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Improving representation of riparian vegetation shading in a regional stream temperature model using LiDAR data

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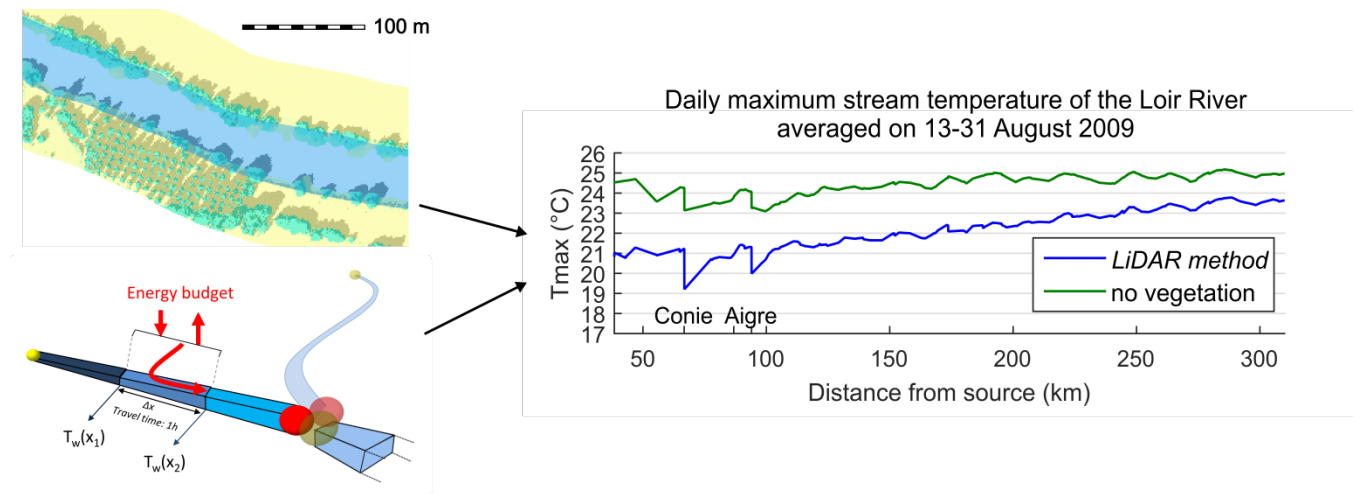
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Keywords: river temperature modelling, regional scale, riparian shading, LiDAR, Loir River.

Highlights:

- Riparian shading was characterised on a 270 km stream using LiDAR data.
- Shading data were injected in a regional stream temperature model.
- Vegetation's cooling effect ranges from -3.0 °C (upstream) to -1.3 °C (downstream).
- Model accuracy is improved compared to simpler shade characterisation methods.
- Riparian vegetation data's quality is a key factor for stream temperature modelling.

Graphical abstract:



Abstract

Modelling river temperature at the catchment scale is needed to understand how aquatic communities may adapt to current and projected climate change. In small and medium rivers, riparian vegetation can greatly reduce maximum water temperature by providing shade. It is thus important that river temperature models are able to correctly characterise the impact of this riparian shading. In this study, we describe the use of a spatially-explicit method using LiDAR-derived data for computing the riparian shading on direct and diffuse solar radiation. The resulting data are used in the T-NET one-dimensional stream temperature model to simulate water temperature from August 2007 to July 2014 for 270 km of the Loir River, an indirect tributary of the Loire River (France). Validation is achieved with 4 temperature monitoring stations spread along the Loir River. The vegetation characterised with the LiDAR approach provides a cooling effect on maximum daily temperature (T_{max}) ranging from 3.0°C (upstream) to 1.3°C (downstream) in late August 2009. Compared to two other riparian shading routines that are less computationally-intensive, the use of our LiDAR-based methodology improves the

30 bias of T_{\max} simulated by the T-NET model by 0.62°C on average between April and September. However,
31 difference between the shading routines reaches up to 2°C (monthly average) at the upstream-most station.
32 Standard deviation of errors on T_{\max} is not improved. Computing the impact of riparian vegetation at the hourly
33 timescale using reach-averaged parameters provides results close to the LiDAR-based approach, as long as it is
34 supplied with accurate vegetation cover data. Improving the quality of riparian vegetation data should therefore
35 be a priority to increase the accuracy of stream temperature modelling at the regional scale.

