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River temperature modelling: a review of process-based approaches and future directions

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Abstract

River temperature has a major influence on biophysical processes in lotic environments. River temperature is expected to increase due to climate change, with potentially adverse consequences for water quality and ecosystems. Consequently, a better understanding of the drivers of river temperature space-time variability is important for developing adaptation strategies. However, existing river temperature archives are often of low resolution or short timespans, and the analysis of patterns or trends can therefore be difficult. In light of these limitations, researchers have increasingly used models to generate river temperature estimates suitable for addressing fundamental and applied questions in river science. Of these models, process-based approaches are well suited to helping improve knowledge of the mechanisms controlling river temperature, because of their ability to explore the energy (and water) fluxes responsible for temperature patterns. While process-based modelling approaches can often be more data intensive than their statistical counterparts, they offer significant advantages with regards to simulating the impacts of projected land-use or climate change, and can provide valuable insights for informing the development of statistical models at larger scales. However, a wide range of process-based river temperature models exist, and choosing the most appropriate model for a given investigation requires careful consideration. In this paper, we review the foundations of process-based river temperature modelling and critically evaluate the features and functionality of existing models with a view to helping river scientists better understand their utility. In conclusion, we discuss key considerations and limitations of currently available process-based models and advocate directions for future research. We hope that this review will enable river researchers and managers to make informed decisions regarding model selection and spur the continued refinement of process-based temperature models for addressing fundamental and applied questions in the river sciences.

1. Introduction

River temperature is one of the most important river habitat variables (Caissie, 2006; Hannah and Garner, 2015), controlling biogeochemical processes (Durance and Ormerod, 2009; Kaushal et al., 2010), ecosystem dynamics (Durance and Ormerod, 2007; Bärlocher et al., 2008; Dugdale et al., 2016) and water quality (Finlay, 2003; Bloomfield et al., 2006; Delpla et al., 2009). Quantifying river temperature is therefore key for improved understanding of fluvial environments. River temperature regimes in most locations are expected to change as a result of future climate change (van Vliet et al., 2013; Caldwell et al., 2015; Hannah and Garner, 2015; Muñoz-Mas et al., 2016) and other anthropogenic drivers (e.g. abstraction, impoundment, land-use change; Poole and Berman, 2001; Hester and Doyle, 2011). However, shortcomings in several key aspects of river temperature research mean that little is currently known about the complex nature of future temperature variability. River temperature science has in the past been based on data with low spatial and temporal resolution, frequently collected as a side product of water quality and/or ecological sampling. Water temperature data quality is consequently highly variable and elucidating the controls of river temperature remains difficult (Webb et al., 2004; Jonsson and Jonsson, 2009; Watts et al., 2015). Efforts have been made to resolve this using novel temperature logger networks (e.g. Isaak et al., 2010; Jackson et al., 2016; Boyer et al., 2016) or remote sensing techniques (see. Dugdale, 2016). While such investigations are fast becoming the new norm, process-based understanding has not always kept pace with methodological development, and the exact mechanisms controlling river temperature heterogeneity remain difficult to isolate (Hannah and Garner, 2015). Further research into river temperature dynamics is consequently of key importance with regards to predicting the impacts of future climate change on river environments.

Several key review papers (including Webb, 1996; Caissie, 2006; Webb et al., 2008; Hannah and Garner, 2015) summarise the current state-of-the-art with regard to the processes driving river temperature. At the fundamental level, river temperature is determined by so-called 'first-order' climatic and hydrological processes (Hannah & Garner et al., 2015) which govern the initial temperature of the stream at the headwater and control rates of downstream warming or cooling due to radiative, latent, sensible and advective heat exchanges. However, the degree with which a river channel responds to these broad scale climatic and hydrological processes depends upon 'second-' and 'third-order' controls pertaining to the properties of the river basin (ie. land-use, hydrogeology, hydromophology), which influence energy and mass transfers at a range of nested scales (Figure 1). At the whole-river scale, riparian forests and steep topography act as 'second-order' controls on stream temperature by moderating incoming solar or longwave radiation (e.g. Leach and Moore, 2010; Benyahya et al., 2012; Garner et al., 2014; Garner et al., 2015). Topography also drives localised variability in precipitation (Hannah and Garner, 2015), in addition to controlling the distribution of advective inputs from tributaries or diffuse groundwater inputs (e.g. Webb and Zhang, 1999; Yearsley, 2009) through interactions with geology and subsurface stratigraphy (eg. Malcolm et al., 2008). At the reach scale, channel morphology and topology constitute 'third-order' controls on river temperature. Localised advective warming or cooling is driven by discrete or diffuse groundwater inputs (e.g. Torgersen et al., 1999; Dugdale et al., 2015) linked to channel morphology, or by hyporheic exchange (engendered by gravel bars; e.g Gooseff et al., 2006; Burkholder et al., 2008). Deep stratified pools may also create pockets of cool water (Matthews et al., 1994; Nielsen et al., 1994). When combined, these processes interact to create a mosaic of river temperature heterogeneity along a river's length (ie. a river's 'thermal landscape'; Steel et al., 2017). However, although these processes are reasonably well understood in isolation, the way in which they interact to determine stream temperature is still the subject of considerable research. These mechanisms must therefore be unravelled to better understand river temperature patterns and processes.

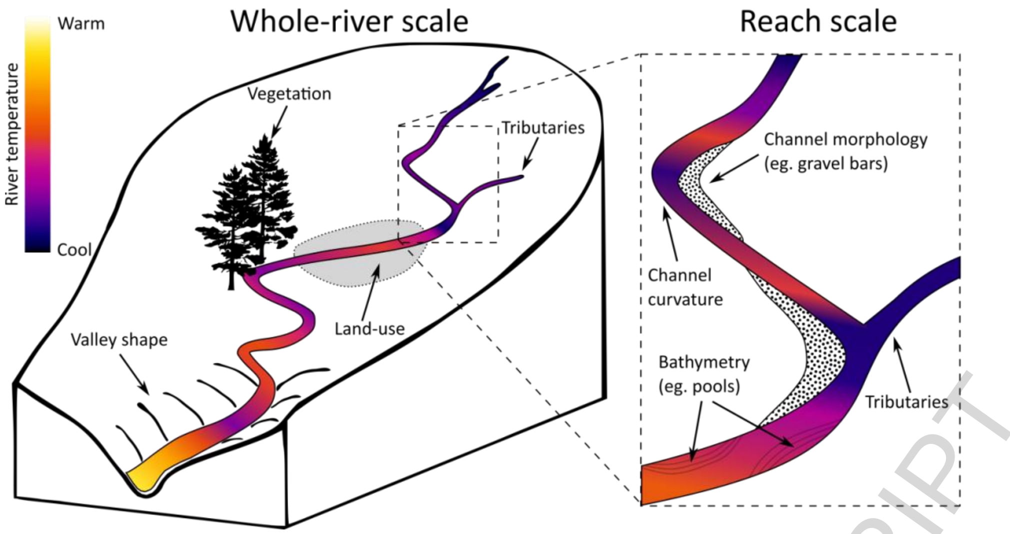

Figure 1. Basin controls on river water temperature heterogeneity across multiple scales

In light of such knowledge gaps, researchers have increasingly turned to models to explore space-time variance in river temperature patterns (e.g. Tung et al., 2006; Ruesch et al., 2012) and to yield process-based understanding of stream temperature dynamics (e.g. Garner et al., 2014). Because river temperature science is still a relatively data-poor domain, models are one of the few ways in which researchers can generate estimates of river temperature and its associated energy transfers suitable for answering these fundamental questions.

River temperature models can be divided into those based in statistics and those that simulate physical processes (alternately labelled 'deterministic', 'mechanistic' or 'process-based' models) to predict water temperature (Caissie, 2006). Benyahya et al. (2007) provide a detailed account of statistical water temperature models. Broadly speaking, they function through fitting statistical linkages between water temperature and a range of related covariates, either by parametric means (eg. regressive, correlative or autoregressive models) or through non-parametric approaches (eg. artificial neural networks, nearest-neighbours approaches; Benyahya et al., 2007). Statistical temperature models can generate accurate stream temperature predictions (e.g. Jeong et al., 2013; Daigle et al., 2015) and are particularly useful at large spatial scales where the data requirements of process-based models make their application unfeasible (eg. Isaak et al., 2015; Jackson et al. 2017; Steel et al., 2016). They can also be used to infer the drivers of river temperature variability (e.g. Hrachowitz et al., 2010; Imholt et al., 2013; Jackson et al., 2017). However, they are unable to reveal the specific energy transfer mechanisms responsible for stream temperature patterns, and their space-time transferability to dissimilar locations is limited. In contrast, process-based models simulate the processes controlling river temperature. Unlike statistical models, the intricacy of these processes means that such models are relatively data-intensive and highly parameterised (Benyahya et al., 2007), and they can be difficult to apply very large scales. However, they are particularly useful for a) providing process-based insights into the drivers of river temperature, b) for informing appropriate metrics to use in larger statistically based models and c) for predicting temperature response to climate or land-use change scenarios (e.g. Morin and Couillard, 1990; Caissie et al., 2007) in situations where statistical solutions may break down due to scenarios outside of their calibration range.

A range of process-based stream temperature models have been produced and published (often on a non-commercial basis) for use by the research community (Table 1). However, there are considerable differences between the types of models available and their utility for simulating water temperature in various contexts. Choosing the most appropriate model for a given investigation is therefore often difficult, due to differences in model functionality, features, outputs and data requirements. Furthermore, elucidating the key features of the various models is often laborious as important details regarding the functionality of some models can be buried within the grey literature. Consequently, a detailed understanding of the advantages and limitations of the various river temperature models is vital for making an informed choice of temperature model.

In this review, we aim to evaluate existing process-based stream temperature models with a view to helping researchers (and potentially managers) identify the most appropriate model for their given purpose, building on the previous meta-analyses presented in Norton and Bradford (2009) and Ficklin et al. (2012). To achieve this, the article is structured around four key objectives:

1. Review the foundations of process-based river temperature modelling.
2. Compare the ways in which currently available process-based temperature models represent the physical energy flux processes responsible for river temperature dynamics.
3. Document differences in model implementation, features and practicalities.
4. Discuss limitations, future prospects and key considerations regarding model use.

In an attempt to aid readability, citations for individual models are given by numbers (1 - 21) corresponding to the rows in Tables 1-6. Standard references for each model are given in Table 1. We only explicitly consider 'named' models that a) have been published in the peer-reviewed literature, b) have been used for more than one study and c) for which information is readily available. Every attempt has been made to gain accurate information about each model, although in some cases, the difficulty in elucidating the models' technical details means that it has been necessary to simplify the contents of Tables 1-6. We do not examine models that have only been documented on single occasions or that only appear in the grey literature. Furthermore, we only detail the most up-to-date incarnation of a given model (or series of models), as an appraisal of a model's evolutionary development is outside the scope of this article.

Table 1. List of reviewed process-based river temperature models (including programming language, source code and availability)

No.	Model name	Main reference(s)	Further reading	Language	Availability	Source code	URL for model download
1	BasinTemp	Allen (2008)	Allen et al. (2007)	N/a	Proprietary (Stillwater Sciences)		N/a
2	CE-QUAL-W2	Cole & Wells (2015)	Rounds (2007) Norton & Bradford (2009)	Fortran / Visual Basic	Free download	Yes	http://www.ce.pdx.edu/w2/
3	CEQUEAU	Morin & Paquet (2007)	Morin & Couillard (1990) St-Hilaire et al. (2000)	MATLAB / C++	Available on request	Yes	http://ete.inrs.ca/ete/publications/cequeau-hydrological-model
4	CrUSTe	LeBlanc et al. (1997)	LeBlanc & Brown (2000)	STELLA	N/a		N/a
5	Delft3D-FLOW	Deltares (2014)	Carrivick et al. (2012) Shen et al. (2014)	Fortran	Free download	Yes	http://oss.deltares.nl/web/delft3d/download
6	Heat Source	Boyd & Casper (2003)	Bond et al. (2015) Woltemade et al. (2016)	Python / Visual Basic	Free download	Yes	http://www.oregon.gov/deq/wq/tmdls/Pages/TMDLs-Tools.aspx
7	DHVSM-RBM	Sun et al. (2015) Yearsley et al. (2001)	Yearsley et al. (2009) Yearsley et al. (2012)	Fortran	Free download	Yes	http://www.hydro.washington.edu/Lettenmaier/Models/RBM/index.shtml
8	GIS-STRTemp	Sansone (2001)	Sridhar et al. (2004)	N/a	N/a		https://www.niwa.co.nz/freshwater-and-estuaries/our-services/catchment-modelling/water-allocation-impacts-on-river-attributes-waiora
9	HEC-RAS	Brunner (2016)	Drake et al. (2010)	Java	Free download		http://www.hec.usace.army.mil/software/hec-ras/
10	MIKE 11	DHI (2016)	Loinaz et al. (2013)	N/a	Commercially available		https://www.mikepoweredbydhi.com/products/mike-11
11	MNSTREM	Sinokrot & Stefan (1993)	Sinokrot & Stefan (1994)	Fortran	Free download	Yes	N/a
12	Qual2K	Chapra et al. (2012)	Kannel et al. (2007)	Fortran / Visual Basic	Free download	Yes	http://www.ecy.wa.gov/programs/eap/models.html
13	RAFT	Pike et al. (2013)	Danner et al. (2012)	N/a	N/a		N/a
14	RMA11	King (2016)	Lowney (2000)	Fortran	Proprietary (Resource Modelling Associates)		http://ikingrma.iinet.net.au/
15	SHADE-HSPF	Becknell et al. (1997)	Chen et al. (1998a) Chen et al. (1998b)	Fortran	Free download	Yes	https://www.epa.gov/exposure-assessment-models/hspf
16	SNTemp	Theurer et al. (1984)	Bartholow (1984) Norton & Bradford (2009)	Basic, Fortran	Free download	Yes	https://www.fort.usgs.gov/products/sb/7557
17	Streamline	Rutherford et al. (1997)	Rutherford et al. (2004)	Fortran / Visual Basic	Available on request		N/a
18	TVA-RMS	Deas et al. (2003)	Null et al. (2010)	C	Available on request	Yes	N/a
19	WAIORA	Jowett et al. (2004)	Davies-Colley et al. (2009)	Delphi	Free download		
20	WASP7	Wool et al. (2008)		Fortran	Free download	Yes	https://www.epa.gov/exposure-assessment-models/water-quality-analysis-simulation-program-wasp
21	WET-Temp	Cox & Bolte (2007)	Watanabe et al. (2005)	C++	Available on request	Yes	N/a

2. Basics of process-based water temperature models

2.1 Energy fluxes determining stream temperature

Stream temperature is determined by a series of energy and hydrological exchanges that act at the air-water and water-streambed interface (Eq. 1, Figure 2; Hannah et al., 2008). At the air-water interface, net radiative (longwave and shortwave energy) fluxes dominate (Caissie, 2006; Hannah et al., 2004). Incident shortwave radiation (H_{sw}) from the sun is typically the largest source of energy for a river system (particularly during summer months; Webb & Zhang, 1997), although bankside objects such as vegetation and/or topography can reduce the amount of solar radiation received by the river through providing shade (e.g. Garner et al., 2014, 2017). Longwave radiation (H_{lw}; thermal energy emitted by all objects with a temperature above 0 °K; Dugdale, 2016) can be both a heat source and sink, with downwelling longwave radiation from clouds, the land surface and bankside vegetation contributing to heat gains, and upwelling radiation from the water surface driving energy losses from the stream (e.g. Benyahya et al., 2012). Energy at the air-water interface is also gained or lost through non-radiative means (latent and sensible heat fluxes; Hannah & Garner, 2015). Latent heat flux (H_e) comprises energy lost (gained) by the stream during evaporation (condensation) as water moves from a higher to lower energy state (or *vice versa*). Sensible heat flux (H_s) encompasses mainly convective exchange between the air and water surface depending upon temperature differences and atmospheric mixing (Webb & Zhang, 1999).

