Science of the Total Environment xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Coupling LiDAR and thermal imagery to model the effects of riparian vegetation shade and groundwater inputs on summer river temperature

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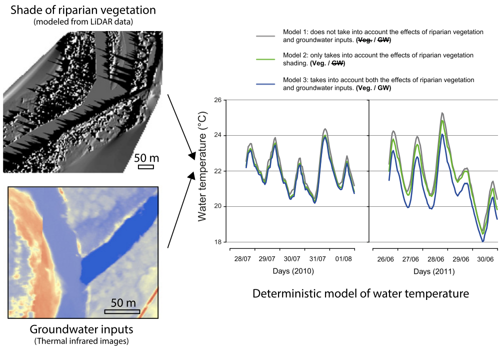
HIGHLIGHTS

- We model the effects of riparian shading and groundwater inputs on water temperature.
- Shadows of the riparian forest are modeled using LiDAR data.
- Groundwater inputs are determined using thermal infrared images and discharge data.
- Both factors can mitigate high water temperatures during summer.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 January 2017
Received in revised form 2 March 2017
Accepted 2 March 2017
Available online xxxx

Editor: D. Barcelo

Keywords:
1-D deterministic model
LiDAR data
Thermal infrared (TIR) remote sensing
Ain River (France)

ABSTRACT

In the context of global warming, it is important to understand the drivers controlling river temperature in order to mitigate temperature increases. A modeling approach can be useful for quantifying the respective importance of the different drivers, notably groundwater inputs and riparian shading which are potentially critical for reducing summer temperature. In this study, we use a one-dimensional deterministic model to predict summer water temperature at an hourly time step over a 21 km reach of the lower Ain River (France). This sinuous gravel-bed river undergoes summer temperature increase with potential impacts on salmonid populations. The model considers heat fluxes at the water-air interface, attenuation of solar radiation by riparian forest, groundwater inputs and hydraulic characteristics of the river. Modeling is performed over two periods of five days during the summers 2010 and 2011. River properties are obtained from hydraulic modeling based on cross-section profiles and water level surveys. We model shadows of the vegetation on the river surface using LiDAR data. Groundwater inputs are determined using airborne thermal infrared (TIR) images and hydrological data. Results indicate that vegetation and groundwater inputs can mitigate high water temperatures during summer. Riparian shading effect is fairly similar between the two periods (−0.26 ± 0.12 °C and −0.31 ± 0.18 °C). Groundwater input cooling is variable between the two studied periods: when groundwater discharge represents 16% of the river discharge, it cools the river down by 0.68 ± 0.13 °C while the effect is very low (0.11 ± 0.01 °C) when the groundwater discharge contributes only 2% to the discharge. The effect of shading varies through the day: low in the

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http://dx.doi.org/10.1016/j.scitotenv.2017.03.019

Please cite this article as: Wawrzyniak, V., et al., Coupling LiDAR and thermal imagery to model the effects of riparian vegetation shade and groundwater inputs on summer river temper..., Sci Total Environ (2016), http://dx.doi.org/10.1016/j.scitotenv.2017.03.019

morning and high during the afternoon and the evening whereas those induced by groundwater inputs is more constant through the day. Overall, the effect of riparian vegetation and groundwater inputs represents about 10% in 2010 and 24% in 2011 of water temperature diurnal amplitudes.

1. Introduction

The consequences of global warming on river temperature have been widely studied in recent decades (Arnell, 1999; Kaushal et al., 2010; Van Vliet et al., 2011; Webb, 1996). Increases in temperature have strong ecological impacts on freshwater ecosystems (Daufresne and Boët, 2007; Durance and Ormerod, 2007; Isaak et al., 2010). In this context, it is important to understand the different drivers of river temperature, notably those that can mitigate temperature increase.

River temperature varies through space and time and modeling is therefore required to quantify the drivers of this temperature variability. Early statistical stream temperature models (Benyahya et al., 2007; Caissie, 2006; Mohseni et al., 1998; Webb and Nobilis, 1997; Webb et al., 2003) only consider temperature at one point, i.e. they are not spatially distributed (Caissie, 2006), and air temperature is the single input parameter. New spatially distributed statistical models have been recently developed (Isaak et al., 2015; Jackson et al., 2016; Steel et al., 2016), notably to predict water temperature in rivers at the river network scale (Beaufort et al., 2016; Detenbeck et al., 2016).Deterministic models of river temperature (Morin and Couillard, 1990; Sinokrot and Stefan, 1993; Caissie et al., 2005; Caissie et al., 2007; Cox and Bolte, 2007; Herbert et al., 2011), also called process-based models, use an energy budget and can be applied in one (Loheide and Gorelick, 2006; Westhoff et al., 2007; Deitchman and Loheide, 2012), two (Carrivick et al., 2012; Ouellet et al., 2014) or three dimensions (e.g. Delft3D). These models have the advantage of quantifying the different heat fluxes acting on the river (Caissie, 2006). They can also evaluate the effects of various scenarios in term of climate change (Diabat et al., 2013) or riparian management (Lawrence et al., 2014).