36

37 **1. Introduction**

38 Temperature is a major water quality parameter because it controls not only oxygen solubility (Moatar et al.,
39 2001) but also chemical and metabolic reactions (Haag and Westrich, 2002). Hence, it affects fish behaviour and
40 survival (Magnuson et al., 1979). River water temperature modelling is thus important for understanding the
41 distribution of aquatic species at regional scales, under present or future climatic conditions (Buisson et al.,
42 2008; Tisseuil et al., 2012; Boisneau et al., 2008; Brown et al., 2005). River temperature is already increasing
43 across French water courses, a trend which is expected to continue further under projected climate change
44 (Moatar and Gailhard, 2006; Bustillo et al., 2014; Hannah and Garner, 2015). Such a warming could have severe
45 consequences for a range of aquatic species, and adaptation measures are currently being sought with a view to
46 ensuring the continued survival of temperature sensitive fluvial organisms. In this context, riparian shade and
47 groundwater exchanges have been given increasing research attention, because of their ability to regulate river
48 temperature (Lalot et al., 2015; Leach and Moore, 2010). Indeed, many studies have shown that shade can
49 moderate water temperature of relatively small rivers (Moore et al., 2005; Garner et al., 2014). Conversely, in
50 larger rivers, Teti (2006) showed (using shade measurements acquired along an increasing-width stream) that
51 riparian vegetation has a limited impact on rivers larger than 30 m. DeWalle (2008) quantified the maximal
52 wetted width for which riparian vegetation can effectively reduce received solar radiation. However, no study
53 has yet quantified the impact of shading on temperature on rivers of intermediate width (>15 m and <30 m) or
54 at the regional scale.

55 Process-based river temperature models function by simulating the energy exchange processes heating
56 or cooling a river, in particular through the input of solar radiation. This solar radiation is composed of direct
57 (solar rays) and diffuse radiation (scattered by atmosphere), both of which are influenced in different ways by
58 the presence of riparian vegetation. The impact of riparian vegetation on the direct radiation can be quantified
59 by computing a shadow factor (SF), which is the proportion of a river being shaded at a given time. Several
60 methods have been proposed to compute it at an hourly time step. Chen et al. (1998) detailed a method to
61 compute riparian shade from GIS polygons of riparian vegetation. Their method used stream azimuth and tree
62 height (alongside solar position) to determine whether a section of stream channel was in shade. However, this
63 technique only accounted for the effect of vegetation located perpendicular to the stream centreline, and
64 furthermore, did not denote the fraction of the channel cross-section that was shaded. As a result, Li et al.
65 (2012) developed an enhanced version of the Chen et al. (1998) methodology, allowing for the determination of
66 the amount of channel cross-section covered by shade. This new method also enables the simulation of

67 overhanging vegetation, but like its predecessor, only considers the effect of vegetation located perpendicular
68 to the river reach. Approaches capable of simulating the effects of vegetation non-perpendicular to the reach
69 include that of Cox and Bolte (2007), who devised a methodology capable of simulating shadow cast by
70 vegetation located in 8 directions (steps of 45°) around each centreline node, and the Solar Analyst extension
71 for ArcGIS (Fu and Rich, 1999), which can compute shadow factor at much finer spatial and temporal scales.
72 Indeed, Johnson and Wilby (2015) applied this method to a small catchment in order to quantify the potential of
73 planting trees, without using a physically-based river temperature model.

74 The impact of riparian vegetation on diffuse radiation can be quantified by computing a sky view factor
75 (SVF). It is the ratio between the diffuse radiation actually reaching the water and the diffuse radiation that
76 would reach this surface with no vegetation around. In a lowland area where topographic shade can be
77 neglected, the tree view factor (TVF) can be defined as 1-SVF. Unlike SF, these view factors (VF) are constant in
78 time since they do not depend on the sun's position. For short reaches, a precise calculation can be achieved
79 through hemispheric photography. For larger areas, remote sensing products or vegetation polygons are
80 needed. Most previous studies (Chen et al., 1998, Cox and Bolte, 2007, Loinaz et al., 2013, Sun et al., 2015)
81 simply use the angle between the horizon and the tree in the directions perpendicular to the river, from one
82 fixed point of view (usually the centre of the river). Moore et al. (2014) introduced the computation of width-
83 averaged sky view factors, with equations considering infinitely long rivers, with or without overhanging trees.

84 With an approach similar to the one used to compute direct radiation, the Solar Analyst extension for
85 ArcGIS handles the computation of diffuse radiation by overlaying a viewshed and a discretised sky map. Two
86 different methods can be used to quantify the amount of radiation coming from each cell of the open sky
87 (uniform radiation or depending on the zenith angle). This method was modified and used by Sridhar et al.
88 (2004) to include the shading effects of near stream vegetation.