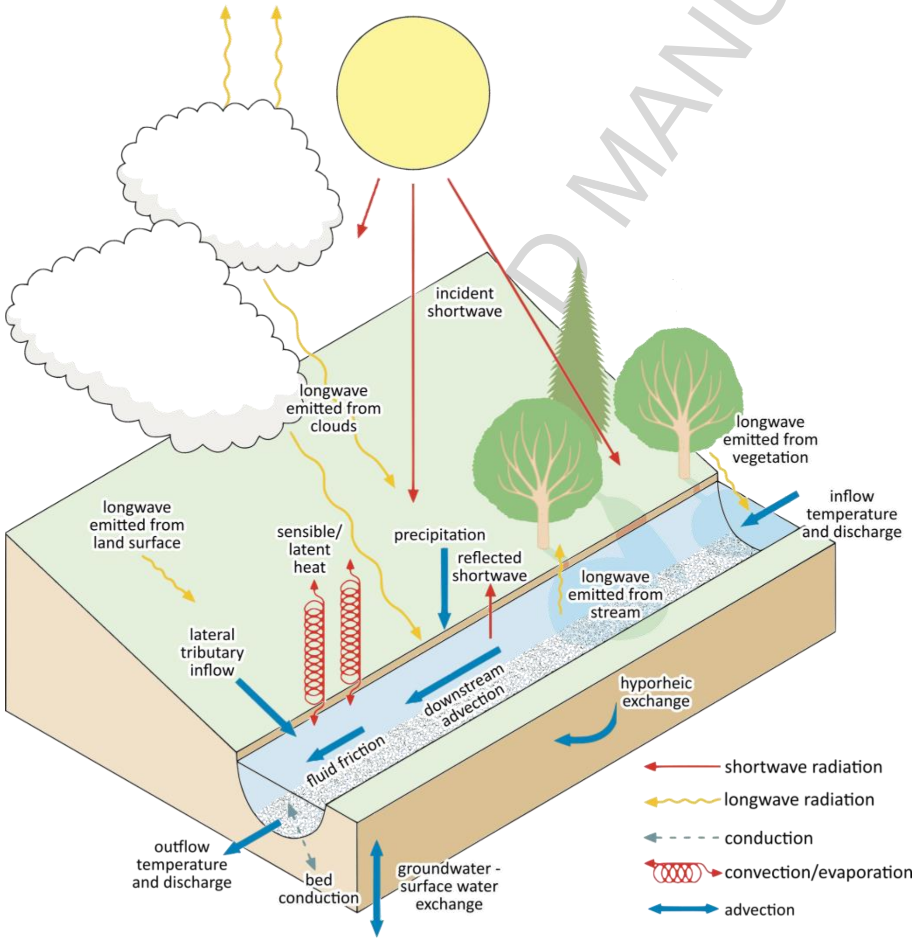

Figure 2. Energy and hydrological exchanges determining stream temperature (modified from Hannah et al., 2008)

At the water-streambed interface, heat is principally exchanged through advective (H_a) and conductive (H_{bhf}) processes. Advective heat transfers from groundwater exfiltration and hyporheic exchanges drive both river temperature warming and cooling (e.g. Hannah et al., 2009; Hébert et al., 2011). Because the temperature of groundwater is broadly stable over the year and the water column exhibits a sinusoidal annual cycle, streambed advective exchanges contribute to stream cooling in the summer and warming during winter months (Caissie, 2006). In addition to these advective processes, conduction between the water column and streambed also drives heat exchange. These fluxes generally act in the same direction as advective transfers, with heat being lost from the water column to the (comparatively) cooler bed in the summer (Webb & Zhang, 2004). However, radiative (shortwave) heating of the bed in in shallow streams can also drive positive conductive transfers from the bed to the water column (e.g. Evans et al, 1998). A final source of energy at the water-streambed interface is fluid friction between the water column and bed/banks. Friction gains are generally minor (e.g. Evans et al., 1998) and often considered negligible (Carrivick et al., 2012) for most rivers, but are sometimes observed in energetic environments (i.e. mountainous streams) with high roughness coefficients (Brown & Hannah, 2008) or large bed material (Chikita et al., 2010).

Taken together, the sum of these heat fluxes occurring at both the air-water and water-streambed interfaces exerts a direct control on the thermal regime of a river. However, the relative magnitude of the fluxes can vary substantially between locations (e.g. Webb & Zhang, 1999; Hannah et al., 2008; Hebert et al., 2011) as a function of variability in prevailing first-order climatic/hydrologic processes and their subsequent modification by second- and third-order river basin controls (Hannah & Garner, 2015). Consequently, the potential of a process-based river temperature model to provide accurate predictions of water temperature is reliant on its capacity to faithfully represent these energy transfers and their interaction with the physical environment through which the river flows.

2.2 Mathematical basis of stream temperature models

Process-based river temperature models function by simulating the addition (removal) of heat to (from) the river channel as a result of the processes detailed in section 2.1. This is achieved by calculating energy fluxes associated with each of these processes and subsequently computing the temperature change to a volume of water. Process-based models are based around two key equations which quantify these processes. Energy fluxes to or from the river channel are first calculated using an energy balance equation (see Webb and Zhang, 1997; Hannah et al., 2004) which describes the net energy gains or losses as a series of radiative, latent, sensible and advective heat exchanges:

(1) $$H_{total} = H_{sw} + H_{lw} + H_e + H_s + H_{bhf} + H_a$$

where H_{total} represents the total energy available for transfer to or from the river channel, H_{sw} is the net shortwave solar radiation flux, H_{lw} is the net longwave radiation flux, H_e is the net energy flux due to evaporation or condensation (latent heat flux), H_s is the net energy gain or loss from convection or conduction (sensible heat flux), H_{bhf} represents heat fluxes to or from the river bed and H_a is the energy gained or lost from groundwater or tributary inflows (all in W m^{-2}).

Depending on the complexity and scope of the river temperature model, some of these energy exchange terms may be omitted from the overall energy balance equation. Indeed, some models only compute surface fluxes and consider bed energy transfers to be negligible. Depending on available data, the individual heat flux terms in Equation 1 are computed using a mix of observed hydrometeorological values and values derived from these observations using empirical or physically based equations. Ouellet et al. (2014b) provide an in-depth review of the various formulae.

Once net heat flux has been calculated, the river temperature change resulting from this energy gain (loss) is computed using Equation 2. The literature contains many variations on this equation (e.g. Sinokrot and Stefan, 1993; Rutherford et al., 1997; Tung et al., 2006; Hebert et al., 2011; Garner et al., 2014) which attempt to account for variability in discharge and channel morphology or compute heat transport in multiple dimensions. However, the basic one-dimensional heat advection-dispersion equation for an open channel of constant cross section and flow is given by Sinokrot and Stefan (1993):

$$(2) \qquad \frac{\partial T_w}{\partial t} = -U\frac{\partial T_w}{\partial x} + D_L\frac{\partial^2 T_w}{\partial x^2} + \frac{H_{total}}{\rho \cdot c_p \cdot d}$$

where T_w is water temperature (°C) at time t, U is mean channel velocity (m s^{-1}), x is streamwise distance (m), D_L is an empirically derived longitudinal dispersion coefficient (m s^{-2}), ρ is the density of water (kg m^{-3}), c_p is the specific heat of water (41.8 x 10^3 J kg^{-1} °C^{-1}) and d is the mean channel depth (m). Equation 2 allows for Eulerian (temporal) computation of river temperature; its rearrangement in the form $\left(\frac{\partial T_w}{\partial x}\right)$ also permits the calculation of river temperature in a Lagrangian (spatial) framework (e.g. Garner et al., 2014). Provided that the channel is well mixed and does not contain notable lateral temperature gradients, the combination of Equations 1 and 2 can be used to simulate water temperature as a function of the input hydrometeorological and geomorphological data.

3. Representation of energy exchange processes

All process-based river temperature models use observed hydrometeorological data to calculate the energy fluxes detailed in Equation 1. However, there exists considerable disparity between the various energy flux terms included within each model and between the routines used to calculate them. This means that the numerical representation of the physical energy fluxes can vary substantially between different river temperature models, and has implications for both model complexity and the quality of river temperature simulations. In this section, we evaluate differences between the models in terms of how they represent the energy fluxes required to compute Equation 1.

3.1 Quantification of radiative fluxes

3.1.1 Incoming solar shortwave radiation

Typically, radiative fluxes (net shortwave and longwave radiation) dominate the heat budget of most river environments (Caissie, 2006), with solar shortwave radiation generally being the largest heat source for a river or stream (Morin and Couillard, 1990; Webb and Zhang, 1997, 2004). If observations of solar radiation are available for a given location, most models (2-5, 7, 9-12, 14-20; Table 2) allow for the direct input of such data. However, observations of incoming solar radiation are often scarce compared to other meteorological variables (i.e. air temperature, precipitation, wind speed, pressure). Consequently, many process-based river temperature models (1, 4-10, 13, 14, 16, 20, 21) contain complex routines capable of approximating the solar radiation received by a given point on the Earth's surface as a function of the date and time (see Boyd and Kasper (2003) for appropriate algorithms). Because such algorithms yield predictions of solar radiation uninfluenced by the atmosphere, these models include further functions allowing for solar radiation values to be corrected for atmospheric transmissivity resulting from a range of factors (e.g. cloud cover, atmospheric dust/water vapour scattering; see Theurer et al. (1984) and Boyd and Kasper (2003) for more detailed summary). Certain models (4, 5, 7, 9, 10, 14, 16, 20) even offer the facility to use both observed solar radiation values and computed data, aiding their flexibility for application in data-poor regions. However, care must be taken when using computed solar radiation values to ensure that they provide a good analogue of real data, either by comparing them to in-situ measurements acquired using a pyranometer or data from meteorological re-analysis programmes (eg. Rienecker et al., 2011). Model choice should therefore be informed by an appraisal of existing solar radiation data and (when using computed values) an appreciation of how well a given model is able to replicate observed data.

3.1.2 Net longwave radiation

While outgoing longwave radiation from the river channel represents a common heat sink, especially during night time or the winter months, studies have also demonstrated that incoming longwave energy from the atmosphere (and riparian vegetation) can mediate heat losses in certain circumstances (Benyahya et al., 2012; Hannah et al., 2008). The effect of longwave radiation must therefore be properly accounted for by the stream temperature model. Some studies involving process-based river temperature models (e.g. Garner et al., 2014) incorporate observations of longwave radiation acquired from net radiometers, but such data are rarely available from meteorological service databases. As a result, all of the river temperature models summarised in Table 1 offer the ability to compute longwave radiative fluxes as a function of other meteorological variables using a variant of the equation:

(3) $$H_{lw} = H_{lw\_atm} - H_{lw\_stream}$$

given:

(4) $$H_{lw\_atm} = (1 - R_L) \cdot \varepsilon_{atm} \cdot \sigma \cdot {T_a}^4$$

(5) $$H_{lw\_stream} = \varepsilon_w \cdot \sigma \cdot {T_w}^4$$

where ε_{atm} and ε_w (≈ 0.97) are the emissivity of the stream and the atmosphere respectively, R_L is the reflectance coefficient of the stream surface (given as 1 - ε_w), σ is the Stefan-Boltzmann constant (5.670367×10^{-8} W m^{-2} K^{-4}) and T_a and T_w are the air and water temperature (°K) respectively.

While these equations may appear relatively simple, complexities arise from the range of different formulae available for the calculation of ε_{atm} (Table 2). Most models (1-4, 7, 8, 10, 11, 14-20) calculate ε_{atm} as a function of either air temperature or vapour pressure using simple empirically derived formulae (air temperature; Swinbank, 1963; Idso and Jackson, 1969; vapour pressure; Brunt, 1932; Anderson, 1954), while others (6, 12) use the physically derived method of Brutsaert (1975) to compute ε_{atm} as a function of both air temperature and vapour pressure. Some models (5, 12) even offer multiple or composite methods for characterising ε_{atm}. Additionally, because atmospheric emissivity is heavily influenced by cloud cover, a number of models (1, 4, 6, 7, 12, 14-19) offer the ability to correct computed emissivity values for the effect of cloud cover using the approach of Bolz (1949), something that is particularly useful in regions where cloudy/overcast conditions dominate. However, several models (5, 9, 13, 21) omit information detailing the method (or derivation thereof) used to compute ε_{atm}. This, coupled with the wide choice of formulae available, means that the choice of river temperature model should therefore be informed by both the availability of data required by the given ε_{atm} equation and an *a priori* assessment of the importance of the longwave radiation contribution to the given river's energy budget. Indeed, particular care should be taken when attempting to apply a river temperature model in environments with potential for a high proportion of longwave fluxes (eg. those with substantial tree/vegetation cover, or cloud-dominated meteorology); in such instances, it may be advisable to quantify incoming radiative energy (eg. Hannah et al., 2008) using net radiometers.

