). No studies could be found where logistic regressions were applied to monthly data probably because the evaporative cooling at that time scale is hidden within the averaging of the temperatures and, therefore, the linear model is preferred.

When the water temperature modelling is carried out for daily time steps, both stochastic and deterministic models are most often found within the literature. Stochastic models are the simpler of the two because they require only air temperature as the input parameter, whereas deterministic models used all relevant meteorological data to calculate energy components. A stochastic modelling technique often involves separating the water temperature time series into two components, namely the long-term annual component (annual cycle) and the short-term component. The annual component represents the change in water temperature on a seasonal basis (Fig. 3) and can be represented by a Fourier series or a sinusoidal function (Kothandaraman, 1971; Cluis, 1972). The short-term component represents the departure of water temperatures from the annual component. As such, this is the component being modelled to predict water temperatures using air temperature data and time-series analysis (Cluis, 1972; Marceau *et al*., 1986; Caissie *et al*., 1998). The short-term component can be modelled using Box and Jenkins methods and/or Markov process; the modelling takes into account the autocorrelation within the water temperature time series and its relation to air temperatures. Good modelling results at a daily time scale have been obtained with stochastic models with error (e.g. root-mean-square error) generally less than 2 °C. Stochastic models are very efficient for modelling daily water temperatures, especially when air temperatures are the only available data within a region (e.g. meteorological stations without solar radiation and wind speed data). Notably, regression and stochastic models can be applied over significantly large geographical areas, i.e. anywhere air temperature data are available.

Deterministic models have been applied extensively (Vugts, 1974; Sinokrot & Stefan, 1993; Kim & Chapra, 1997; Younus, Hondzo & Engel, 2000) on a variety of problems and issues. For instance, when carrying out impact studies such as the impact of thermal effluent from power plants or coldwater releases downstream of reservoirs, deterministic models are better adapted because they consider the different energy fluxes and mixing zones within the river. The objective of deterministic modelling is to quantify the total energy flux experienced by the river and then fit the total energy flux to observed changes in water temperatures. Early modelling studies have relied on quantifying the energy fluxes at the air/water surface interface to predict river water temperatures (Marcotte & Duong, 1973; Morin & Couillard, 1990), whereas most recent studies have also quantified the streambed heat fluxes part of the modelling (Sinokrot & Stefan, 1993; Kim & Chapra, 1997; Younus *et al*., 2000). The total energy exchange is generally obtained by balancing energy components to river conditions, i.e. by adjusting factors for solar radiation and wind speed that minimise the errors between observed and predicted water temperatures. The application of deterministic models on a daily (or hourly) basis revealed similar modelling performances to those for stochastic models, i.e. predictions or errors within 1–2 °C. For instance, Sinokrot & Stefan (1993) showed that stream exposure varied between 30% and 100% while wind sheltering was in the range of 10–30%. This study of five rivers in the U.S.A. showed that the streambed heat fluxes are more important to consider when modelling hourly data (compared to daily data), due to the strong diel variability in water temperatures and heat exchange within the day. Errors reported by Sinokrot & Stefan (1993) were <1.1 °C while Younus *et al.* (2000) showed similar results (1.3 °C) for Little Pine Creek (Indiana) and for hourly temperatures as well. These studies were applied for relatively short duration (<25 days) whereas Marceau *et al.* (1986) carried out a deterministic water temperature modelling for the Sainte Anne River in Quebec for four summers (1968–71). Errors expressed as the root-mean-square errors were calculated between 1.4 and 2.9 °C for daily water temperature data.