89
90 In order to quantify the impact of riparian shading, existing regional-scale stream temperature models
91 usually rely on theoretical values regarding vegetation characteristics (Sun et al., 2015; Loinaz et al., 2013), on
92 simplified assumptions regarding shading process (Haag and Luce, 2008; Cheng and Wiley, 2016), or incorporate
93 shading data from low-resolution DEMs (Cox and Bolte, 2007). Nowadays however, LiDAR can provide accurate
94 data at a large scale. In order to develop a tool for riparian shade inventories using LiDAR data, Guzy et al.
95 (2015) adapted the insolation module of the Heat Source model (Boyd and Kasper, 2003). They created
96 polygons of homogenous potential canopy height and extracted the 75th percentile of the computed frequency
97 distribution of canopy height provided by LiDAR. Greenberg et al. (2012) used LiDAR data and the r.sun module
98 of GRASS GIS to compute clear-sky solar radiation for three summer days in order to understand the impact of a
99 potential trees removal around a delta, without the use of a network based temperature model. Finally,
100 Wawrzyniak et al. (2017) used LiDAR data to compute the impact of riparian forest in a deterministic water
101 temperature model of a 21 km-long reach, during 5 days in summer 2010 and 2011. There is thus a range of
102 data sources and methods available to compute both SF and VF. However, there remains a lack of information
103 comparing the various methodologies, especially with regards to shading routines in regional-scale models.

104 Moreover, the use of LiDAR as a method for the computation of riparian shading is still in its infancy and has
105 never been used to compute the impact of riparian vegetation in a large-scale stream temperature model,
106 during a whole annual cycle.

107 The goal of this paper is therefore to test the influence of shadow and sky view factor computed from
108 LiDAR data on the simulation of maximum daily water temperature (T_{max}) with the T-NET model, a dynamic
109 physically based model for simulating stream temperature at the regional scale using the equilibrium
110 temperature concept. We compute SF and VF based on a LiDAR-derived raster and incorporate these data into
111 the radiative balance of a T-NET model of the Loir River (France) (see Beaufort et al., 2016). We then compare
112 the T_{max} simulated with LiDAR data to two other methods used in the T-NET model for computing riparian
113 shading at the regional scales. Model validation is achieved using data from 4 temperature monitoring stations
114 that are spread over the Loir River.

115 **2. Methods**

116 **2.1. Principles of T-NET model**

117 T-NET is a 1D physically-based model designed to compute water temperature along the longitudinal dimension
118 of a hydrographic network (a GIS polyline). Reaches of this network are limited by two confluences, or by a
119 source and a confluence (for first order reaches). T-NET was designed and applied at the regional scale (110 000
120 km²) by Beaufort et al. (2016). T-NET runs at an hourly time step and is based on the equilibrium temperature
121 concept, which is defined as the water temperature at which the net rate of heat exchange at the interface of a
122 water body is null (Bustillo et al., 2014). The model considers six fluxes [$W \cdot m^{-2}$]: net solar radiation, atmospheric
123 longwave radiation, longwave radiation emitted from the water surface, evaporative heat flux, convective heat
124 flux, and groundwater heat inflow. To compute these terms, the model uses the following parameters as
125 gridded input data: air temperature [$^{\circ}C$], specific humidity [$kg \cdot kg^{-1}$], wind velocity [$m \cdot s^{-1}$], atmospheric longwave
126 radiation [$W \cdot m^{-2}$] and direct and diffuse solar radiation [$W \cdot m^{-2}$]. Parameters are allocated to each river reach as
127 a function of the ratio between the length of the reach within a grid cell and the total reach length. All
128 meteorological parameters except solar radiation are derived from the SAFRAN atmospheric reanalysis dataset
129 (Vidal et al., 2010). These data are produced by Météo-France from both observations and modelling at an
130 hourly time step and a spatial resolution of 8 km. Direct and diffuse solar radiation are derived from the
131 Helioclim3-v5 dataset (Marchand et al., 2017), generated with the help of Meteosat satellite imagery at an
132 hourly time step and a resolution of $\sim 3 \times 5$ km. Inputs pertaining to river discharge and groundwater
133 contributions to river flow are also required by the model. These are computed at a daily time step with the
134 semi-distributed hydrological model EROS (Thiéry and Moutzopoulos, 1992). Both parameters are modelled at
135 the outlets of sub-basins for which river discharge observations are available for calibration. They are then
136 scaled to the reaches inside each sub-basin using the partial area concept. T-NET simulates longitudinal
137 variability in water temperature between the upstream and downstream nodes of each reach, with a spatial
138 resolution depending on the travel time (Figure 1). Water velocity is given by the ratio between discharge and
139 channel cross-section, which is computed using the ESTIMKART empirical model developed by Lamouroux et al.
140 (2010). At the confluence of two reaches, the output temperature is defined as the sum of the product of the

141 two confluences' temperature and discharge divided by the sum of the discharge of the two confluences. T-NET
 142 was thus designed to be applied on well mixed streams and not on standing waters or large estuaries, where 2D
 143 (Cole and Wells, 2006; Becker et al., 2010; Ouellet et al., 2014) or 3D models (Maderich et al., 2008) are more
 144 suitable.