3.1.3 Accounting for the effects of riparian vegetation/topography on radiative fluxes

The presence of near-stream vegetation and topography (ie. steep terrain such as canyons) can have a large influence on the amount of radiation received by a given river reach. Indeed, numerous studies have highlighted how shading from riparian tree cover or steep valley walls can moderate high temperatures, particularly in summer months (e.g. St-Hilaire et al., 2000; Malcolm et al., 2004; Hannah et al., 2008; Leach and Moore, 2010; Garner et al., 2014; Garner et al., 2015). As a result, it is necessary to account for the effect of trees and topographic shading on radiative fluxes when modelling stream temperature in such environments. While some models (3, 5, 9, 10, 13, 14, 20) do not contain any mechanism to account for the effect of vegetation/topography on radiation fluxes, most incorporate algorithms that are able to simulate the reduction in solar shortwave radiation received by the stream (Table 2). Although an in-depth appraisal of the various shading algorithms is beyond the scope of this article, it is pertinent to note that there are clear differences between them. Some models (16, 18, 19) compute the effects of shading using (amongst other variables) sun elevation, tree/topographic height and bank distance, canopy density and stream azimuth to compute a 'shade factor' coefficient that represents the fraction of radiation that does not reach the stream surface due to shading. This coefficient can then be applied to scale the solar radiation components of Equation 1. Other more complex algorithms (2, 6-8, 15, 17, 21) function similarly, but partition incoming solar radiation into its direct and diffuse components. The direct solar radiation received at the stream surface is subsequently calculated either through application of the 'shade factor' coefficient (2, 6, 17) or through modelling the amount by which the solar 'beam' is attenuated as it travels through the tree canopy (7, 8, 15, 21). The fraction of diffuse radiation received by the stream is then quantified separately, usually by means of an algorithm that computes the reach's sky view factor (e.g. 6, 7, 15, 21), a coefficient that represents the fraction of the hemisphere that is unblocked by tree cover/topography. Most shading algorithms are directly integrated within their given stream temperature model. However, some models (1, 4, 11, 12) require that the shading correction be computed externally. Generally, these models rely on GIS analysis or similar to compute either the shade factor coefficients (1, 11, 12) or canopy transmissivity values (4) which are then entered manually into the model. Although this additional step may mean that such models require more time to implement, the ability to manually enter shade correction values means that they are a) able to make use of advances in new shade correction algorithms or b) can be used with field-derived values for shade correction (e.g. Rutherford et al., 1997) that do not rely on the application of an algorithm.

Most shading algorithms are concerned with modifying solar radiation fluxes but some models also apply shading correction to longwave fluxes (4, 6, 7, 16, 17, 19, 21). Atmospheric longwave radiation is affected by riparian/topographic shading in much the same as the diffuse component of solar radiation flux (Hannah et al., 2008). As such, the impact of shading on the atmospheric longwave flux is generally calculated by computing a given reach's sky view factor (e.g. Cox and Bolte, 2007) and applying the resulting coefficient to scale the longwave flux given by Equation 4. Given that all objects with a temperature >0 °K emit longwave radiation, radiation from near-stream vegetation or topography can also represent a significant source of longwave energy. Indeed, studies show that longwave radiation from tree cover can contribute significantly to river temperature during night-time (in comparison to open reaches; Benyahya et al., 2012; Hannah et al., 2008). As a result, the same models also contain routines that compute incident longwave radiation from riparian tree cover and/or topography. This allows such models to estimate longwave radiation fluxes in tree-covered reaches with a high degree of accuracy, potentially improving their utility for predicting water temperature in steep headwater streams or heavily forested catchments.

An additional consideration concerns the spatial discretisation of the computed impacts of riparian vegetation on stream temperature. Because riparian vegetation can vary substantially along a river, any correction for riparian shading or longwave fluxes must account for spatial variability in riparian vegetation. All of the models reviewed here contain routines capable of generating such spatially explicit data using either GIS polygons, tree height rasters or shading coefficients as input data to correct radiative fluxes at the scale of the model's structure (see section 4.3). However, it is important that the chosen model's resolution is sufficiently high to encapsulate true spatial variability in the impacts of riparian vegetation on stream temperature. Similarly, the riparian vegetation data provided to the model must be of a resolution equal to or better than that of the model itself. Recent studies have demonstrated the utility of LiDAR data for providing high resolution raster datasets of riparian vegetation height/shading (eg. Wawrzyniak et al., 2017); such data are therefore particularly appropriate if attempting to model the fine-scale (ie. sub-reach) impacts of vegetation on stream temperature.

Table 2. Methods used to compute radiative flux by reviewed temperature models

		Solar radiation			Longwave radiation			
No.	**Model name**	**Computed or observed**	**Shading correction**	**Solar radiation partitioning (direct, diffuse)**	**Sky emissivity equation(s)**	**Sky emissivity corrected for cloud cover**	**Shading correction**	**Incident longwave from vegetation/ topography**
1	BasinTemp	Computed	Yes (computed externally)		Swinbank (1963)	Yes		
2	CE-QUAL-W2	Observed	Yes	Yes	Brunt (1932)			
3	CEQUEAU	Observed			Anderson (1954)			
4	CrUSTe	Both	Yes (computed externally)		Swinbank (1963)	Yes	Yes	Yes
5	Delft3D-FLOW	Both			Brunt (1932) Modified Brutaseart (1975)			
6	Heat Source	Computed	Yes	Yes	Brutaseart (1975)	Yes	Yes	Yes
7	DHVSM-RBM	Both	Yes	Yes	Swinbank (1963)	Yes	Yes	Yes
8	GIS-STRTemp	Computed	Yes	Yes	Idso and Jackson (1969)			Yes
9	HEC-RAS	Both			N/a			
10	MIKE 11	Both			Brunt (1932)			
11	MNSTREM	Observed	Yes (computed externally)		Idso and Jackson (1969)			
12	Qual2K	Observed	Yes (computed externally)		Brunt (1932) Brutaseart (1975) Koburg (1964)	Yes		
13	RAFT	Computed (from circulation model)			N/a			
14	RMA11	Both			Swinbank (1963)	Yes		
15	SHADE-HSPF	Observed	Yes	Yes	Swinbank (1963)	Yes		
16	SNTemp	Both	Yes		Brunt (1932)	Yes	Yes	Yes
17	Streamline	Observed	Yes	Yes	Swinbank (1963)	Yes	Yes	Yes
18	TVA-RMS	Observed	Yes		Swinbank (1963)	Yes		
19	WAIORA	Observed	Yes	Yes	Brunt (1932)	Yes	Yes	Yes
20	WASP7	Both			Brunt (1932)			
21	WET-Temp	Computed	Yes	Yes	Equation based on relative humidity		Yes	Yes

3.2 Modelling latent and sensible heat fluxes

3.2.1 Latent heat flux

Latent (evaporative) heat loss is a significant energy sink at the river surface (Webb and Zhang, 1997, 2004), particularly in large or open rivers (Maheu et al., 2013; Caissie, 2016). Because direct measurements of energy gains or losses from latent or sensible heat fluxes are rare (Maheu et al., 2013; Caissie, 2016), all of the river temperature models reviewed here derive net latent and sensible heat from meteorological observations. The majority of equations for calculating latent heat fluxes take the same initial form:

(6) $H_e = \rho W \cdot L_e \cdot \bar{E}$

where ρW is the density of water (1x10^{3} kg m^{-3}), L_e is the latent heat of vaporisation (2.5x10^{6} J kg^{-1}) and $\bar{E}$ is the rate of evaporation (m s^{-1}). However, differences in computed latent heat fluxes arise from the choice of equation used to compute $\bar{E}$ (Table 3). While some models (3) currently offer only relatively basic functionality for predicting evaporation rates as a function of air temperature and number of daylight hours (using the Thornthwaite (1948) formula), the majority (1, 2, 4, 5, 7, 9-21) use a variation on Dalton's equation for evaporation (see Lim et al., 2012) to compute evaporation rates using wind speed, actual vapour pressure and saturation vapour pressure. Most equations based around Dalton's equation involve some kind of empirical expression that estimates the adiabatic portion of evaporation as a function of wind speed and field-derived coefficients (referred to as the 'wind function', common coefficients for which can be found in Boyd and Kasper (2003) and Cole and Wells (2015). The accuracy of evaporation predictions can thus depend greatly upon the coefficients used.

In an attempt to reduce the uncertainty associated with such empirical approaches, other models (6, 8) offer the ability to use physically based equations (e.g. Penman, 1948; Monteith, 1965; Priestly and Taylor, 1972) that calculate evaporation rates based on a range of input hydrometeorological data (e.g. net irradiance, wind speed, saturation vapour pressure curve, aerodynamic conductance, etc). The use of a model that incorporates a physically-based evaporation routine may be advisable when implementing a river temperature model in an environment for which 'wind function' coefficients needed by Dalton-type approaches are unavailable. However, comparative studies present conflicting results regarding the relative accuracy of the various methods for computing evaporation (e.g. McJannet et al., 2013; Ouellet et al., 2014b; Alazard et al., 2015) meaning that is may not be advisable to apply these more complex routines unless evaporation rates predicted by simpler methods (e.g. Dalton's equation) are clearly erroneous. Conversely, while evaporative fluxes are generally of greater magnitude in warmer climates, they can represent a highly significant component of stream energy budgets in temperate regions (eg. Hannah et al., 2008). It may therefore be advisable to measure the importance of evaporative flux using an energy balance study (eg. Hannah et al., 2008) or evaporation pan experiments (eg. Maheu et al., 2014) prior to determining whether to apply a model with more complex routines for computing latent heat flux. As a result, model choice must be driven by a) an appreciation of the relative importance of evaporative flux in comparison to other heat fluxes and b) the availability of data required by a given model's evaporation routines.

Table 3. Methods used to calculate evaporation rate by reviewed river temperature models

No.	Model name	Evaporation rate equation
1	BasinTemp	Dalton's equation
2	CE-QUAL-W2	Dalton's equation
3	CEQUEAU	Thornthwaite (1948)
4	CrUSTe	Dalton's equation
5	Delft3D-FLOW	Dalton's equation
6	Heat Source	Dalton’s equation, Penman (1948)
7	DHVSM-RBM	Dalton's equation
8	GIS-STRTemp	Penman (1948)
9	HEC-RAS	Dalton's equation
10	MIKE 11	Dalton's equation (modified)
11	MNSTREM	Dalton's equation
12	Qual2K	Dalton's equation
13	RAFT	Dalton's equation
14	RMA11	Dalton's equation
15	SHADE-HSPF	Dalton's equation
16	SNTemp	Dalton's equation
17	Streamline	Dalton's equation
18	TVA-RMS	Dalton's equation
19	WAIORA	Dalton's equation
20	WASP7	Dalton's equation
21	WET-Temp	Dalton's equation

3.2.2 Sensible heat flux

The magnitude of energy lost or gained through sensible heat exchange is generally lower than radiative or latent fluxes (Caissie, 2006). However, sensible heat fluxes can nonetheless impose a non-negligible control on river temperature (e.g. Webb and Zhang, 1997), acting as both a heat sink in the winter and a heat source during summer months. All of the models reviewed here calculate sensible heat exchanges in essentially the same way following the method of Bowen (1926), either through multiplying the product of the wind function and the air-water temperature gradient by an empirical coefficient, or by applying the Bowen ratio (itself a function of air and water temperature and vapour pressure) to the evaporative flux. Consultation of the literature for the various temperature models documented here reveals minor discrepancies between the various sensible heat flux equations and coefficients used therein (e.g. 4, 9, 10, 15, 16), largely resulting from either unit conversions and/or the necessity of accounting for different wind function coefficients. There is consequently little effective difference in sensible heat flux estimates yielded by the various models discussed here, meaning that model selection is generally driven by other (greater magnitude) sources of thermal energy (eg. radiative, latent and advective fluxes).

3.3 Heat fluxes at the streambed interface

3.3.1 Bed heat flux

While generally smaller in magnitude than surface heat fluxes (Sinokrot and Stefan, 1994; Evans et al., 1998), energy exchange at the streambed-water interface has been noted an important component of the energy balance in some studies, particularly in the winter (e.g. Webb and Zhang, 1997; Hannah et al., 2004; Leach & Moore, 2014). Some river temperature models do not incorporate routines capable of calculating bed heat flux (Table 4), considering its effect on water temperature to be negligible (3-5, 8-10, 21). This is presumably because the majority of these models are designed for application in large river systems where the magnitude of heat exchanges at the streambed interface is particularly diminished in relation to other fluxes (Caissie et al., 2014). However, many other models (1, 2, 6, 7, 11-20) do incorporate bed heat fluxes into their energy balance computations. This is generally accomplished using a variation on Fourier's Law (eg. Story et al., 2003) whereby bed heat flux is computed as a function of the streambed thermal gradient (change in temperature between the streambed-water interface and a given depth within the streambed; Theurer et al., 1984) multiplied by the bed thermal conductivity (the product of bed sediment density, bed heat capacity and bed thermal diffusivity; Boyd and Kasper, 2003). Most of these models refer to this equation as quantifying heat flux arising from conduction between the bed and the water column. However, Hannah et al. (2004) note that it is extremely difficult to disaggregate bed conduction, convection and advection when estimating bed heat flux. Bed heat flux computed with this method may therefore be considered a combination of these three energy exchanges.

As with other heat fluxes detailed here, the quality of bed heat flux predictions is reliant on input data quality and availability. Bed temperature gradient is generally measured using temperature loggers installed at given depths within the bed or modelled numerically given *a priori* knowledge of the bed material and temperature gradients within the riverbed (e.g. Sinokrot and Stefan, 1993), while thermal conductivity is governed by the type of bed material (ie. lithology, porosity, etc) and derived from laboratory analysis of bed sediments (data for which are often available in the literature; Hondzo and Stefan, 1994). Observations of these parameters can be difficult to ascertain, and it is often necessary to provide estimates to the temperature model. However, owing to the high degree of heterogeneity often present in bed temperatures (eg. Birkel et al., 2016), obtaining even an average or estimate can be difficult. In such circumstances, care must be taken to ensure that modelled bed heat fluxes stay within realistic values. Furthermore, given the importance of conductive and advective (eg. hyporheic-driven) bed heat fluxes in some regions (eg. Leach & Moore, 2014), the use of such 'bulk' approaches for computing bed heat fluxes produces a highly simplified estimate of true bed energy transfer processes. Although recent research (eg. Kurylyk et al., 2016; Caissie and Luce, 2017) has proposed improved methods for quantification of bed heat fluxes (and subsequent partitioning into their conductive, convective and advective components), these approaches have not yet been integrated into existing river temperature models and accurate modelling of bed heat fluxes therefore remains a challenge.

In addition to the calculation of 'bulk' bed heat fluxes, some models (6, 13, 18) also include separate routines capable of estimating heat flux due to solar heating of the bed. In most cases, river temperature models function under the assumption that the channel is deep enough that all solar radiation is attenuated within the water column. However, in certain circumstances (ie. shallow headwater streams, streams with considerable exposed boulder material, very low turbidity environments; Chen et al., 1998a), solar warming of the streambed may contribute significantly to river temperature warming (e.g. Evans et al., 1998; Clark et al., 1999; Webb and Zhang, 1999; Johnson, 2004). Because the magnitude of such heat fluxes is both temporally or spatially variable (Webb and Zhang, 1997), it may be beneficial to choose a model that accounts for these processes when modelling temperature in environments where radiative streambed warming is thought to occur. Where possible, it is therefore advisable to quantify the magnitude of bed heat fluxes either by means of Fourier's law (eg. Story et al., 2003) or by using soil heat flux plates, in order to determine whether a) the use of a model capable of accounting for bed heat fluxes is necessary and b) the extent to which modelled fluxes approximate observed data.