It should be pointed out that when carrying out water temperature modelling using both regression and/or stochastic models, temperatures are predicted at specific sites only, i.e. 'zero dimensional', 0D. Multiple site predictions are generally carried out independently and this can be a drawback of these models, especially when changes in water temperatures are required at different spatial scales. Under these conditions, deterministic models are used, because they can be carried out at different spatial scales (1D, 2D, etc.) as well as for specific sites, similar to regression and stochastic models. However, deterministic modelling is most often carried out as a one-dimensional problem where the temperature is simulated along the river's principal axis. This is because water temperature in rivers is relatively uniform with depth and only small changes are usually observed in the transverse direction (i.e. rivers are well mixed). In fact, information in the literature suggests that stratification in river water temperature is generally not observed at depths below 4–5 m (Bormans & Webster, 1998) and that cross-sectional temperature gradients are generally observed at the confluence with other rivers or tributaries (with a different thermal signature), although microthermal gradients have been observed at the local scale (Clark *et al*., 1999). Deterministic models have the advantage not only of being able to quantify the different heat fluxes acting on the river environment but they are also capable of considering the impact of different scenarios, such as removing streamside vegetation, modification to the river discharge, etc. Such anthropogenic perturbations will be discussed in *Anthropogenic impacts on the thermal regime* followed by a consideration of the potential impact of the river thermal regime on aquatic habitat. In general, the literature shows that the selection of a particular water temperature model depends on the modelling objective as well as the data requirements.

Anthropogenic impacts on the thermal regime

The thermal regime of rivers in forested ecosystems

The literature on the thermal regime of rivers related to forestry is voluminous, particularly with regard to the impact of streamside forest removal on river water temperature (e.g. Gray & Edington, 1969; Ringler & Hall, 1975; Lynch, Rishel & Corbett, 1984; Beschta *et al*., 1987; Johnson & Jones, 2000). This literature has played an important role in the overall understanding of the thermal behaviour of rivers, as well as in modelling studies. For instance, it provided information about issues such as heat transfer processes and the role of solar radiation versus convective heat transfer. Changes in water temperature due to timber harvesting and its effect on aquatic habitat have been well documented in a review by Beschta *et al*. (1987).

Throughout the years, studies have focused on the impact of timber harvesting practices on river water temperatures with most studies showing increases in water temperatures following streamside forest removal (Feller, 1981; Hewlett & Fortson, 1982; Rutherford *et al*., 1997). For example, Brown & Krygier (1967) showed an increase of 7.8 °C in mean monthly maximum water temperatures in Oregon's Alsea River Basin, while Swift & Messer (1971) showed an increase of 6.7 °C in the Coweeta experimental basin, North Carolina. Brown & Krygier (1970) also found an increase in water temperature with no streamside buffers and concluded that summer maximum water temperature approached prelogging values after approximately 6 years. These studies were among the first to point out that small streams are highly vulnerable to increase in water temperature due to their low thermal capacity. To develop some predictive capabilities for addressing streamside forest removal, Brown (1970) presented a formula relating water temperature increases to the heat 'load' and discharge data. Based on a compilation of data from many West Coast studies, Mitchell (1999) showed that streamside vegetation removal resulted in a greater rate of increase at higher water temperature. This study used mean monthly water temperature during pre- and post-timber harvesting for the analysis.

Partial removal of forest from the riparian buffer zone can also influence stream water temperature as reported by Feller (1981). This study showed that a 66 % removal of the overstorey resulted in an increase of 5 °C in summer daily mean water temperature.

Long-term studies are reported in the literature (Beschta & Taylor, 1988; Hostetler, 1991; Johnson & Jones, 2000). For example, a 30-year study was carried out by Beschta & Taylor (1988) showing an increase of 6 °C in mean daily maximum water temperature in Salmon Creek (Oregon), whereas increases of over 8 °C (1969–89) were reported in the Steamboat Creek (Hostetler, 1991). Johnson & Jones (2000) showed similar results (increase of 7 °C) and estimated a 15-year period for a gradual recovery to preharvest temperature. Most studies have shown that it takes between 5 and 15 years for rivers to recover their natural thermal regime following vegetation regrowth (Murray, Edmonds & Marra, 2000). The importance of riparian buffers in protecting streams from heating was also evident from data presented by Burton & Likens (1973), who showed that successive opening of the streamside canopy contributed to increases in water temperature. They also pointed out that water temperature tends to recover in buffered sections of streams, presumably due to colder groundwater or water exchange within the stream substratum.