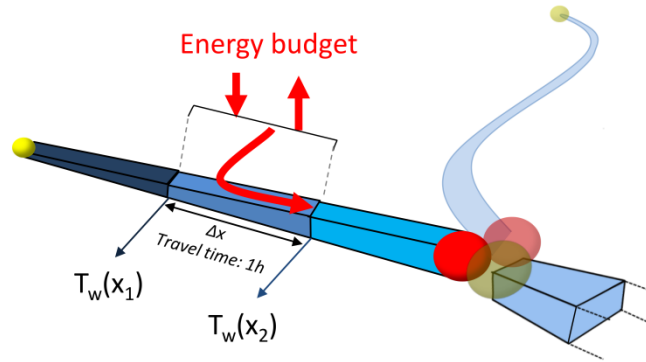


Figure 1: Principles of T-NET model

145
 146
 147

148 2.2. Net solar radiation calculation

149 In order to improve T-NET's ability to model the impact of riparian vegetation on solar radiation, modifications
 150 were made to the original model detailed by Beaufort et al. (2016). Similar to the approach of LeBlanc et al.
 151 (1997), net solar radiation (H_{ns}) is now computed as:

$$152 H_{ns} = R_{dir} (1 - \alpha_{dir}) ((1 - SF) + SF \tau) + R_{diff} (1 - \alpha_{diff}) ((1 - TVF) + TVF \tau) \quad (\text{Eq. 1})$$

153 Where R_{dir} and R_{diff} are the direct and diffuse solar radiation [$\text{W}\cdot\text{m}^{-2}$] derived from the Helioclim3-v5 product, α_{dir}
 154 and α_{diff} are the water surface albedo associated with direct and diffuse radiation respectively, τ is the
 155 transmissivity of riparian vegetation (i.e. the fraction of solar radiation that passes through the canopy), SF is the
 156 shadow factor and TVF is the tree view factor. α_{diff} was held at a constant of 0.09, following the recommendation
 157 of Sellers (1965) and α_{dir} was computed using the formulation of Anderson (1954):

$$158 \begin{aligned} \alpha_{dir} &= 1 && \text{if } \Psi < 1.24^\circ \\ \alpha_{dir} &= 1.18 * \Psi^{-0.77} && \text{otherwise} \end{aligned} \quad (\text{Eq. 2})$$

159 Where Ψ is the angle between the horizon and the sun in degrees.

160 τ was fixed at 50% in winter and 15% in summer. These values are the averages of global solar radiation
 161 transmissivities given by Cantón et al. (1994), Sattin et al. (1997) and Konarska et al. (2014) for deciduous tree
 162 species. Transitions between winter and summer values are described with an ascending and descending logistic
 163 regression whose equation is:

$$164 \tau = \frac{\kappa}{1 + \exp(\pm \gamma \cdot DoY - \beta)} + \mu \quad (\text{Eq. 3})$$

165 Where DoY is the day of year and κ , β , γ and μ are the parameters fitted by least squares adjustment to an
 166 averaged annual cycle of ground-based NDVI measured from oak trees during 2008-2012 (Soudani et al., 2012).
 167 These trees are located in the forest of Fontainebleau (60 km to the south of Paris and ~150 km away from the
 168 centre of the Loir catchment). Data from Lebourgeois et al. (2008) indicate that, for oak trees, there is little
 169 phenologic difference between Fontainebleau and the Loir catchment. However, remote sensing observations

170 from Muller (1995) show that, in 1987 and in the region of Toulouse (South of France), leaf emergence of
 171 riparian trees occurs about 15 days earlier than for oaks. In order to take into account this difference between
 172 oak and riparian species, we hence considered an enlarged growing season compared to oak's phenology (β -15
 173 days in spring, β +15 days in autumn). After fitting the four parameters on NDVI values, κ and μ , representing the
 174 upper and lower values, are adjusted to fit the winter and summer values of transmissivity (50 and 15%,
 175 respectively).

177 2.3.Shadow factor and view factor calculations

178 In order to test the influence of different riparian shading algorithms on water temperatures simulated with T-
 179 NET, we used three approaches to compute both the shadow factor (SF) and the tree view factor (TVF).

180 In the first approach (hereafter referred to as the *constant* method), SF and TVF are held as coefficients
 181 that are constant in time but vary as a function of Strahler order based on the equation:

$$182 \quad SF = TVF = vc \times k \quad (\text{Eq. 4})$$

183 where vc is vegetation cover (%) computed at the reach scale in a buffer of 10 m around the river, and k is a
 184 coefficient aiming to account for the influence of the reach width on shadow (where 1 (maximum impact)
 185 denotes a Strahler order of 1 and 0 (no impact) is associated with a Strahler order of 8). This approach is used in
 186 Beaufort et al. (2015, 2016).