Table 4. Details of reviewed river temperature models' capacity to include bed heat fluxes

No.	Model name	Computes bed heat flux	Computes flux from radiative warming of bed	Computes fluid friction with bed/banks
1	BasinTemp	Yes		
2	CE-QUAL-W2	Yes		
3	CEQUEAU			
4	CrUSTe			
5	Delft3D-FLOW			
6	Heat Source	Yes	Yes	
7	DHVSM-RBM	Yes		
8	GIS-STRTemp			
9	HEC-RAS			
10	MIKE 11			
11	MNSTREM	Yes		
12	Qual2K	Yes		
13	RAFT	Yes	Yes	
14	RMA11	Yes		
15	SHADE-HSPF	Yes		
16	SNTemp	Yes		Yes
17	Streamline	Yes		
18	TVA-RMS	Yes	Yes	
19	WAIORA	Yes		Yes
20	WASP7	Yes		
21	WET-Temp			

3.3.3 Fluid friction with the bed and banks

Heat gains from fluid friction can be a significant source of heat in steeper streams with high roughness coefficients (e.g. Hannah et al., 2004; Chikita et al., 2010; Khamis et al., 2015). Although only two publicly available models (16, 19) currently include routines for calculating fluid friction, a range of studies have used the same simple equation for manually estimating friction-driven heat fluxes (e.g. Marsh, 1990; Webb and Zhang, 1997; Hannah et al., 2004; Tung et al., 2006; Chikita et al., 2010; Cardenas et al., 2014). Should suspicions arise that the non-accounting for fluid friction by a given model is biasing temperature estimates (eg. in the case where the user is confident that all other heat flux parameters are accurately modelled but temperature simulations still do not match observed data), it should at least possible to estimate friction gains/losses outside of the model. Furthermore, many coupled hydraulic-water temperature models already include routines for quantifying fluid friction as part of their hydraulic computations. Given the ready ability to customise/script these models, it may be possible to devise routines which use the outputs of these computations to improve temperature estimates in high gradient streams. Nevertheless, with the exception of a few studies (e.g. Webb and Zhang, 1997, 1999) where fluid friction was estimated to be high, such heat exchanges are generally assumed to be minor and can be considered negligible for the majority of temperature modelling scenarios (e.g. Carrivick et al., 2012; Johnson et al., 2014). The ability of a model to account for fluid friction can therefore be considered a low priority during model selection, unless working in particularly high-energy environments.

3.4 Advective heat fluxes

Inflows from tributaries or subsurface inputs can engender substantial temperature gradients in river systems (e.g. Torgersen et al., 1999; Torgersen et al., 2001). All of the models covered in this review contain routines capable of computing advective heat fluxes (Table 5) using the same general equation:

(6) $T_{w,x} = \frac{(T_{w,x-1} \cdot Q) + (T_{in} \cdot Q_{in})}{Q + Q_{in}}$

where Q *and* Q_{in} are the discharge of the main channel and inflow respectively and T_{in} is the temperature of the inflow (Boyd and Kasper, 2003). However, differences between the various models arise from a) the way in which boundary conditions are assigned to advective inputs, b) the way in which inflows arriving from different sources are disaggregated and c) the resolution at which inflows can be assigned within the model.

In terms of assigning boundary conditions to advective inputs, the majority of temperature models require the user to manually input discharge and temperature data associated with inflows. These observations are relatively easy to obtain for surface inflows by means of temperature loggers and discharge gauges. Subsurface inputs are harder to quantify, given the scarcity of groundwater temperature records in many locations and the difficulty of quantifying groundwater flux. Groundwater temperature is therefore often assigned a value equal to mean annual air temperature given the close correlation between these two variables (e.g. Karanth, 1987). However, in regions where groundwater temperature departs significantly from this trend, advective heat fluxes resulting from groundwater inflows may be over- or under-represented. The need for flow or temperature observations can be minimised by using coupled hydraulic or hydrological models (e.g. 3, 7, 9, 10, 15; see sections 4.1 and 4.2) which are able to estimate the flows and temperatures associated with advective inputs. However, although these models are able to simulate surface water contributions with a reasonable degree of accuracy, the resolution of simulated groundwater inflows is often extremely course, requiring additional data on groundwater exfiltration/temperature to be manually entered.

In terms of the disaggregation of inflows resulting from different sources, some models discriminate between tributary inflows and those arising from groundwater processes, allowing tributary inflows to be assigned as point inputs, with groundwater inflows (or indeed, losses to the aquifer; Boyd and Kasper, 2003) modelled as diffuse inputs distributed along a given reach (e.g. 1, 4, 6, 8, 12, 19, 21). Because inflows from different subsurface zones (ie. hyporheic vs. shallow groundwater) have varying hydrologic characteristics (ie. groundwater flux generally involves a permanent change in water volume whereas hyporheic flux is characterised by recurrent exchanges to and from the bed over shorter distances and time periods), some models even offer the ability to model thermal inputs from different subsurface zones (ie. saturated vs unsaturated zones; 3; hyporheic flow; 7, 12, 18). However, other models (2, 5, 10, 14, 16-18, 21) require input of 'bulk' inflows at discrete intervals within the model which merge surface and groundwater inputs together. This means that the true location of a given inflow may not be accurately represented within the model as the 'merging' of several inflows will require that their input location is also a reflection of their combined values. Because subsurface inflows are often more diffuse than tributaries, the merging of advective inputs in this manner may result in a river temperature response that is not properly representative of true subsurface or surface water mixing processes (Pike et al., 2013). Assigning temperatures to these combined inflow data can be difficult given the likely temperature difference between surface and subsurface inflows owing to their different thermal characteristics. In such instances, it may therefore be advisable to apply Equation 6 to estimate the bulk temperature of the combined inflows before it is input into the model. However, it should be noted that through merging diffuse and discrete advective inputs in this manner, a model may produce a false representation of the location and magnitude of warm or cool water inputs which may have implications for certain studies focusing on such phenomena (eg. the ecological significance of cool water refuges; Dugdale et al., 2016).

The ability of a river temperature model to represent advective fluxes is also dependent upon its resolution and structure (covered in further detail in section 4.3). While less of an issue for models using a high resolution gridded structure (2, 5, 13, 14, 20) whereby inflows can be assigned to each grid cell (allowing for multiple advective inputs in a relatively small spatial scale), models operating at reach scales only allow for inflows to be assigned at the resolution of nodes/segments (2, 5, 7, 9, 12, 16-18, 20, 22). An appropriate segment resolution must be chosen in order to ensure that the river temperature response to local advective inputs is represented in the correct geographic location in order that modelled temperature accurate reflects observed data when conducting model calibration. Model selection should therefore be informed by an appreciation of both the relative importance of advective heat inputs (ascertained through flow accretion surveys, tributary gauging, piezometric measurements or similar techniques) and the distribution of these inputs along the study river; in the case of rivers found to have strong advective inflows, only those models capable of accurately representing these features should be considered.

Table 5. Details of reviewed river temperature models' capacity to include advective heat fluxes (bulk inflows vs. separate surface and groundwater inputs)

No.	Model name	Advective input separation	Details
1	BasinTemp	Separate	Can incorporate groundwater inputs, assumes linear mixing along model segment
2	CE-QUAL-W2	Bulk	
3	CEQUEAU	Separate	Hydrological model component allows for separate computation of inflows from surface and saturated and unsaturated subsurface zones
4	CrUSTe	Separate	Can incorporate groundwater inputs, assumes linear mixing along model segment
5	Delft3D-FLOW	Bulk	
6	Heat Source	Separate	Can incorporate point and diffuse groundwater inputs, hyporheic inflows
7	DHVSM-RBM	Separate	Hydrological model component allows for computation of groundwater inflows. Lagrangian (cellular) structure of model permits inflows from different sources (tributaries/groundwater) at each cell
8	GIS-STRTemp	Separate	Can incorporate groundwater inputs, assumes linear mixing along model segment
9	HEC-RAS	Separate	Models groundwater seepage/throughflow using Darcy's Law (see Drake et al., 2010)
10	MIKE 11	Bulk	Hydrological component allows for computation of groundwater inflows
11	MNSTREM	Bulk	
12	Qual2K	Separate	Can assign separate point and diffuse advective fluxes
13	RAFT	Separate	Lagrangian (cellular) structure of model permits inflows from different sources (tributaries/groundwater) an each cell
14	RMA11	Bulk	
15	SHADE-HSPF	Separate	Hydrological component allows for computation of groundwater inflows
16	SNTemp	Bulk	
17	Streamline	Bulk	
18	TVA-RMS	Bulk	
19	WAIORA	Separate	Can incorporate groundwater inputs, assumes linear mixing along model segment
20	WASP7	Bulk	
21	WET-Temp	Separate	Can incorporate groundwater inputs, assumes linear mixing along model segment

4. Model implementation

The differences between the available temperature models are not limited simply to their representation of physical energy fluxes. Indeed, there is also substantial variability in the ways in which the various models are implemented. These differences lie in their ability to model hydraulic (ie. flow velocity and wetted cross-section) and/or hydrological (ie. discharge or rainfall-runoff) data, their structure (ie. their spatio-temporal resolution and dimensionality; Figure 3), considerations regarding their calibration, and the degree to which the models are publicly available and/or open to customisation.   These differences have substantial implications regarding the choice of a suitable river temperature model for a given purpose, and require careful consideration prior to a given model's application (see Table 6 for guidance regarding key model features and contexts in which they may be advantageous). In this section, we review these logistical and operational differences.

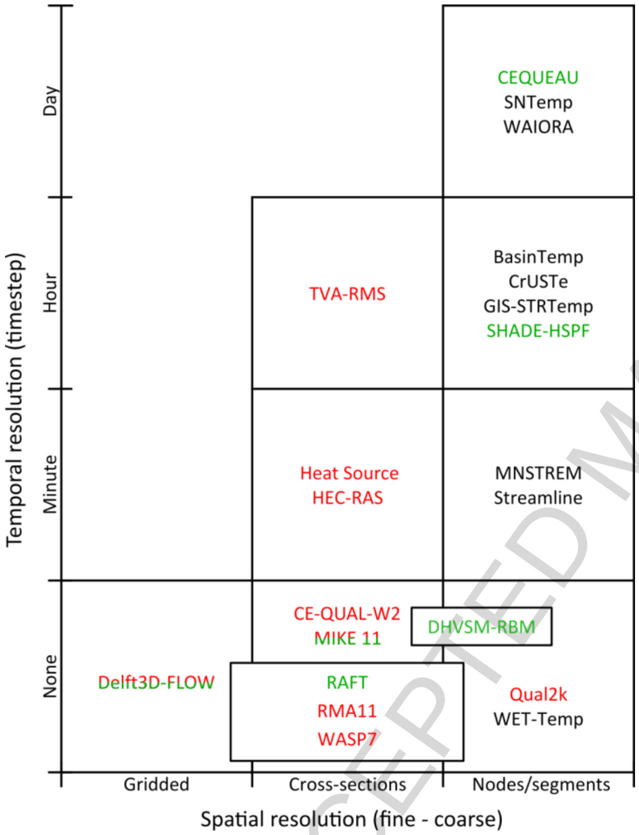

Figure 3. Spatial and temporal resolution of reviewed process-based river temperature models. Red text indicates model with hydraulic coupling, green text indicates hydrological coupling. Figure is greatly simplified for sake of clarity. We acknowledge that spatial resolution can be variable and that it is possible to have node/segment-based models with higher resolution than gridded models.

Table 6. Key model features and contexts in which they may be advantageous

Model feature	When/where is it advantageous?	Energy flux affected (where appropriate)
Ability to estimate incoming solar radiation as a function of date/time and location	Regions for which observations of solar radiation data are scarce.	Shortwave flux
Multiple methods for computation/correction of atmospheric emissivity	Areas prone to overcast conditions and/or significant cloud cover.	Longwave flux
Routines capable of accounting for riparian and topographic shading	Rivers in areas of high forest cover and/or steep topography (ie. valleys, canyons).	Radiative (shortwave and longwave) fluxes. NB. Riparian vegetation also impacts turbulent fluxes (through alterations to the riparian microclimate; see Dugdale et al., 2018), although no existing models account for this (see section 5).
Ability to enter external riparian/topographic shading data	Make use of advances in shading algorithms; input of direct shading observations (eg. from hemispheric photography; Garner et al., 2014).	Radiative (shortwave and longwave) fluxes
Physically based latent heat flux equations	When more basic (ie. Dalton-type) equations fail to provide a reasonable estimate of latent heat flux; areas with high latent heat flux.	Turbulent (evaporative and sensible) fluxes. Predominantly latent heat flux, but can also impact sensible heat flux through application of Bowen ratio (see section 3.2.2).
Ability to model bed heat flux	Rivers with significant groundwater or hyporheic contributions; regions with permeable bedrock and/or elevated water-table.	Bed heat flux
Ability to disaggregate advective inflows from multiple different sources (ie. surface vs groundwater)	Rivers with strong spatial temperature heterogeneity.	Advective flux
Hydraulic model coupling	Dynamic rivers; environments prone to rapid spatio-temporal changes in width:depth or velocity	-
Hydrological model coupling	Regions where hydrometric data are scarce; prediction of potential climate change impacts on rivers	-
Higher dimensionality (ie. 2D, 3D)	Rivers with strong vertical or lateral temperature gradients or stratification (eg. impounded rivers, estuaries)	-
Sub-daily model timestep	Generation of advanced thermal metrics (ie. degree hours, time spent above a given threshold)	-

4.1 Hydraulic model integration and representation of channel morphology

As accurate temperature predictions require a good representation of channel morphology, it is important to consider the methodology that a given temperature model uses to obtain these parameters. At the most basic level, a river temperature model requires input data concerning the area and time over which energy transfers occur (e.g. Theurer et al., 1984) in order to calculate total heat flux for a given section of river. Values of channel width, depth, and velocity for each element within a model must be available in order to compute Equation 2. While these data are generally derived from field measurements or GIS databases, one of the principal limitations of stream temperature models that require these data is their assumption that channel width, depth and velocity remain temporally stable. In reality, variations in discharge will inherently lead to changes in wetted cross-section and flow velocity, which will alter energy fluxes at the channel surface and bed. In ideal circumstances, time series of width, depth and velocity change (obtained using dataloggers or similar) would enable the appropriate values to be input into the model at each timestep, but such data (especially spatially distributed observations) are rarely available in practise. Instead, some temperature models have a limited ability to account for changes in wetted cross-section and/or velocity either through the use of Manning's equation (e.g. Robert, 2003) to compute changes in width/depth as a function of stream gradient and velocity (e.g. 21) or by using empirically derived discharge-width and discharge-velocity ratings curves (e.g. 13, 17). However, given that these methods rely on empirical or semi-empirical functions, the temperatures predicted by such models may only hold true in relatively steady-state environments where there is little spatio-temporal change in channel morphology or flow velocity.