By intercepting solar radiation, riparian vegetation stores heat at the expense of the river. Vegetation also reflects solar radiation. Riparian vegetation therefore reduces water temperature increases (Moore et al., 2005; Rutherford et al., 1997; Webb et al., 2008). Many studies consider the interception of solar radiation by riparian vegetation in water temperature models (Chen et al., 1998; Bartholow, 2000; Caissie et al., 2007; Cox and Bolte, 2007; Woltemade and Hawkins, 2016). The riparian shading factor (SF), which is the ratio between the shaded river area and the total river area, is frequently used to evaluate the attenuation of solar radiation by the forest. However, the effect of shading is often considered homogeneous over the study reach and the shading computations are often quite simplistic and based on incomplete data. Garner et al. (2014) used hemispherical photographs to estimate solar radiation passing through the canopy at different locations in the river. Canopy topography has been derived from LiDAR (Hollaus et al., 2006) or photogrammetry (Lisein et al., 2013). Greenberg et al. (2012) used LiDAR-derived topography to estimate insolation under riparian vegetation. This type of data could be incorporated in deterministic models of river temperature in order to quantify the effect of riparian vegetation shade.

In summer, groundwater is generally colder than river water and therefore groundwater inputs may lower river temperature. There is an extensive literature about the identification and the quantification of groundwater and surface water interactions (Anderson, 2005; Becker et al., 2004; Constantz, 1998; Kalbus et al., 2006; Keery et al., 2007) but there are few studies about the downstream impacts of groundwater inputs on river temperature (Burkholder et al., 2008; Herbert et al., 2011; Lalot et al., 2015; Loheide and Gorelick, 2006; Westhoff et al., 2007). Moreover, these studies mainly concern hyporheic exchanges (Acuña and Tockner, 2009; Burkholder et al., 2008) or small streams (Loheide and Gorelick, 2006; Westhoff et al., 2007). Thermal effects of groundwater inputs for larger rivers (Lalot et al., 2015; Moatar and Gailhard, 2006) are not well-known and Loheide and Gorelick (2006) emphasize that further research is still needed at coarse spatial scales.

Identifying groundwater inputs in rivers is a challenging issue and difficult to address with only temperature loggers. Thermal infrared (TIR) remote sensing can be worthwhile to highlight the spatial distribution of radiant water temperatures and to locate discontinuities (Torgersen et al., 2001). Satellite TIR remote sensing (Handcock et al., 2006; Wawrzyniak et al., 2012; Lalot et al., 2015) is limited to large rivers and spatial resolution does not allow the observation of lateral thermal heterogeneities. Ground-based TIR remote sensing (Cardenas et al., 2008; Dunckel et al., 2009; Tonolla et al., 2010) is spatially limited. Airborne TIR data is accurate enough to assess fine-scale thermal patterns over river reaches of several kilometres (Dugdale et al., 2015; Wawrzyniak et al., 2016). Depending on flight elevation and TIR camera specifications, thermal images usually have centimetric to metric resolutions (Torgersen et al., 2001; Loheide and Gorelick, 2006; Burkholder et al., 2008; Cristea and Burges, 2009; Eschbach et al., 2016) which allow the location of groundwater inputs.

This paper aims to predict summer water temperature at an hourly time step over a 21 km reach of the Ain River (France) using a one-dimensional deterministic model. The model takes into account heat fluxes at the water-air interface, attenuation of solar radiation by riparian vegetation and groundwater inputs. Riparian vegetation shade is computed from LiDAR data and groundwater inputs are located using TIR images. This paper also aims to analyze and discuss the sensitivity of the different parameters and potential effects of the riparian cover and the groundwater contribution.

2. Study area

The Ain River is a tributary of the Rhône River in France (Fig. 1). The lower Ain River is the downstream section of the river between the Allement dam and the confluence with the Rhône. It is a sinuous gravel-bed river with a channel width of about 60 m. Since 1968, its flow regime has been strongly influenced by the hydroelectric Vouglan dam (located 60 km upstream of the studied reach). The mean annual discharge is 121 $m^3 s^{-1}$ in Chazey-sur-Ain (measured at a gauging station over the 1959–2016 period). High flows occurs between autumn and spring (mean November–April discharge: 163 $m^3 s^{-1}$) while summers are characterized by low flow conditions (mean July–August discharge: 50 $m^3 s^{-1}$). The minimum flow downstream of the Allement dam is 12.3 $m^3 s^{-1}$ during the summer. The river flow is turbulent and the water column is well mixed.

By releasing deep water from stratified reservoirs, several hydroelectric dams, located upstream of the study area, buffer water temperature. Deep water releases during summer considerably decrease downstream temperature (Poirel et al., 2010). The temperature in July at Chazey-sur-Ain is on average 18 °C over the 1990–2010 period (Poirel et al., 2010) but can reach 25 °C during warm periods (Poirel et al., 2016). The Ain River has shown a 1.8 °C increase in mean annual water temperature over the 1997–2006 period, and the greatest increases are observed during summer months (EDF, 2010; Poirel et al., 2010). Simulations indicate a possible rise of summer water temperature up to 4 °C by the end of the century due to air temperature increase and flow decrease (Poirel et al., 2010). While statistical models can predict the temperature of the Ain River based on air temperature and

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