187 In the second approach (hereafter referred to as the *variable* method), SF and TVF are derived from
 188 geometric calculations made at the reach scale, taking into account river width, tree height, vegetation cover,
 189 and position of the sun (for the shadow factor).

190 To compute SF at an hourly time step, the model of Li et al. (2012) was implemented in its simplest version, i.e.
 191 considering rectangular trees, located at the edge of the bank, without overhang:

$$192 \quad SF = \frac{H \times \cot \Psi \times \sin \delta}{W} \times vc \quad (\text{Eq. 5})$$

193 where H is tree height, W is river width, Ψ is the solar elevation angle, δ is the angle between solar azimuth and
 194 the mean azimuth [0° - 180°] of each T-NET reach (computed by considering the first and last vertices of each
 195 reach).

196 To compute VF, we used the second model described in Moore et al. (2014). It provides SVF for channels of
 197 infinite length, without taking into account overhanging trees. For a channel with vertical banks and fixed tree
 198 height, the width- and reach-averaged tree view factor is computed as:

$$199 \quad TVF = \left[1 - \frac{0.5}{W} \left(\sqrt{H^2 + W^2} + \sqrt{H^2 + W^2} - 2H \right) \right] \times vc \quad (\text{Eq. 6})$$

200
 201 The third approach (subsequently referred to as the *lidar* method) is a spatially-explicit method that
 202 computes SF and TVF from a LiDAR-derived digital surface model (DSM). It requires a) a high-resolution digital
 203 surface model (~ 1 m) describing the elevation of riparian vegetation, b) information about the exact location of
 204 the river in order to define water and non-water pixels and c) polygons of river area, allowing the DSM pixels to
 205 be linked to a given T-NET reach.

206 To compute SF, we modified the r.sun module (Hofierka and Suri, 2002) of GRASS GIS (GRASS Development
 207 Team, 2015) to map per-pixel shade cast by the DSM. Using this algorithm, a water pixel is defined as being in
 208 shade if the elevation of the highest DSM pixel located along a 50 m track in the direction of the sun is greater
 209 than the solar elevation. Dividing the number of shaded pixels by the number of water pixels belonging to each
 210 river polygon thus provides a shadow factor for each T-NET reach. Because shading at a given hour vary slowly
 211 throughout the year, the computation was done every hour when the sun is above the horizon, every 15 days of
 212 a standard non-leap year, for every water pixel. A piecewise cubic interpolation is then applied to the SF of each
 213 hour separately in order to get a value for each day of the year.

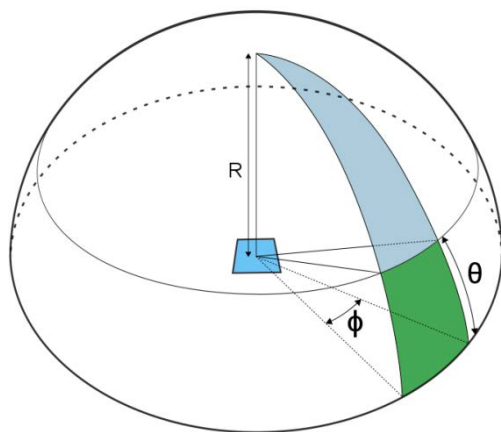
214 To compute SVF from the DSM, we represented the sky as a hemisphere of radius R centred on a water pixel (as
 215 in Essery et al. (2008), Johnson and Watson (1984) and Tung et al. (2006); Figure 2). We used the r.horizon
 216 module of GRASS GIS to calculate the angle θ between the horizon and the highest DSM pixel as seen from each
 217 water pixel at horizontal azimuth steps ϕ of 10° . The whole hemisphere is thus made of $n=36$ segments. The
 218 diffuse radiation emission is considered to be isotropic and the river surface to be horizontal. The SVF for each
 219 segment is computed from the sphere area formula:

$$220 \frac{R^2 \int_0^{\frac{\pi}{2}} \int_0^\phi \cos \theta \sin \theta d\phi d\theta}{R^2 \int_0^{\frac{\pi}{2}} \int_0^\phi \cos \theta \sin \theta d\phi d\theta} = \frac{1 + \cos 2\theta}{2} \quad (\text{Eq. 7})$$

221 It therefore follows that the SVF for the whole hemisphere is given by:

$$222 SVF = \frac{1}{2} + \frac{1}{n} \sum_{i=1}^n \cos 2\theta_i \quad (\text{Eq. 8})$$

223 An averaged TVF value (TVF=1-SVF) is subsequently attributed to each T-NET reach as the mean TVF value for all
 224 DSM pixels located within the reach.