In an attempt to address these limitations, many river temperature models are now coupled to hydraulic models (Table 7), allowing them to simulate flow velocity and wetted cross-section as a function of input channel morphology data for the entire range of discharges exhibited by the river (2, 5, 6, 9, 10, 12, 14, 18, 20). The ability to incorporate spatially and temporally explicit hydraulic data into the temperature model means that such models are able to calculate energy fluxes in more dynamic fluvial environments with a greater degree of accuracy, improving temperature predictions. However, such models are necessarily more complex, and their increased data requirements and higher parameterisation may mean that their use is beyond the scope of some river temperature studies. Additionally, the hydraulic model's velocity/stage predictions must also be thoroughly calibrated/validated against observed data, meaning that the implementation of such models can be time consuming when compared to more simplistic systems. Nevertheless, when working in environments that are particularly dynamic and/or prone to rapid changes in width/depth ratio which could greatly impact stream temperature (eg. upland environments), the selection of a hydraulically-coupled model may be advisable.

Table 7. Details of hydraulic/hydrological coupling, dimensionality, and spatial and temporal resolution/structure for reviewed river temperature models

No.	Model name	Hydraulically coupled	Hydrologically coupled	No. dimensions	Minimum timestep	Model structure
1	BasinTemp			1	Hourly	Nodes/segments
2	CE-QUAL-W2	Yes		2 (longitudinal, vertical)	None	Cross-sections with vertical cells (2D)
3	CEQUEAU		Yes	1	Daily	Gridded hydrological model, but 1D temperature (node-based)
4	CrUSTe			1	Hourly	Nodes/segments
5	Delft3D-FLOW	Yes	Yes	3	None	Gridded (2D/3D)
6	Heat Source	Yes		1	Minute	Cross-sections
7	DHVSM-RBM		Yes	1	None	Nodes/segments (each segment subdivided into cells for Lagrangian functionality)
8	GIS-STRTemp			1	Hourly	Nodes/segment
9	HEC-RAS	Yes		1	Minute	Cross-sections
10	MIKE 11	Yes	Yes	1	None	Cross-sections
11	MNSTREM			1	Minute	Nodes/segments
12	Qual2K	Yes		1	None	Cross-sections
13	RAFT		Yes	1	None	Cellular (Lagrangian)
14	RMA11	Yes		1 to 3	None	Nodes/segments (1D) or gridded (2D/3D)
15	SHADE-HSPF		Yes	1	Hourly	Nodes/segments
16	SNTemp			1	Daily	Nodes/segments
17	Streamline			1	15 minutes	Nodes/segments
18	TVA-RMS	Yes		1	Hourly	Cross-sections
19	WAIORA			1	Daily	Nodes/segments
20	WASP7	Yes		1 to 3	None	Nodes/segments (1D) or gridded (2D/3D)
21	WET-Temp			1	None	Nodes/segments

4.2 Hydrological model integration

In addition to hydraulic functionality, other river temperature models offer full hydrological coupling, enabling the simulation of discharge (as a function of input meteorology data) in addition to temperature (Table 7). Such models are useful for simulating river temperature in remote or sparsely gauged watersheds where hydrometric data are rare. Additionally, these models often allow for the representation of different thermal characteristics of multiple source water components, offering a high degree of utility for assessing the consequences of changing hydroclimatic conditions on stream temperature across watersheds with varying patterns of recharge and discharge. However, the prediction of water temperature is often not the prime function of such models. Indeed, of the coupled temperature-hydrological models detailed here, two were first conceived as hydrological models, with water temperature routines being added at a later date (3, 15), while (5) and (10) are principally hydraulic/hydrodynamic models which also offer routines for rainfall-runoff and water temperature simulation. This does not necessarily mean that temperature simulations from such models will be of lower accuracy than dedicated river temperature models. However, model implementation is generally more complex and the data requirements greater than dedicated water temperature models. Nevertheless, because coupled temperature-hydrological models allow for the simultaneous simulation of discharge and temperature, they offer increased utility with regards to predicting the effects of climate change to river ecosystems (e.g. Danner et al., 2012; van Vliet et al., 2012; Ficklin et al., 2014), given that climate change is expected to influence both of these metrics in the future. The use of a coupled temperature-hydrological model may therefore be advisable should the scope of a study extend to modelling the impacts of future climatic warming on river ecosystems or should temperature predictions be required for a river that lacks discharge measurements. However, the hydrological model's discharge simulations must be thoroughly calibrated/validated prior to use, a process which can be time consuming. This, coupled with the relative complexity of hydrological model implementation means that such models will generally be unnecessary for most 'conventional' stream temperature studies.

4.3 Model structure and resolution

4.3.1 Spatial resolution and dimensionality

The spatio-temporal resolution of river temperature simulations varies substantially between the various models discussed here (Figure 3). While some models are limited to providing temperature predictions at relatively coarse scales and time steps, others effectively offer no upper limit on resolution, allowing temperature predictions to be discretised at a scale of the user's choosing. In terms of spatial resolution, model choice is largely informed by the intended application. Models capable of providing data at fine spatial scales offer increased utility to understanding linkages between ecosystem dynamics and water temperature (through the use of models to locate cool or warm water refuges or determine the fine-scale response of stream temperature to vegetation), while lower resolution models may be more relevant for providing synoptic data to inform water resources management. In examining their spatial resolution, river temperature models can generally be separated into two classes: one-dimensional models, and multi-dimensional (gridded) models (Table 7).

In one-dimensional models (1, 3, 4, 6-13, 15-19, 21), the river channel is generally discretised as a series of segments or nodes of essentially homogeneous conditions whose length is dependent on the requirements of the study and/or the presence of longitudinal discontinuities (e.g. tributary inflows, substantial changes in channel morphology). Hydrometeorological data necessary for computing Equation 1 are attributed to each segment/node. Because meteorological observations are rarely discretised at the resolution of each segment/node, meteorological data are either attributed to each model segment/node manually (4, 6, 10, 12, 15-18) or by interpolation from one or more nearby weather stations (3, 7, 9, 21). Channel morphology and hydrometric data necessary for computing Equation 2 are also attributed to each node or segment; in the case of 1D coupled hydraulic-temperature models (6, 9, 10, 12, 18) nodes are assigned detailed measurements of channel cross-section required by the hydraulic computations. Where applicable, measurements of riparian vegetation necessary for the shading routines of the model are also attributed to each segment/node. Equations 1 and 2 are subsequently computed for each segment/node, yielding temperature simulations in a single (longitudinal) dimension. The longitudinal resolution of simulated temperatures is thus dependent upon either the length of the segments or the spacing between model nodes, and is generally a user-defined property. In theory, this means that such models should allow for predictions at extremely fine spatial resolution where required. However, in practise, the resolution of temperature predictions is driven largely by the resolution of the input channel morphology and hydrometeorological data. While interpolation can be used to increase the resolution of input data allowing for finer scale simulations, the memory and processing/programming limitations of the model may prohibit the use of very high resolutions. Although some one dimensional temperature models focus on providing simulations for single thread channels (4, 8, 11, 17), most also allow for the computation of river temperature across entire networks, through representing the river network as a directed graph (1, 3, 6, 7, 9, 10, 12, 13, 15, 16, 18, 19, 21). Such models are particularly useful for providing basin-wide predictions of water temperature, should such information be needed for management purposes or similar.

Gridded models (2, 5, 14, 20) allow for the simulation of temperature in multiple dimensions. This facility is often unnecessary in smaller rivers but such models are useful in larger systems where significant vertical and/or lateral temperature gradients exist such as impounded rivers with deep stratified channels and reservoirs (e.g. Wang and Martin, 1991; Hanna et al., 1999) or large rivers/estuarine environments (e.g. Ouellet et al., 2014a). Gridded models function in the same general manner as 1D models using Equations 1 and 2. However, Equation 2 also computes advection/dispersion in multiple dimensions and is necessarily more complex. Furthermore, because most gridded temperature models are based on hydraulic/hydrodynamic models, temperature simulations are provided at the same resolution as the bathymetric grid used for hydraulic simulations (e.g. Deltares, 2014). While this means that temperature predictions from gridded models can be of a higher resolution than their 1D counterparts, input hydrometeorological data used in Equation 1 are generally interpolated up to the resolution of the model grid. Therefore, despite the higher spatial resolution, the accuracy of temperature predictions is largely dependent on the quality of the interpolation, and may not be better than 1D simulations. Furthermore, at particularly fine resolution, the extremely small modelled temperature differences between successive grid cells may indeed be smaller than the error of the model itself. In light of this and the fact that 2D and 3D river temperature models are generally more complex to implement than simpler 1D models (and have substantially increased processing requirements), the additional functionality of gridded models may be redundant unless a study specifically requires the ability to simulate water temperature in multiple dimensions (eg. in the presence of significant stratification or highly variable turbulence/mixing patterns).

4.3.2 Temporal resolution

Temporal resolution is also an important consideration when choosing a river temperature model. While some applications (ie. stream thermal regime classification) require only simple daily metrics (eg. mean/maximum temperature) generated by models operating at low temporal resolution, higher frequency data are often important. Indeed, models operating at higher temporal resolution are able to generate more advanced thermal metrics (eg. period of time spent above a given threshold), which can be useful for detailed studies of stream thermal ecology or for informing river management decisions.

The difference between models in terms of their temporal resolution is considerably more limited than in terms of their spatial resolution (Table 7). The lowest temporal resolution models reviewed here (4, 17, 20) provide temperature simulations on a daily timestep, allowing for broad characterisation of river temperature metrics. However, the majority of models offer considerably shorter timesteps, simulating temperature on hourly or sub-hourly steps (1, 4, 6, 8, 9, 11, 15, 17, 18) or even offering no effective minimum temporal resolution (2, 5, 7, 10, 12-14, 20, 21). Such models are readily able to reproduce diurnal temperature variability and allow for the extraction of key temperature metrics relevant to fluvial ecology or water quality studies. However, similar to that noted in section 4.3.1, the minimum timestep of a model is essentially governed by the temporal resolution of the input hydrometeorological data used to drive it, meaning that model choice should be advised by both the requirements of the study and the available discharge and meteorology observations. Given that model runtime is intrinsically linked to the number of model timesteps (ie. the length of the simulation period divided by the temporal resolution), model selection must be made with an appreciation of the processing time required to generate a temperature simulation.

4.4 Model calibration/validation

Most river temperature models require calibration/validation to ensure that they produce an accurate representation of true river temperature. This is because models contain a simplified representation of true energy fluxes and basin physiography (see section 3, 4.1-4.3), meaning that simulations do not provide a perfect analogue of true river temperature. In order to ensure that simulated temperatures are as close to observed data as possible, the model must be calibrated by tuning coefficients related to the empirical elements of the heat budget equations (see Ouellet et al., 2014b) or channel morphology (e.g. bed thermal conductivity, Manning's roughness) of the study river. Descriptive statistics are then used to quantify the relative performance of the model against temperature observations recorded *in-situ*. Because of the strong seasonal component present in river temperature series, the use of the model's root mean-squared error (RMSE) is generally preferred to the Nash-Sutcliffe model efficiency coefficient (NSE; see Janssen and Heuberger, 1995) or other similar measures due to the fact that RMSE remains unbiased by seasonal cyclicity. Some river temperature models are relatively highly parameterised, meaning that model calibration can be laborious. In such cases, it may be advisable to calibrate the model using algorithmic approaches (e.g. Zheng and Wang, 1996; Hansen and Ostermeier, 2001; Arsenault et al., 2014) that optimise model calibration by iteratively refining parameters to minimise the difference between observed and predicted values (ie. by minimising RMSE). However, when using such algorithms, care must be taken to ensure that physically plausible bounds are used to constrain the calibration coefficients to ensure that the algorithm does not automatically arrive at a calibration which produces good temperature simulations at the expense of unrealistic energy fluxes. It may also be advisable, when calibrating highly parameterised models, to conduct sensitivity analyses to better understand how changes to the various parameters influence model predictions. Such an exercise may help to reveal not only important information regarding model functionality and the influence of various parameters on simulated temperatures, but may also infer the dominant processes controlling the thermal regime of the modelled river.

In terms of data required for model calibration/validation, the vast majority of studies involving river temperature modelling use temperature loggers to provide observations of true water temperature. Loggers are typically installed within the active channel and housed in shielding to prevent bias from solar radiation and damage from collision with bedload. The spatial distribution and logging frequency (temporal resolution) of temperature observations acquired using loggers is informed by the study and chosen model. While loggers are an appropriate source of data for calibration/validation in most studies, models operating at particularly fine longitudinal scales may require data at higher spatial resolutions. Indeed, spatially-continuous data from fibre-optic distributed temperature sensing (FO-DTS) technology (eg. Bond et al., 2015) or airborne thermal infrared (TIR) data (eg. Boyd and Casper, 2003; Cristea and Burges, 2009) have been successfully used as data sources for river temperature model calibration/validation (models 6, 12). However, it should be noted that all three of these methodologies (loggers, FO-DTS and airborne TIR) have limitations; loggers in terms of their inability to provide spatially-continuous data, FO-DTS in terms of the relatively short distance over which it can be used and airborne TIR in terms of its ability to provide only a temporal 'snapshot' of longitudinal river temperature variability. Where possible, efforts should therefore be made to combine these approaches for achieving the best possible model calibration/validation.

4.5 Model availability and customisability

Another key consideration when determining the most appropriate river temperature model for a given study is the model's availability and potential for customisation to a specific application (Table 1). Of the models discussed in this paper, the majority are either publicly available (as of 2016) or have been made available at some point during their development cycle. However, it is necessary to differentiate between models that are freely available to download (2, 5-7, 9, 11, 12, 15, 16, 19, 20) or on request from the authors (3, 17, 18, 21) and those that are either proprietary (1, 14) or only available commercially (10). Although some studies will require the additional functionality of proprietary/commercial models (eg. full hydrodynamic integration; 10, 14), the range of publicly available models that now exists means that open-source/freeware alternatives are often the preferred option for studies involving river temperature modelling. Additionally, the source code of many publicly available models is also available for modification (2, 3 5-7, 11, 12, 15, 16, 18, 20, 21), allowing the user to edit the model routines and develop new modules as required. Such a facility offers increased flexibility to a given temperature model, with user-driven development of new functions allowing it to stay abreast of advances in river temperature research. For example, the authors are aware of at least one river temperature model where ready access to the model's source code is driving user development of improved evaporative flux and canopy shading functions (see St-Hilaire et al., 2015).