A few studies have used deterministic models with a shading component to study the dynamics of riparian vegetation and solar heating (Theurer, Lines & Nelson, 1985; Chen *et al.*, 1998a,b; Bartholow, 2000). These models generally calculate solar input based on sun position, stream location, orientation and other relevant parameters. Such a model was tested for the Upper Grande Ronde Catchment in Northeast Oregon (Chen *et al.*, 1998b), where they studied hypothetical riparian restoration scenarios. Beschta (1997) discussed the fact that streamside vegetation is not only important to protect streams against solar heating, but the vegetation (e.g. roots) also served to protect the stream by providing better stream bank stability.

Many studies have been carried out to determine the impact of forest removal, although few have looked at the impact of varying the buffer width. Zwieniecki & Newton (1999) studied 14 streams and with riparian buffers ranging from 8.6 to 30.5 m. Following forest removal, they noted a higher than normal warming trend which they attributed to timber harvesting; however, a rapid recovery was also observed downstream (in the order of 150 m) from the buffered zone. This study concluded that, despite substantial harvesting, a buffer zone can be adequate to maintain water temperature within the normal warming trends of fully covered streams. No conclusion could be drawn from this study related to the most effective buffer width which would protect the stream environment. Studies within the forestry literature have shown that the microclimate conditions at the edge of clearcuts can penetrate the forest up to 240 m depending on forest composition (Chen, Frankin & Spies, 1995; Brosofske *et al.*, 1997). This information clearly shows that the determination of the most effective buffer width depends on the type of forest as well as on stream size, and remains a research issue.

From the literature on the impact of timber harvesting on rivers we can conclude the following points. First, the solar input plays a dominant role in the overall thermal conditions of rivers and contributes significantly to the impact. Second, the size of the stream (i.e. thermal capacity) is an important factor in determining the impact, and smaller streams have surprisingly not been associated with the greatest change in temperature. Third, although a few studies have suggested that near stream soil heating (e.g. timber harvest blocks) is an important source of heat to the river (Hewlett & Fortson, 1982), more research is required to quantify this impact more accurately. Finally, the groundwater contribution remains an important factor, especially in small headwaters.

Climate change and other anthropogenic perturbations

Although a great deal of research has been carried out on the impact of timber harvesting on stream temperature, the thermal regime of rivers can be affected by many other anthropogenic perturbations. These include changes in stream water temperature due to: (i) thermal effluents; (ii) reductions in river flow (e.g. irrigation, hydroelectric); and (iii) water releases to river from dams upstream. More recent studies evaluated the effect of climate change (Mohseni, Erickson & Stefan, 1999; Mohseni *et al.*, 2003), although it is difficult to take a global perspective on water temperature trends due to a lack of data in many parts of the world as pointed out by Webb (1996). Anthropogenic perturbations can modify the thermal regime of rivers and, as a result, can ultimately affect fisheries and aquatic resources.

A reduction of river discharge, resulting from water withdrawal (e.g. irrigation) or water diversion projects (e.g. hydroelectric), has been shown to affect water temperatures (Morse, 1972; Dymond, 1984; Bartholow, 1991; Morin *et al.*, 1994). For instance, Hockey, Owens & Tapper (1982) studied the impact of water withdrawal on water temperature in the Hurunui River (New Zealand) using a deterministic model. The model was calibrated for a discharge of 62 $m^3 s^{-1}$ and was run at low flows of 10 $m^3 s^{-1}$ for similar meteorological conditions. They found that, at low flows, river water temperature exceeded critical values of 22 °C for over 6 h. Bartholow (1991) studied the impact of water withdrawal on the Cach la Poudre River near Fort Collins, Colorado (U.S.A.) using a deterministic model, i.e. Stream Network TEMPerature model (SNTEMP). This addressed the thermal habitat conditions of rainbow (*Oncorhynchus mykiss* Walbaum) 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% provided little cooling, although increasing the river discharge by 3 $m^3 s^{-1}$ would maintain acceptable water temperature. Sinokrot & Gulliver (2000) also showed that the reduction of river flow greatly influenced thermal regime, specifically resulting in the increased occurrence of high temperature events. They demonstrated that a gradual decline in the number of days with temperature exceeding 32 °C in the Platte River (U.S.A.) could be obtained by increasing river discharge.