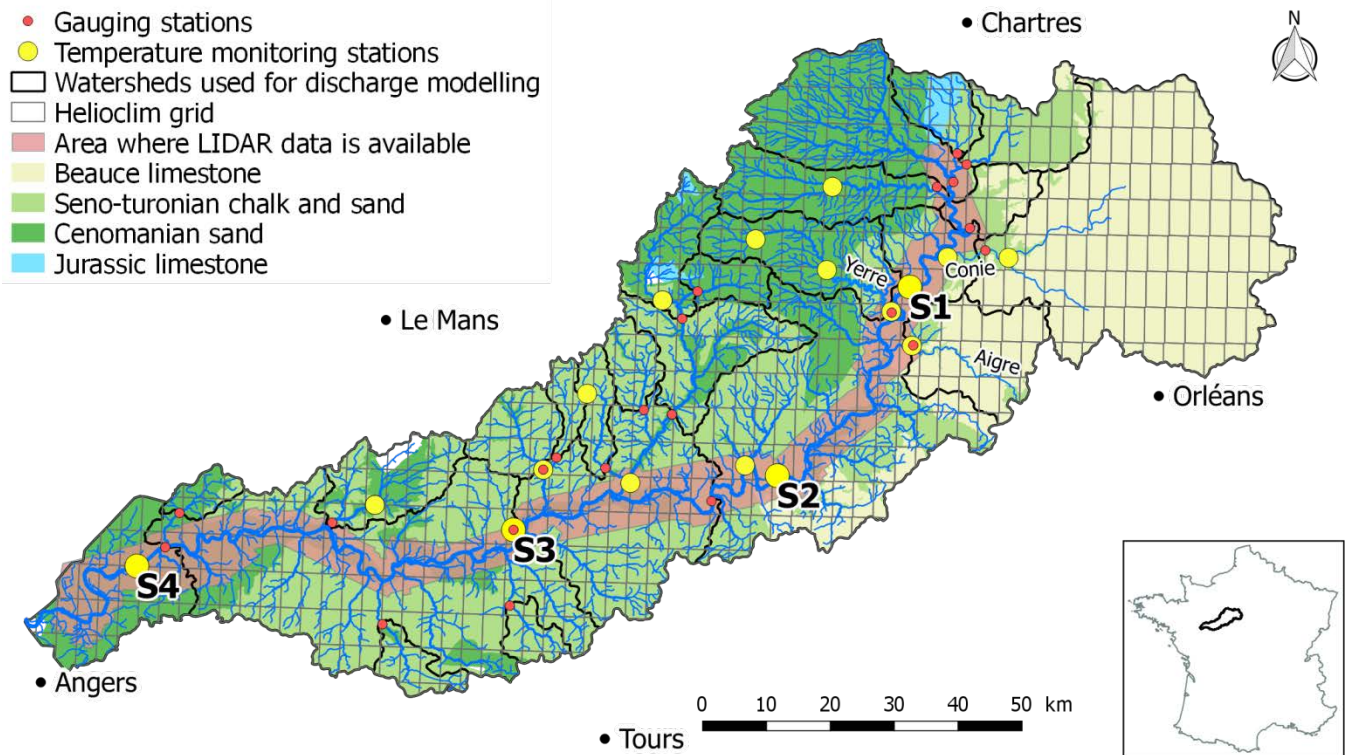


225
 226 **Figure 2: Calculation of a sky view factor from measures of θ , the angle between the horizon and**
 227 **the highest vegetation seen from a water pixel and with an angular step ϕ of 10° . R is the radius of the hemisphere**
 228

229 **2.4. Study site and water temperature observations**

230 The Loir River basin is an 8283 km² sub-catchment of the Maine River watershed located in central France
 231 (Figure 3). The river network of the Loir basin is 4420 km long, of which the Loir River itself is 316 km. The basin
 232 is generally low-lying, with altitudes ranging from 20 to 140 meters above sea level. As highlighted by the river
 233 network's variable drainage density (Figure 3), a calcareous aquifer with high permeability is present in the