5. Current limitations and opportunities for future research

Despite the generally high degree of accuracy with which modern process-based temperature models are able to simulate thermal processes in rivers (e.g. RMSE $\lesssim$1.0 °C at sub-hourly to hourly timesteps over seasonal to annual periods; Garner et al., 2014; Hébert et al., 2015; Woltemade and Hawkins, 2016), there remain several limitations to their application. Primarily, these limitations relate to issues associated with the energy balance calculations or input resolution (see sections 3 and 4.3). In terms of energy balance, models are often limited by the relative simplicity of their process representation. Surface fluxes usually dominate the energy budget (Caissie, 2006) and so models have focused on quantifying surface heat transfers with a good degree of detail. However, there is still room for improvement, particularly with regards to modelling the impacts of riparian vegetation on heat fluxes at the air-water interface. While most models are now capable of computing the impact of riparian tree cover on radiative fluxes, none are currently able to quantify how bankside vegetation alters turbulent heat fluxes through alterations to the riparian microclimate (eg. Dugdale et al., 2018). Improvements in this regard would aid model performance in forested regions and help efforts to understand future impacts of land-use or climate change on river temperature regimes.

Energy fluxes at the streambed interface are less well represented by currently available models, and many provide only a relatively generalised ability to quantify bed heat fluxes or advective heat transfer. Because of this, modelling river temperature in systems with major groundwater contributions requires special attention. The limited ability of currently available models to represent heat and mass transfers from different sources (eg. soil water, groundwater) coupled to the lack of large-scale estimates of certain inflow types (eg. hyporheic flow) is a major challenge, and future research should therefore focus on improving model representation of subsurface fluxes. The potential coupling of river temperature models to detailed groundwater-surface water flux routines (e.g. Kurylyk et al., 2014) could help to address this shortcoming, as could further research characterising the spatio-temporal variability (and driving mechanisms) of hyporheic fluxes (eg. Birkel et al., 2016). Such advances would help improve model performance in groundwater dominated regions and also shed new light on the role of subsurface hydrological processes in driving river temperature (a research gap noted by Hannah and Garner, 2015).

In addition to groundwater, the representation of energy advected by other phenomena such as precipitation (e.g. Null et al., 2013) or meltwater (e.g. Greene and Outcalt, 1985) is often omitted from the energy balance. While these energy transfers are sometimes covered by coupled hydrological-water temperature models (e.g. van Vliet et al., 2012), more 'unusual' fluxes such as heat generated through fluid viscosity (resulting from friction generated by the movement of water molecules against each other) or energy contributions from in-stream chemical and biological processes (Webb & Zhang, 1997) or precipitation are very rarely quantified. The development of model routines capable of computing these heat fluxes would help to 'close' the model's energy balance, minimising errors resulting from the non-representation of such fluxes. Indeed, such data would reduce uncertainty regarding whether model errors arise from the simplicity of the model's heat budget or from other sources. Further research is therefore needed into how best to implement these 'unusual' energy fluxes within river temperature models and the circumstances where they may represent a significant source (sink) of energy. However, it is important to remember that in the majority of cases, the conventional energy balance equation (Equation 1) produces a more-than-adequate representation of heat fluxes, and the addition of such extra layers of complexity is generally unnecessary.

Another limitation of current process-based river temperature models relates to the availability and resolution of input meteorological and physiographic data. Because process-based models require input meteorology or land-use data, their utility for modelling temperatures in remote locations is limited. Furthermore, even when data does exist, river temperature model inputs are often based on point data (i.e. single isolated meteorological stations or coarse-resolution land-use data) which are unable to encapsulate variability in hydrometeorology or basin physiography. Difficulties in scaling up model inputs from these point locations to the resolution of the chosen model can impact simulation quality. There is consequently a need to develop approaches for the acquisition and/or upscaling of data necessary for modelling temperatures in inaccessible regions or at increased resolutions. Geostatistical approaches have previously been used with success to upscale meteorological data (e.g. air temperature; Spadavecchia and Williams, 2009) and channel morphology (e.g. Legleiter and Kyriakidis, 2008; Merwade, 2009). However, neither of these approaches has been applied in a river temperature modelling context, and more research is therefore needed in order to facilitate the application of process-based models in data-poor regions. Similarly, while remote sensing has shown strong potential for deriving fine scale observations of meteorology (e.g. Rienecker et al., 2011; Vinukollu et al., 2011) and/or channel morphology (e.g. Marcus and Fonstad, 2008; Fonstad et al., 2013) that would be suitable as inputs to river temperature models, studies combining these remote sensing approaches with river temperature modelling are uncommon. Future research combining statistical upscaling methods with remote sensing should thus be prioritised with a view to generating high resolution meteorology and physiographic inputs necessary for improving river temperature model performance, particularly in remote locations. Given that remote sensing has been demonstrated useful both for deriving and providing fine scale temperature data needed for model calibration/validation (through the application of thermal infrared imagery; Handcock et al., 2012), the combination of river temperature models with remote sensing data (e.g. Vatland et al., 2015) clearly has potential.

A final limitation to the use of water temperature models concerns the necessity of specifying boundary conditions to the model and the implications of this for reach- to watershed-scale temperature models. In all process-based water temperature models, water temperature is both the product and a boundary condition of the energy balance because it is required for the calculation of outgoing longwave radiation, turbulent heat fluxes and bed heat flux (see sections 3.1.2, 3.2 and 3.3.1) which are in turn used to compute water temperature (Moore et al, 2005). This means that data concerning water temperature are actually required by the model to then simulate temperature. For small reach-scale models with few advective inputs, a single upstream temperature boundary condition may suffice. However, in the case of larger models with multiple inflows, it is necessary to attribute a temperature boundary condition to each of these inputs, meaning that additional input river temperature observations are required. Unfortunately, this can lead to considerable data requirements when modelling entire river networks. The use of coupled hydrological-water temperature models (which effectively simulate river discharge and temperature from source to confluence; e.g. 3, 7, 15) may alleviate this problem, as only the boundary condition required is the water temperature of the headwater exfiltration (which can be approximated by mean annual air temperature; e.g. Karanth, 1987). Alternatively, spatial regression models or spatial statistical network models (eg. Jackson et al., 2017; Isaak et al., 2015) could be used to provide boundary conditions at locations for which temperature observations do not exist. However, it is necessary to note that composite model approaches such as these may increase model error due to the multiple layers of uncertainty associated with the simulated data.

In their review paper, Benyaha et al. (2007) noted the importance of the newer generation of statistical models for understanding the influence of environmental variables on stream temperature. We suggest that process-based temperature models have an equally important role to play in the river sciences and that the two approaches are highly complementary. Because of process-based models' unique ability to illuminate the fundamental processes driving river temperature dynamics, they are ideally positioned to inform appropriate metrics to be used in larger-scale statistical approaches. Conversely, statistical approaches provide a potential solution for addressing issues of data or boundary condition availability within process-based models. There is therefore substantial scope to combine statistical and process-based models in a complementary capacity, not only to improve the quality of river temperature simulations from existing models, but also to better identify and understand the fundamental linkages between hydrometeorology, river basin properties, and river temperature. Such advances will allow for more accurate river temperature projections in space and time, and will be of great use to water resource managers and other environmental practitioners charged with better understanding and protecting sensitive river environments. We hope that the information presented here spurs further investigations using process-based river temperature models, in terms of both their continued refinement and their use for addressing fundamental questions in the river sciences.

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References

Alazard, M., Leduc, C., Travi, Y., Boulet, G., & Ben Salem, A. (2015). Estimating evaporation in semi-arid areas facing data scarcity: Example of the El Haouareb dam (Merguellil catchment, Central Tunisia). *Journal of Hydrology: Regional Studies, 3*, 265-284

Allen, D.M. (2008). *Development and application of a process-based, basin-scale stream temperature model.* PhD thesis. University of California, Berkeley, CA

Allen, D.M., Dietrich, W., Baker, P., Ligon, F., & Orr, B. (2007). Development of a Mechanistically Based, Basin-Scale Stream Temperature Model: Applications to Cumulative Effects Modeling. In R.B. Standiford, G.A. Giusti, Y. Valachovic, W.J. Zielinski, & M.J. Furniss (Eds.), *Proceedings of the redwood region forest science symposium: What does the future hold? General Technical Report PSW-GTR-194* (pp. 11-24). Albany, CA: US Forest Service

Anderson, E. (1954). Energy Budget Studies. *Water-loss investigations; Lake Hefner studies, technical report, USGS Professional Paper 269*, Washington, D.C.: US Geological Survey, 71-119

Arsenault, R., Poulin, A., Côté, P., & Brissette, F. (2014). Comparison of Stochastic Optimization Algorithms in Hydrological Model Calibration. *Journal of Hydrologic Engineering, 19*, 1374-1384

Bärlocher, F., Seena, S., Wilson, K.P., & Dudley Williams, D. (2008). Raised water temperature lowers diversity of hyporheic aquatic hyphomycetes. *Freshwater Biology, 53*, 368-379

Bartholow, J.M. (1989). *Stream temperature investigations: field and analytic methods. Biological Report 89(17)*. Washington, D.C.: US Fish and Wildlife Service, 139 p

Benyahya, L., Caissie, D., Satish, M.G., & El-Jabi, N. (2012). Long-wave radiation and heat flux estimates within a small tributary in Catamaran Brook (New Brunswick, Canada). *Hydrological Processes, 26*, 475-484

Benyahya, L., Caissie, D., St-Hilaire, A., Ouarda, T.B.M.J., & Bobée, B. (2007). A Review of Statistical Water Temperature Models. *Canadian Water Resources Journal / Revue canadienne des ressources hydriques, 32*, 179-192

Birkel, C., Soulsby, C., Irvine, D.J., Malcolm, I., Lautz, L.K., & Tetzlaff, D. (2016). Heat-based hyporheic flux calculations in heterogeneous salmon spawning gravels. *Aquatic Sciences*, 78, 203-213

Bloomfield, J.P., Williams, R.J., Gooddy, D.C., Cape, J.N., & Guha, P. (2006). Impacts of climate change on the fate and behaviour of pesticides in surface and groundwater—a UK perspective. *Science of The Total Environment, 369*, 163-177

Bolz, H.M. (1949). Die Abhängigkeit der infraroten Gegenstrahlung von der Bewölkung. *Zeitschrift für Meteorologie, 3*, 201-203

Bond, R.M., Stubblefield, A.P., & Van Kirk, R.W. (2015). Sensitivity of summer stream temperatures to climate variability and riparian reforestation strategies. *Journal of Hydrology: Regional Studies, 4, Part B*, 267-279

Bowen, I.S. (1926). The Ratio of Heat Losses by Conduction and by Evaporation from any Water Surface. *Physical Review, 27*, 779-787

Boyd, M., & Kasper, B. (2003). *Analytical methods for dynamic open channel heat and mass transfer: Methodology for Heat Source model version 7.0*. Portland, OR: Oregon Department of Environmental Quality, 193 p

Boyer, C., St-Hilaire, A., Bergeron, N.E., Daigle, A., Curry, R.A., & Caissie, D. (2016). RivTemp: A water temperature network for Atlantic salmon rivers in eastern Canada. *Water News, 35*, 10-15

Breau, C., Cunjak, R.A., & Bremset, G. (2007). Age-specific aggregation of wild juvenile Atlantic salmon Salmo salar at cool water sources during high temperature events. *Journal of Fish Biology, 71*, 1179-1191

Brown, L.E., & Hannah, D.M. (2008). *Spatial heterogeneity of water temperature across an alpine river basin. Hydrological Processes, 22*, 954-967

Brunner, G.W. (2016). *HEC-RAS River Analysis System: User's Manual (version 5.0)*. Davis, CA: US Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, 962 p

Brunt, D. (1932). Notes on radiation in the atmosphere. *Quarterly Journal of the Royal Meteorological Society, 58*, 389-420

Brutsaert, W. (1975). On a derivable formula for long-wave radiation from clear skies. *Water Resources Research, 11*, 742-744

Burkholder, B.K., Grant, G.E., Haggerty, R., Khangaonkar, T., & Wampler, P.J. (2008). Influence of hyporheic flow and geomorphology on temperature of a large, gravel-bed river, Clackamas River, Oregon, USA. *Hydrological Processes, 22*, 941-953

Caissie, D. (2006). The thermal regime of rivers: a review. *Freshwater Biology, 51*, 1389-1406

Caissie, D. (2016). River evaporation, condensation and heat fluxes within a first-order tributary of Catamaran Brook (New Brunswick, Canada). *Hydrological Processes, 30*, 1872-1883

Caissie, D., Kurylyk, B.L., St-Hilaire, A., El-Jabi, N., & MacQuarrie, K.T.B. (2014). Streambed temperature dynamics and corresponding heat fluxes in small streams experiencing seasonal ice cover. *Journal of Hydrology, 519, Part B*, 1441-1452

Caissie, D., Satish, M.G., & El-Jabi, N. (2007). Predicting water temperatures using a deterministic model: Application on Miramichi River catchments (New Brunswick, Canada). *Journal of Hydrology, 336*, 303-315

Caissie, D., & Luce, C.H. (2017). Quantifying streambed advection and conduction heat fluxes. *Water Resources Research, 53*, 1595-1624

Caldwell, P., Segura, C., Gull Laird, S., Sun, G., McNulty, S.G., Sandercock, M., Boggs, J., & Vose, J.M. (2015). Short-term stream water temperature observations permit rapid assessment of potential climate change impacts. *Hydrological Processes, 29*, 2196-2211

Cardenas, M.B., Doering, M., Rivas, D.S., Galdeano, C., Neilson, B.T., & Robinson, C.T. (2014). Analysis of the temperature dynamics of a proglacial river using time-lapse thermal imaging and energy balance modeling. *Journal of Hydrology, 519, Part B*, 1963-1973

Carrivick, J.L., Brown, L.E., Hannah, D.M., & Turner, A.G.D. (2012). Numerical modelling of spatio-temporal thermal heterogeneity in a complex river system. *Journal of Hydrology, 414–415*, 491-502

Chapra, S., Pelletier, G., & Tao, H. (2012). *QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality, Version 2.12: Documentation and Users Manual*. Medford, MA: Department of Civil and Environmental Engineering, Tufts University, 97 p

Chen, Y.D., Carsel, R.F., McCutcheon, S.C., & Nutter, W.L. (1998a). Stream Temperature Simulation of Forested Riparian Areas: I. Watershed-Scale Model Development. *Journal of Environmental Engineering, 124*, 304-315

Chen, Y.D., McCutcheon, S.C., Norton, D.J., & Nutter, W.L. (1998b). Stream Temperature Simulation of Forested Riparian Areas: II. Model Application. *Journal of Environmental Engineering, 124*, 316-328

Chikita, K.A., Kaminaga, R., Kudo, I., Wada, T., & Kim, Y. (2010). Parameters determining water temperature of a proglacial stream: The Phelan Creek and the Gulkana Glacier, Alaska. *River Research and Applications, 26*, 995-1004