The thermal regime of rivers is also influenced downstream of reservoirs (Webb & Walling, 1993b; Lowney, 2000). As reported by Troxler & Thackston (1977) coldwater releases from reservoirs can have a profound impact on the downstream thermal regime. They studied five facilities which had water release close to 10 °C and while gathering meteorological data, they noted significant and unexpected changes in microclimatic conditions. Notably, the cooled air resulting from the water release within the valley promoted the formation of fog, which reduced natural heat exchange between the river and the atmosphere. Water releases have also been noted to influence the growth rate of fishes downstream of reservoirs (Robinson & Childs, 2001). Webb & Walling (1993b) showed that the water downstream of reservoirs is warmer overall, with an increase in mean annual water temperature. In summer, downstream temperature tends to be lower and the annual component (annual cycle) was often delayed. This study also showed that, temperature below reservoirs is modified most strongly in winter compared with the normal thermal regime, and winter freezing can be eliminated entirely (Webb & Walling, 1993b). In such conditions, the hatching and emergence of brown trout could be advanced by over 50 days. Warm water releases in winter are especially problematic in northern latitudes, where the ambient downstream water temperature would normally be close to 0 °C. Winter water temperature increase at these sites could potentially have a greater impact on aquatic ecosystems (e.g. incubation of salmonid eggs) than that caused by summer conditions. Water temperature below reservoirs shows changes not only in the annual cycle, but also in the diel variation (Webb & Walling, 1996). For instance, steady reservoir discharge in summer, at relatively constant cooler temperature, can result in marked diel variations in downstream temperatures compared to normal conditions (Lowney, 2000). Although current knowledge suggests that reservoirs simply tend to regulate river flow and temperature, a long-term study in the U.K. (15 years; Webb & Walling, 1997) showed that reservoir discharge resulted in a highly complex downstream thermal regime.

Thermal pollution from industrial effluent, including power generating station cooling water, can also adversely affect aquatic resources by reducing the available area of suitable habitat. Wright *et al.* (1999) showed significant impacts of power plants on the Missouri River that were comparable to the predicted change due to climate change. The effects of thermal discharges on aquatic habitat were well documented by Langford (1990). For instance, this research described many effects of thermal discharge, including physical and chemical effects, as well as their impact on many aquatic species (e.g. bacteria, algae, vertebrates, etc.). Langford (1990) also provided information on the combined effects of thermal discharge and the toxicity of many contaminants, which are shown to increase with temperature.

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 & Stefan, 2001; Stefan, Fang & Eaton, 2001). For instance, Sinokrot *et al.* (1995) noted that water temperature below reservoirs 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) is likely to cause an impact downstream due to increased water temperature. When researching water temperature time series and in relation to climate change, few long-term data sets are available to enable the implication of climate change for the thermal conditions of rivers to be studied effectively. Webb & Nobilis (1997) carried out a long-term study, in which they analysed 90 years of water temperature data from north-central Austria. No specific trend was reported in water temperatures in this long-term study. In contrast, Webb & Nobilis (1994) showed a significant increase of 0.8 °C over a similar time period in the River Danube and attributed the increase mostly to human activities. Increases in water temperature over a 30-year period were also observed in Scotland, particularly in winter and spring (Langan *et al*., 2001). Climate change will probably modify the thermal regime of rivers and other aquatic habitats as discussed in *River water temperature and aquatic habitats*.

River water temperature and aquatic habitats

Many biological factors and conditions, as well as stream productivity, are strongly linked to stream water temperature. Thus, it is important to have a good understanding of some of the biological implications related to the river thermal regime. This section provides a general overview but is not exhaustive.