234 north-east of the catchment. It feeds the river network with groundwater exchanges in its upstream sections
 235 (Baratelli et al., 2016). Channel slope (computed from a 25 m resolution digital terrain model of the watershed)
 236 ranges from 0.01% to 5%, with a median value of 0.5%. The main tributaries of the Loir are the Conie, the Yerre
 237 and the Aigre, with catchments areas of 530, 300 and 280 km² respectively. The mean discharge of the Loir at its
 238 downstream-most gauging station (1961-2015) is 31.8 m³·s⁻¹ (specific discharge = 4.0 l·s⁻¹·km⁻²). The flows of the
 239 Aigre (specific discharge = 5.4 l·s⁻¹·km⁻²) and the Conie (specific discharge = 3.4 l·s⁻¹·km⁻²) show little variation
 240 during the year, compared to the Loir. However, interannual fluctuations are much greater, driven by
 241 piezometric fluctuations of the Beauce aquifer.
 242 Eighteen temperature loggers allowing for the model validation are located in the catchment. They acquired
 243 data at an hourly time step with varying periods of availability (extending from summer 2008 to summer 2014).
 244 The loggers were generally placed at a depth greater than 1 meter (according to the mean interannual water
 245 level), and steps were taken to ensure that they were installed within well-mixed sections of the channel to
 246 avoid potential stratification biases. Four of these stations are located within the main stem of the Loir (S1 to
 247 S4), where LiDAR data are available. The period of measurement is different for each station and is given in
 248 Figure 4. The annual cycle of mean daily temperature of the Loir River ranges from 2 to 24 °C at station 1
 249 (between 08/2010 and 07/2011), while the annual amplitude of the Aigre and the Yerre are smaller because of
 250 the groundwater fluxes (5-21 °C and 4-16 °C on the same period, respectively). Temperature regime of the Conie
 251 River is strongly dependent on the groundwater level. Its variability can be similar to the Loir River (2009, 2010)
 252 or very limited (annual range of 8-14 °C in 2014).



253
 254 **Figure 3: Map of the Loir catchment, with stream temperature monitoring stations, gauging stations,**
 255 **watersheds used for discharge modelling, LiDAR area, geologic formations, Helioclim grid.**
 256

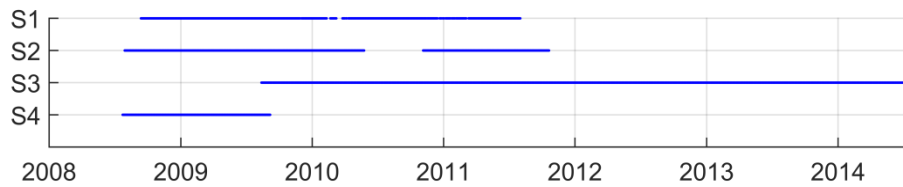


Figure 4: Period of availability of stream temperature observation at the four logger stations located on the Loir River

2.5. T-NET model implementation and criteria of model performance

The Loir River basin was implemented in the T-NET model. It consists of 2206 reaches, of which the Loir River itself is covered by 161 reaches. Simulated discharge and groundwater inputs used to drive T-NET (derived from the EROS hydrological model) were found to agree reasonably well with observed data. Nash-Sutcliffe (Nash and Sutcliffe, 1970) model efficiency coefficient (NSE) calculated against hydrometric observations ranged from 0.59 to 0.95 (1974-2012 period) for 21 of the 23 sub-basins of the Loir catchment. The remaining two sub-basins ($<0.10 \text{ m}^3 \cdot \text{s}^{-1}$; located in the upper portions of the watershed) yielded negative NSE values. In order to compare the three shading methods detailed in section 2.3, we ran the T-NET model three times on seven hydrologic years (from August 2007 to July 2014).

For the *constant* method, vegetation cover (*vc*) was derived from a dataset available at the national scale (Valette et al., 2012), which is based on river and vegetation polygons from the BD TOPO® database, provided by Institut national de l'information géographique et forestière (IGN).

For the *variable* method, *vc* was also derived from this dataset. Tree height *H* was fixed at 15m and river width *W* was estimated using the ESTIMKART empirical model (Lamouroux et al., 2010).

For the *lidar* method, the digital surface model (DSM) required for the shading computation was derived from a LiDAR survey conducted by IGN on approximately 270 km of the Loir River (85% of the total river length) on 26 May 2012. That day, average discharge was $25.5 \text{ m}^3 \cdot \text{s}^{-1}$ at the downstream-most gauging station (interannual average is $31.8 \text{ m}^3 \cdot \text{s}^{-1}$). The DSM was generated by gridding the LiDAR first returns at a resolution of 1 m^2 . LiDAR accuracy was assessed as $\sim 60 \text{ cm}$ in the horizontal and $\sim 20 \text{ cm}$ in the vertical components. Because water does not reflect the LiDAR pulses, no data was available for the water pixels (unless emergent aquatic vegetation was present), and we used this property to discriminate water vs. non-water pixels inside the river polygons of the BD TOPO database. Elevations for these water pixels as well as for other sporadic data gaps were computed by attributing values from a digital elevation model (DEM) to the no data pixels. This 1-m resolution DEM, built from LiDAR final returns, provides values above water by interpolation of altitudes between the river banks. Finally, polygons from BD TOPO were also used to attribute DSM pixels to each reach of the T-NET network. Because LiDAR data were not available on the tributaries and the headwaters of the Loir, the *constant* method was applied on these reaches. With this configuration, the *lidar* method takes less than 5 hours to run on a computer with 16 CPUs and 64 Gb of RAM. Finally, in order to compare the *lidar* method with a situation without riparian vegetation, a supplementary simulation was done with SF and TVF fixed at zero everywhere.