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

Cole, T.M., & Wells, S.A. (2015). *CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 3.72*. Portland, OR: Department of Civil and Environmental Engineering, Portland State University, 797 p

Cox, M.M., & Bolte, J.P. (2007). A spatially explicit network-based model for estimating stream temperature distribution. *Environmental Modelling & Software, 22*, 502-514

Cristea, N.C., & Burges, S.J. (2009). Use of Thermal Infrared Imagery to Complement Monitoring and Modeling of Spatial Stream Temperatures. *Journal of Hydrologic Engineering, 14*, 1080-1090

Daigle, A., Jeong, D.I., & Lapointe, M.F. (2015). Climate change and resilience of tributary thermal refugia for salmonids in eastern Canadian rivers. *Hydrological Sciences Journal, 60*, 1044-1063

Danner, E.M., Melton, F.S., Pike, A., Hashimoto, H., Michaelis, A., Rajagopalan, B., Caldwell, J., DeWitt, L., Lindley, S., & Nemani, R.R. (2012). River Temperature Forecasting: A Coupled-Modeling Framework for Management of River Habitat. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 5*, 1752-1760

Datt, P. (2011). Latent Heat of Vaporization/Condensation. In V.P. Singh, P. Singh, & U.K. Haritashya (Eds.), *Encyclopedia of Snow, Ice and Glaciers.* Dordrecht: Springer Netherlands, pp. 703-703

Daufresne, M., Roger, M.C., Capra, H., & Lamouroux, N. (2004). Long-term changes within the invertebrate and fish communities of the Upper Rhône River: effects of climatic factors. *Global Change Biology, 10*, 124-140

Davies-Colley, R.J., Meleason, M.A., Hall, R.M.J., & Rutherford, J.C. (2009). Modelling the time course of shade, temperature, and wood recovery in streams with riparian forest restoration. *New Zealand Journal of Marine and Freshwater Research, 43*, 673-688

Deas, M.L., Abbott, A., & Bale, A. (2003). *Shasta River flow and temperature modelling project*. Napa, CA: Watercourse Engineering, 166 p

Delpla, I., Jung, A.V., Baures, E., Clement, M., & Thomas, O. (2009). Impacts of climate change on surface water quality in relation to drinking water production. *Environment International, 35*, 1225-1233

Deltares (2014). *Delft3D-FLOW. Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments. User Manual*. Delft, The Netherlands: Deltares Systems, 684 p

DHI (2016). *MIKE 11: A Modelling System for Rivers and Channels. Reference Manual*. Horsholm, Denmark: Danish Hydraulic Institute, 498 p

Drake, J., Bradford, A., & Joy, D. (2010). Application of HEC-RAS 4.0 temperature model to estimate groundwater contributions to Swan Creek, Ontario, Canada. *Journal of Hydrology, 389*, 390-398

Dugdale, S.J. (2016). A practitioner's guide to thermal infrared remote sensing of rivers and streams: recent advances, precautions and considerations. *Wiley Interdisciplinary Reviews: Water*, 3, 251-268

Dugdale, S.J., Bergeron, N.E., & St-Hilaire, A. (2015). Spatial distribution of thermal refuges analysed in relation to riverscape hydromorphology using airborne thermal infrared imagery. *Remote Sensing of Environment, 160*, 43-55

Dugdale, S.J., Franssen, J., Corey, E., Bergeron, N.E., Lapointe, M., & Cunjak, R.A. (2016). Main stem movement of Atlantic salmon parr in response to high river temperature. *Ecology of Freshwater Fish, 25*, 429-445

Dugdale, S.J., Malcolm, I.A., Kantola, K., & Hannah, D.M. (2018). Stream temperature under contrasting riparian forest cover: Understanding thermal dynamics and heat exchange processes. *Science of the Total Environment*, 610–611, 1375-1389

Durance, I., & Ormerod, S.J. (2007). Climate change effects on upland stream macroinvertebrates over a 25-year period. *Global Change Biology, 13*, 942-957

Durance, I., & Ormerod, S.J. (2009). Trends in water quality and discharge confound long-term warming effects on river macroinvertebrates. *Freshwater Biology, 54*, 388-405

Elliott, J.M., & Elliott, J.A. (2010). Temperature requirements of Atlantic salmon Salmo salar, brown trout Salmo trutta and Arctic charr Salvelinus alpinus: predicting the effects of climate change. *Journal of Fish Biology, 77*, 1793-1817

Evans, E.C., McGregor, G.R., & Petts, G.E. (1998). River energy budgets with special reference to river bed processes. *Hydrological Processes, 12*, 575-595

Ficklin, D.L., Barnhart, B.L., Knouft, J.H., Stewart, I.T., Maurer, E.P., Letsinger, S.L., & Whittaker, G.W. (2014). Climate change and stream temperature projections in the Columbia River basin: habitat implications of spatial variation in hydrologic drivers. *Hydrol. Earth Syst. Sci., 18*, 4897-4912

Ficklin, D.L., Luo, Y., Stewart, I.T., & Maurer, E.P. (2012). Development and application of a hydroclimatological stream temperature model within the Soil and Water Assessment Tool. *Water Resources Research, 48*, W01511

Finlay, J.C. (2003). Controls of streamwater dissolved inorganic carbon dynamics in a forested watershed. *Biogeochemistry, 62*, 231-252

Fonstad, M.A., Dietrich, J.T., Courville, B.C., Jensen, J.L., & Carbonneau, P.E. (2013). Topographic structure from motion: a new development in photogrammetric measurement. *Earth Surface Processes and Landforms, 38*, 421-430

Garner, G., Malcolm, I.A., Sadler, J.P., & Hannah, D.M. (2014). What causes cooling water temperature gradients in a forested stream reach? *Hydrol. Earth Syst. Sci., 18*, 5361-5376

Garner, G., Malcolm, I.A., Sadler, J.P., Millar, C.P., & Hannah, D.M. (2015). Inter-annual variability in the effects of riparian woodland on micro-climate, energy exchanges and water temperature of an upland Scottish stream. *Hydrological Processes, 29*, 1080-1095

Garner, G., Malcolm, I.A., Sadler, J.P., & Hannah, D.M. (2017). The role of riparian vegetation density, channel orientation and water velocity in determining river temperature dynamics. *Journal of Hydrology*, 553, 471-485

Gooseff, M.N., Anderson, J.K., Wondzell, S.M., LaNier, J., & Haggerty, R. (2006). A modelling study of hyporheic exchange pattern and the sequence, size, and spacing of stream bedforms in mountain stream networks, Oregon, USA. *Hydrological Processes, 20*, 2443-2457

Greene, G.M., & Outcalt, S.I. (1985). A simulation model of river ice cover thermodynamics. *Cold Regions Science and Technology, 10*, 251-262

Handcock, R.N., Torgersen, C.E., Cherkauer, K.A., Gillespie, A.R., Tockner, K., Faux, R.N., & Tan, J. (2012). Thermal Infrared Remote Sensing of Water Temperature in Riverine Landscapes. *Fluvial Remote Sensing for Science and Management* (pp. 85-113): John Wiley & Sons, Ltd

Hanna, R.B., Saito, L., Bartholow, J.M., & Sandelin, J. (1999). Results of Simulated Temperature Control Device Operations on In-Reservoir and Discharge Water Temperatures Using CE-QUAL-W2. *Lake and Reservoir Management, 15*, 87-102

Hannah, D.M., & Garner, G. (2015). River water temperature in the United Kingdom: Changes over the 20th century and possible changes over the 21st century. *Progress in Physical Geography, 39*, 68-92

Hannah, D.M., Malcolm, I.A., Soulsby, C., & Youngson, A.F. (2004). Heat exchanges and temperatures within a salmon spawning stream in the Cairngorms, Scotland: seasonal and sub-seasonal dynamics. *River Research and Applications, 20*, 635-652

Hannah, D.M., Malcolm, I.A., Soulsby, C., & Youngson, A.F. (2008). A comparison of forest and moorland stream microclimate, heat exchanges and thermal dynamics. *Hydrological Processes, 22*, 919-940

Hannah, D.M., Malcolm, I.A., & Bradley, C. (2009). Seasonal hyporheic temperature dynamics over riffle bedforms. *Hydrological Processes, 23*, 2178-2194

Hansen, N., & Ostermeier, A. (2001). Completely Derandomized Self-Adaptation in Evolution Strategies. *Evolutionary Computation, 9*, 159-195

Hébert, C., Caissie, D., Satish, M.G., & El-Jabi, N. (2011). Study of stream temperature dynamics and corresponding heat fluxes within Miramichi River catchments (New Brunswick, Canada). *Hydrological Processes, 25*, 2439-2455

Hébert, C., Caissie, D., Satish, M.G., & El-Jabi, N. (2015). Predicting Hourly Stream Temperatures Using the Equilibrium Temperature Model. *Journal of Water Resource and Protection, 7*, 322-338

Hester, E.T., & Doyle, M.W. (2011). Human Impacts to River Temperature and Their Effects on Biological Processes: A Quantitative Synthesis. *JAWRA Journal of the American Water Resources Association, 47*, 571-587

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

Hrachowitz, M., Soulsby, C., Imholt, C., Malcolm, I.A., & Tetzlaff, D. (2010). Thermal regimes in a large upland salmon river: a simple model to identify the influence of landscape controls and climate change on maximum temperatures. *Hydrological Processes, 24*, 3374-3391

Idso, S.B., & Jackson, R.D. (1969). Thermal radiation from the atmosphere. *Journal of Geophysical Research, 74*, 5397-5403

Imholt, C., Soulsby, C., Malcolm, I.A., Hrachowitz, M., Gibbins, C.N., Langan, S., & Tetzlaff, D. (2013). Influence of scale on thermal characteristics in a large montane river basin. *River Research and Applications, 29*, 403-419

Isaak, D.J., Luce, C.H., Rieman, B.E., Nagel, D.E., Peterson, E.E., Horan, D.L., Parkes, S., & Chandler, G.L. (2010). Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. *Ecological Applications, 20*, 1350-1371

Isaak, D.J., Young, M.K., Nagel, D.E., Horan, D.L., & Groce, M.C. (2015). The cold-water climate shield: delineating refugia for preserving salmonid fishes through the 21st century. *Global Change Biology*, *21*, 2540-2553

Jackson, F.L., Hannah, D.M., Fryer, R.J., Millar, C.P., & Malcolm, I.A. (2017). Development of spatial regression models for predicting summer river temperatures from landscape characteristics: implications for land and fisheries management. *Hydrological Processes*, *31*, 1225-1238

Jackson, F.L., Malcolm, I.A., & Hannah, D.M. (2016). A novel approach for designing large-scale river temperature monitoring networks. *Hydrology Research, 47*, 569-590

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

Jeong, D.I., Daigle, A., & St-Hilaire, A. (2013). Development of a stochastic water temperature model and projection of future water temperature and extreme events in the Ouelle River basin in Québec, Canada. *River Research and Applications, 29*, 805-821

Johnson, M.F., Wilby, R.L., & Toone, J.A. (2014). Inferring air–water temperature relationships from river and catchment properties. *Hydrological Processes, 28*, 2912-2928

Johnson, S.L. (2004). Factors influencing stream temperatures in small streams: substrate effects and a shading experiment. *Canadian Journal of Fisheries and Aquatic Sciences, 61*, 913-923

Jonsson, B., & Jonsson, N. (2009). A review of the likely effects of climate change on anadromous Atlantic salmon Salmo salar and brown trout Salmo trutta, with particular reference to water temperature and flow. *Journal of Fish Biology, 75*, 2381-2447

Jowett, I., Kingsland, S., & Collier, K. (2004). *WAIORA User Guide. Water Allocation Impacts on River Attributes (Version 2.0)*. Hamilton, New Zealand: NIWA, 87 p

Kannel, P.R., Lee, S., Lee, Y.S., Kanel, S.R., & Pelletier, G.J. (2007). Application of automated QUAL2Kw for water quality modeling and management in the Bagmati River, Nepal. *Ecological Modelling, 202*, 503-517

Karanth, K. (1987). *Ground water assessment: development and management*. New Delhi: Tata McGraw-Hill Education, p

Kaushal, S.S., Likens, G.E., Jaworski, N.A., Pace, M.L., Sides, A.M., Seekell, D., Belt, K.T., Secor, D.H., & Wingate, R.L. (2010). Rising stream and river temperatures in the United States. *Frontiers in Ecology and the Environment, 8*, 461-466

Khamis, K., Brown, L.E., Milner, A.M., & Hannah, D.M. (2015). Heat exchange processes and thermal dynamics of a glacier-fed alpine stream. *Hydrological Processes, 29*, 3306-3317

King, I.P. (2016). *RMA-11- A three dimensional finite element model for water quality in estuaries and streams. Version 9.1b*. Sydney, Australia: Resource Modelling Associates, 173 p

Koberg, G.E. (1964). *Methods to compute long-wave radiation from the atmosphere and reflected solar radiation from a water surface. Professional paper 272-F*. Washington, D.C.: US Geological Survey

Kurylyk, B.L., MacQuarrie, K.T.B., & Voss, C.I. (2014). Climate change impacts on the temperature and magnitude of groundwater discharge from shallow, unconfined aquifers. *Water Resources Research*, 3253-3274

Kurylyk, B.L., Moore, R.D., & MacQuarrie, K.T.B. (2016). Scientific briefing: quantifying streambed heat advection associated with groundwater–surface water interactions. *Hydrological Processes, 30*, 987-992

Leach, J.A., & Moore, R.D. (2010). Above-stream microclimate and stream surface energy exchanges in a wildfire-disturbed riparian zone. *Hydrological Processes, 24*, 2369-2381

Leach, J.A., & Moore, R.D. (2014). Winter stream temperature in the rain-on-snow zone of the Pacific Northwest: influences of hillslope runoff and transient snow cover. *Hydrol. Earth Syst. Sci.*, 18, 819-838

LeBlanc, R.T., & Brown, R.D. (2000). The Use of Riparian Vegetation in Stream-Temperature Modification. *Water and Environment Journal, 14*, 297-303

LeBlanc, R.T., Brown, R.D., & FitzGibbon, J.E. (1997). Modeling the Effects of Land Use Change on the Water Temperature in Unregulated Urban Streams. *Journal of Environmental Management, 49*, 445-469

Legleiter, C.J., & Kyriakidis, P.C. (2008). Spatial prediction of river channel topography by kriging. *Earth Surface Processes and Landforms, 33*, 841-867

Lim, W.H., Roderick, M.L., Hobbins, M.T., Wong, S.C., Groeneveld, P.J., Sun, F., & Farquhar, G.D. (2012). The aerodynamics of pan evaporation. *Agricultural and Forest Meteorology, 152*, 31-43