Stream water temperature influences a wide range of aquatic organisms from invertebrates (Hawkins *et al*., 1997; Cox & Rutherford, 2000) to salmonids (Lee & Rinne, 1980). In fact, fishes and other aquatic organisms have specific temperature preferences, which can ultimately determine their distribution within streams (Coutant, 1977; Wichert & Lin, 1996). Water temperature is important for salmonid growth (Edwards, Densem & Russell, 1979; Jensen, 1990; Elliott & Hurley, 1997), for the timing of fish movement (Jensen, Hvidsten & Johnsen, 1998) and emergence (Johnston, 1997; Elliott, Hurley & Maberly, 2000), as well as for the triggering of smolt runs in the spring (Hembre, Arnekleiv & L'Abée-Lund, 2001). A review by Coutant (1999) provides valuable information about thermal habitat conditions and the importance of physiological temperature range (sublethal and lethal) as well as acclimation temperatures.

Functional models have played an important role in the predictions of growth rates of brown trout (Jensen, Forseth & Johnsen, 2000), Atlantic salmon (*Salmo salar* Linnaeus) (Jonsson *et al*., 2001) and the development of salmonid egg and fry (Elliott & Hurley, 1998a,b). Such functional models provide good growth predictions, even among thermally different rivers, with the major difference being the optimal temperature for growth (Forseth *et al*., 2001). In contrast, some studies showed greater differences between observed and predicted growth rates, suggesting that temperature alone cannot account for all spatial and temporal variability (Nicola & Almodóvar, 2004). Moreover, other studies showed that environment conditions (annual mean water temperature), fish density and geographical setting (latitude) played an important role in determining annual growth and could improve the accuracy of growth models (Jensen *et al*., 2000).

Water temperature regression models have been used to predict the growth of brown trout (Crisp & Howson, 1982) and aquatic insects (Markarian, 1980). For instance, Markarian (1980) showed a good level of association between cumulative degree-days and growth of many aquatic insects. This study also revealed that some insects grow at low temperature. Long-term research at Carnation Creek (BC), showed that changes in temperature due to timber harvesting can have an impact on fisheries (Scrivener & Andersen, 1984). This study showed that increased water temperature affected the growth and development, resulting in an earlier downstream movement of fish by as much as 6 weeks (Scrivener & Andersen, 1984; Holtby, 1988).

Water temperature also influences fish habitat conditions within the stream substratum (Shepherd *et al*., 1986; Crisp, 1990). Intragravel temperatures tend to be lower within the substratum during summer and higher in winter when compared to surface water temperatures (Caissie & Giberson, 2003). These temperatures not only influence insect growth but also the development of salmonid eggs (Combs, 1965; Alderdice & Velsen, 1978; Beer & Anderson, 2001).

Instream biological rates in general are related to water temperature and this relationship follows Van't Hoff's rule, which states that the biological activity doubles for every 10 °C increase of water temperatures (as discussed in Brown & Krygier, 1967). This increase in biological rates (and associated oxygen consumption) can become problematic where dissolved oxygen is already depleted due to high water temperature. Consequently, high stream temperature can adversely affect fisheries by limiting fish habitat and increasing mortality. Water temperature between 23 and 25 °C affects the mortality of trout (Lee & Rinne, 1980; Bjornin & Reiser, 1991), whereas salmon can tolerate slightly higher temperatures, in the range of 27–28 °C (Garside, 1973). High sensitivity to temperature depends on life stages and Huntsman (1942) found that, during high temperature events, larger Atlantic salmon died first, followed by small salmon and then parr. Recent studies have shown that high water temperature, although not always lethal, can have an impact on the development of juvenile salmonids (Lund *et al.*, 2002). Lund *et al.* (2002) looked at biomarkers of temperature stress in juvenile salmonids, which were exposed to high temperature in both the laboratory and in the wild, and found protein damage if the stress was prolonged. Diel variability in water temperatures can also impact the mortality, stress and energy reserves of salmonids, as reported by Thomas *et al.* (1986).

Other studies have noted that, at high water temperature, many aquatic species change their behaviour by seeking thermal refuges (Kaya, Kaeding & Burkhalter, 1977; Torgersen *et al.*, 1999; Elliott, 2000). For instance, salmonids aggregate within small, but colder, refuge spaces (Ebersole *et al.*, 2001) or move into coldwater tributaries (Cunjak *et al.*, 1993) during high temperature events. Kaya (1977) found both rainbow and brown trout in a naturally (geothermally heated) warm stream at a temperature of 28.8 °C, which is normally lethal. Moreover, closer observations revealed that trout within this geothermally heated stream used coldwater tributaries as refuges in the summer (Kaya *et al.*, 1977). Ebersole *et al.* (2001) showed that approximately 10–40% of fish were observed close to thermal refuges at midday and such an aggregation of fish resulted in higher densities than those observed elsewhere in the stream. Coldwater areas or patches are therefore very important river ecosystems and can generally be classified as: (i) coldwater tributaries; (ii) lateral seeps; (iii) deep pools; and (iv) cold alcoves (or backwater areas) (Ebersole *et al.*, 2003). Deep pools (with a coldwater source) have been shown to be important thermal refuges for trout, even when dissolved oxygen content is low (Bilby, 1984; Matthews *et al.*, 1994). In fact, when faced with a choice, trout seems to prefer cool water, even if it is low in oxygen (Matthews & Berg, 1997).

Depending on its severity, the global warming could lead to the extinction of some aquatic species or dramatically modify their distribution within river systems, as pointed out in recent studies (Minns *et al.*, 1995; Schindler, 2001; Mohseni *et al.*, 2003). Others have pointed out that, in many parts of North America, fish are already experiencing their upper lethal limit in water temperature (Eaton *et al.*, 1995; Sinokrot *et al.*, 1995). It has been 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 noted that the smoltification age could decrease by 8–29%, depending on the geographical area and the increase in temperature.

Some species are expected to change their distribution as temperature gets warmer. For example, the present distribution of salmonids in Wyoming was found to be related to locations where the July air temperature did not exceed 22 °C (Keleher & Rahel, 1996). This study further concluded that current habitats would become unsuitable under climate change and that salmonids would probably be forced to higher altitude, where coldwater habitats would still exist. A reduction in suitable habitat of approximately 50% is predicted with an associated increase in air temperature of 3 °C. Similar results in terms of northward movements of fishes (and to higher altitudes) were also suggested by Mohseni *et al.* (2003), who studied 57 fish species in the U.S.A. Their study showed that thermal habitat for coldwater fishes could be reduced by 36% under climate change. Projected changes in aquatic habitat under climate change are based on the fact that water temperature is highly related to air temperature, although changes in groundwater temperature are also expected. For instance, Meisner, Rosenfeld & Regier (1988) discussed the importance of groundwater temperatures on aquatic ecosystems and noted that groundwater temperature is also linked to air temperatures (between 1.1 and 1.7 °C greater than the mean annual air temperature). Therefore, any increase in air temperature due to climate change will result in increased groundwater temperature and changes to incubation periods and growth potential. Finally, climate change will not only modify the river thermal regime but other river processes are also projected to change significantly, which will impact on fisheries resources (Schindler, 2001).

In general, the thermal regime of rivers is highly influenced by meteorological and river conditions as well as by their geographical setting. River temperature is arguably one of the most important parameters which determines many aquatic habitat attributes and the general health of river ecosystems. Therefore, it is essential to have a good understanding of river thermal processes, modelling approaches and associated energy fluxes to develop better models for predicting river water temperatures. These models will ultimately result in more effective fisheries management and a better protection of fish habitat. Both the study of natural stream water variability and changes due to anthropogenic perturbations are also important for environmental assessment as well as assessing future climate scenarios on fish habitat.

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