Loinaz, M.C., Davidsen, H.K., Butts, M., & Bauer-Gottwein, P. (2013). Integrated flow and temperature modeling at the catchment scale. *Journal of Hydrology, 495*, 238-251

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*, 2947-2955

Maheu, A., Caissie, D., St-Hilaire, A., & El-Jabi, N. (2014). River evaporation and corresponding heat fluxes in forested catchments. *Hydrological Processes*, 28, 5725-5738

Malcolm, I.A., Hannah, D.M., Donaghy, M.J., Soulsby, C., & Youngson, A.F. (2004). The influence of riparian woodland on the spatial and temporal variability of stream water temperatures in an upland salmon stream. *Hydrology and Earth System Sciences, 8*, 449-459

Malcolm, I.A., Greig, S.M., Youngson, A.F., & Soulsby, C. (2008). Hyporheic Influences on Salmon Embryo Survival and Performance. In D.A. Sear, & P. DeVries (Eds.). *Salmonid Spawning Habitat in Rivers: Physical Controls, Biological Responses, and Approaches to Remediation.* 225-248. Bethesda, MD: American Fisheries Society

Marcus, W.A., & Fonstad, M.A. (2008). Optical remote mapping of rivers at sub-meter resolutions and watershed extents. *Earth Surface Processes and Landforms, 33*, 4-24

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

Matthews, K.R., Berg, N.H., Azuma, D.L., & Lambert, T.R. (1994). Cool Water Formation and Trout Habitat Use in a Deep Pool in the Sierra Nevada, California. *Transactions of the American Fisheries Society, 123*, 549-564

McJannet, D.L., Cook, F.J., & Burn, S. (2013). Comparison of techniques for estimating evaporation from an irrigation water storage. *Water Resources Research, 49*, 1415-1428

Merwade, V. (2009). Effect of spatial trends on interpolation of river bathymetry. *Journal of Hydrology, 371*, 169-181

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

Monteith, J.L. (1965). Evaporation and environment. *Symp Soc Exp Biol, 19*, 205-234

Moore, R.D., Spittlehouse, D.L., & Story, A. (2005). Riparian Microclimate and Stream Temperature Response to Forest Harvesting: A Review. *JAWRA Journal of the American Water Resources Association*, 41, 813-834

Morin, G., & Couillard, D. (1990). Chapter 5: Predicting river temperatures with a hydrological model. In N. Cheremisinoff (Ed.), *Encyclopedia of Fluid Mechanics: Surface and Groundwater Flow Phenomena* (pp. 171-209). Houston, TX: Gulf Publishing

Morin, G., & Paquet, P. (2007). *Modèle hydrologique CEQUEAU, rapport de recherche no R000926*. Québec, QC: Université du Québec, INRS-Eau,Terre et Environnement, 458 p

Muñoz-Mas, R., Lopez-Nicolas, A., Martínez-Capel, F., & Pulido-Velazquez, M. (2016). Shifts in the suitable habitat available for brown trout (Salmo trutta L.) under short-term climate change scenarios. *Science of The Total Environment, 544*, 686-700

Nielsen, J.L., Lisle, T.E., & Ozaki, V. (1994). Thermally Stratified Pools and Their Use by Steelhead in Northern California Streams. *Transactions of the American Fisheries Society, 123*, 613-626

Norton, G.E., & Bradford, A. (2009). Comparison of two stream temperature models and evaluation of potential management alternatives for the Speed River, Southern Ontario. *Journal of Environmental Management, 90*, 866-878

Null, S.E., Deas, M.L., & Lund, J.R. (2010). Flow and water temperature simulation for habitat restoration in the Shasta River, California. *River Research and Applications, 26*, 663-681

Null, S.E., Viers, J.H., Deas, M.L., Tanaka, S.K., & Mount, J.F. (2013). Stream temperature sensitivity to climate warming in California's Sierra Nevada: impacts to coldwater habitat. *Climatic Change, 116*, 149-170

Ouellet, V., Secretan, Y., St-Hilaire, A., & Morin, J. (2014a). Daily averaged 2D water temperature model for the St. Lawrence River. *River Research and Applications, 30*, 733-744

Ouellet, V., Secretan, Y., St-Hilaire, A., & Morin, J. (2014b). Water temperature modelling in a controlled environment: comparative study of heat budget equations. *Hydrological Processes, 28*, 279-292

Penman, H.L. (1948). Natural Evaporation from Open Water, Bare Soil and Grass. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 193*, 120-145

Pike, A., Danner, E., Boughton, D., Melton, F., Nemani, R., Rajagopalan, B., & Lindley, S. (2013). Forecasting river temperatures in real time using a stochastic dynamics approach. *Water Resources Research, 49*, 5168-5182

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

Priestly, C.H.B., & Taylor, R.J. (1972). On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters. *Monthly Weather Review, 100*, 81-92

Rienecker, M.M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G., Schubert, S.D., Takacs, L., Kim, G.-K., Bloom, S., Chen, J., Collins, D., Conaty, A., da Silva, A., Gu, W., Joiner, J., Koster, R.D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C.R., Reichle, R., Robertson, F.R., Ruddick, A.G., Sienkiewicz, M., & Woollen, J. (2011). MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. *Journal of Climate, 24*, 3624-3648

Robert, A. (2003). *River Processes: An introduction to fluvial dynamics*. New York: Arnold, 214 p

Rounds, S.A. (2007). *Temperature Effects of Point Sources, Riparian Shading, and Dam Operations on the Willamette River, Oregon. Scientific Investigations Report 2007-5185*. Reston, VA: US Geological Survey, 34 p

Ruesch, A.S., Torgersen, C.E., Lawler, J.J., Olden, J.D., Peterson, E.E., Volk, C.J., & Lawrence, D.J. (2012). Projected Climate-Induced Habitat Loss for Salmonids in the John Day River Network, Oregon, U.S.A. *Conservation Biology, 26*, 873-882

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

Rutherford, J.C., Marsh, N.A., Davies, P.M., & Bunn, S.E. (2004). Effects of patchy shade on stream water temperature: how quickly do small streams heat and cool? *Marine and Freshwater Research, 55*, 737-748

Sansone, A.L. (2001). A GIS-based temperature model for the prediction of maximum stream temperatures in the Cascade mountain region, MS thesis. University of Washington, Department of Civil and Environmental Engineering, Seattle, WA

Savenije, H.H.G. (2001). Equifinality, a blessing in disguise? *Hydrological Processes, 15*, 2835-2838

Shen, H., Cunderlik, J., Godin, G., Coombs, A., Rimer, A., & Dobrindt, I. (2014). Thermal Effects of the Proposed Water Reclamation Centre Discharge on the East Holland River. *Journal of Water Management Modeling*, DOI: 10.14796/JWMM.C14366

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

Sinokrot, B.A., & Stefan, H.G. (1994). Stream Water-Temperature Sensitivity to Weather and Bed Parameters. *Journal of Hydraulic Engineering, 120*, 722-736

Spadavecchia, L., & Williams, M. (2009). Can spatio-temporal geostatistical methods improve high resolution regionalisation of meteorological variables? *Agricultural and Forest Meteorology, 149*, 1105-1117

Sridhar, V., Sansone, A.L., LaMarche, J., Dubin, T., & Lettenmaier, D.P. (2004). Prediction of stream temperature in forested watersheds. *JAWRA Journal of the American Water Resources Association, 40*, 197-213

St-Hilaire, A., Boucher, M.-A., Chebana, F., Ouellet-Proulx, S., Zhou, Q.X., Larabi, S., Dugdale, S.J., & Latraverse, M. (2015). Breathing new life to an older model: the Cequeau tool for flow and water temperature simulations and forecasting. *Proceedings of the 22nd Canadian Hydrotechnical Conference*, Montréal, Québec, Canada, April 29th - May 2nd

St-Hilaire, A., El-Jabi, N., Caissie, D., & Morin, G. (2003). Sensitivity analysis of a deterministic water temperature model to forest canopy and soil temperature in Catamaran Brook (New Brunswick, Canada). *Hydrological Processes, 17*, 2033-2047

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

Steel, E.A., Beechie, T.J., Torgersen, C.E., & Fullerton, A.H. (2017). Envisioning, Quantifying, and Managing Thermal Regimes on River Networks. *BioScience*, 67, 506-522

Steel, E.A., Sowder, C., & Peterson, E.E. (2016). Spatial and Temporal Variation of Water Temperature Regimes on the Snoqualmie River Network. *JAWRA Journal of the American Water Resources Association*, 52, 769-787

Story, A., Moore, R.D., & Macdonald, J.S. (2003). Stream temperatures in two shaded reaches below cutblocks and logging roads: downstream cooling linked to subsurface hydrology. *Canadian Journal of Forest Research, 33*, 1383-1396

Sun, N., Yearsley, J., Voisin, N., & Lettenmaier, D.P. (2015). A spatially distributed model for the assessment of land use impacts on stream temperature in small urban watersheds. *Hydrological Processes, 29*, 2331-2345

Swinbank, W.C. (1963). Long-wave radiation from clear skies. *Quarterly Journal of the Royal Meteorological Society, 89*, 339-348

Theurer, F.D., Voos, K.A., & Miller, W.J. (1984). *Instream water temperature model. Instream Flow Information Paper 16. FWS/OBS-84/15*. Washington, D.C.: US Fish and Wildlife Service, 321 p

Thornthwaite, C.W. (1948). An Approach toward a Rational Classification of Climate. *Geographical Review, 38*, 55-94

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

Torgersen, C.E., Gresswell, R.E., Bateman, D.S., & Burnett, K.M. (2008). Spatial Identification of Tributary Impacts in River Networks. *River Confluences, Tributaries and the Fluvial Network* (pp. 159-181): John Wiley & Sons, Ltd

Torgersen, C.E., Price, D.M., Li, H.W., & McIntosh, B.A. (1999). Multiscale thermal refugia and stream habitat associations of chinook salmon in northeastern oregon. *Ecological Applications, 9*, 301-319

Tung, C.-P., Lee, T.-Y., & Yang, Y.-C. (2006). Modelling climate-change impacts on stream temperature of Formosan landlocked salmon habitat. *Hydrological Processes, 20*, 1629-1649

van Vliet, M.T.H., Franssen, W.H.P., Yearsley, J.R., Ludwig, F., Haddeland, I., Lettenmaier, D.P., & Kabat, P. (2013). Global river discharge and water temperature under climate change. *Global Environmental Change, 23*, 450-464

van Vliet, M.T.H., Yearsley, J.R., Franssen, W.H.P., Ludwig, F., Haddeland, I., Lettenmaier, D.P., & Kabat, P. (2012). Coupled daily streamflow and water temperature modelling in large river basins. *Hydrol. Earth Syst. Sci., 16*, 4303-4321

Vatland, S.J., Gresswell, R.E., & Poole, G.C. (2015). Quantifying stream thermal regimes at multiple scales: Combining thermal infrared imagery and stationary stream temperature data in a novel modeling framework. *Water Resources Research, 51*, 31-46

Vinukollu, R.K., Wood, E.F., Ferguson, C.R., & Fisher, J.B. (2011). Global estimates of evapotranspiration for climate studies using multi-sensor remote sensing data: Evaluation of three process-based approaches. *Remote Sensing of Environment, 115*, 801-823

Wang, P.-F., & Martin, J.L. (1991). Temperature and Conductivity Modeling for the Buffalo River. *Journal of Great Lakes Research, 17*, 495-503

Watanabe, M., Adams, R.M., Wu, J., Bolte, J.P., Cox, M.M., Johnson, S.L., Liss, W.J., Boggess, W.G., & Ebersole, J.L. (2005). Toward efficient riparian restoration: integrating economic, physical, and biological models. *Journal of Environmental Management, 75*, 93-104

Wawrzyniak, V., Allemand, P., Bailly, S., Lejot, J., & Piégay, H. (2017). Coupling LiDAR and thermal imagery to model the effects of riparian vegetation shade and groundwater inputs on summer river temperature. *Science of The Total Environment*, 592, 616-626

Watts, G., Battarbee, R.W., Bloomfield, J.P., Crossman, J., Daccache, A., Durance, I., Elliott, J.A., Garner, G., Hannaford, J., Hannah, D.M., Hess, T., Jackson, C.R., Kay, A.L., Kernan, M., Knox, J., Mackay, J., Monteith, D.T., Ormerod, S.J., Rance, J., Stuart, M.E., Wade, A.J., Wade, S.D., Weatherhead, K., Whitehead, P.G., & Wilby, R.L. (2015). Climate change and water in the UK – past changes and future prospects. *Progress in Physical Geography, 39*, 6-28

Webb, B., Walsh, A., Webb, B., Acreman, M., Maksimovic, C., Smithers, H., & Kirby, C. (2004). Changing UK river temperatures and their impact on fish populations. *Proceedings of the Hydrology: science and practice for the 21st century, Volume II. Proceedings of the British Hydrological Society International Conference, Imperial College, London, July 2004.*,

Webb, B.W. (1996). Trends in stream and river temperature. *Hydrological Processes, 10*, 205-226

Webb, B.W., Hannah, D.M., Moore, R.D., Brown, L.E., & Nobilis, F. (2008). Recent advances in stream and river temperature research. *Hydrological Processes, 22*, 902-918

Webb, B.W., & Zhang, Y. (1997). Spatial and seasonal variability in the components of the river heat budget. *Hydrological Processes, 11*, 79-101

Webb, B.W., & Zhang, Y. (1999). Water temperatures and heat budgets in Dorset chalk water courses. *Hydrological Processes, 13*, 309-321

Webb, B.W., & Zhang, Y. (2004). Intra-annual variability in the non-advective heat energy budget of Devon streams and rivers. *Hydrological Processes, 18*, 2117-2146

Woltemade, C.J., & Hawkins, T.W. (2016). Stream Temperature Impacts Because of Changes in Air Temperature, Land Cover and Stream Discharge: Navarro River Watershed, California, USA. *River Research and Applications*, 32, 2020-2031

Wool, T.A., Ambrose, R.B., & Martin, J.L. (2008). *WASP7 Temperature and Fecal Coliform – Model Theory and User's Guide. Supplement to Water Quality Analysis Simulation Program (WASP) User Documentation*. Athens, GA: US Environmental Protection Agency, 25 p

Yearsley, J. (2012). A grid-based approach for simulating stream temperature. *Water Resources Research, 48*, W03506

Yearsley, J.R. (2009). A semi-Lagrangian water temperature model for advection-dominated river systems. *Water Resources Research, 45*, W12405

Yearsley, J.R., Karna, D., Peene, S., & Watson, B. (2001). *Application of a 1-D heat budget model to the Columbia River system. Report EPA 091-R-01-004*. Seattle, WA: US Environmental Protection Agency, 65 p

Zheng, C., & Wang, P. (1996). Parameter structure identification using tabu search and simulated annealing. *Advances in Water Resources, 19*, 215-224