In order to characterise differences in vegetation cover between the DSM and that derived from the BD TOPO database (Valette et al., 2012), a DEM was also used to create a raster of vegetation height by subtracting

292 the DEM (ground) elevations from the DSM. A vegetation cover map was then extracted from the vegetation
293 height raster, where vegetation cover was defined as all pixels with vegetation higher than 1 m. A LiDAR-derived
294 river width was also extracted for analysis purposes by dividing the area of water pixel inside each polygon by
295 the length of the T-NET reaches.

296 Three model performance metrics were used to quantify the accuracy of the different methods regarding
297 the maximum daily temperature. The root-mean-square error (RMSE) was used as a global performance metric:

$$298 \text{ RMSE} = \sqrt{\frac{\sum(T_{sim} - T_{obs})^2}{N}} \text{ (Eq. 9)}$$

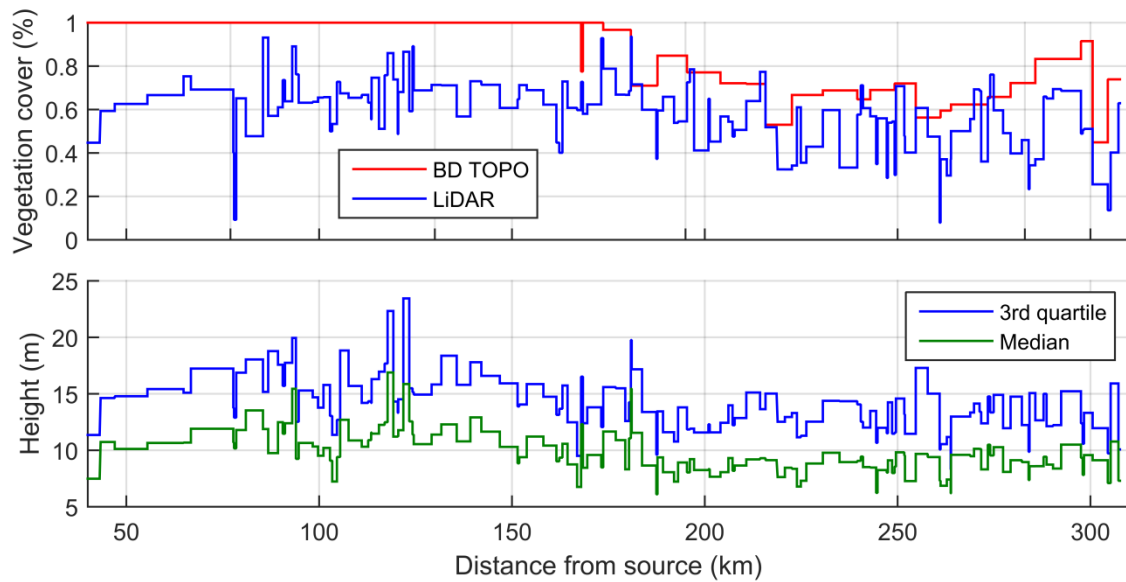
299 where N is the number of observations, T_{sim} is the simulated river temperature and T_{obs} is the observed river
300 temperature. Bias (defined as the mean difference between simulated and measured temperatures) was used
301 to quantify the mean over/underestimation of the model. Finally, the standard deviation of errors (SDE)
302 quantifies the variability of daily biases in a given period. Because the temperature time series used for model
303 validation were not concomitant (Figure 4), model performance was analysed using two methods. First, we
304 compared model performance against all available validation data. This allows for comparison between the
305 three shading methods detailed in section 2.3. Second, in order to compare spatial variability in the model's
306 performance between the 4 temperature logger stations, we used temperature data from the period during
307 which concurrent measures were available at all 4 stations (13th to the 31st August 2009).

308

309 3. Results

310 3.1. Characterisation of riparian vegetation cover

311 Analysis of vegetation cover extracted from the LiDAR data inside a single buffer of 10 m around the 270 km of
312 river shows that 58% of the riparian zone is vegetated. The median vegetation height in this area is 10.0 m and
313 the third quartile of the height (considered by Guzy et al., 2015) is 14.9 m, while the standard deviation is 6.5 m.
314 Longitudinal profiles of vegetation cover, median and 3rd quartile of height are given in Figure 5. There is a slight
315 but significant decreasing downstream trend for these three variables (p-value = 0.014). In comparison with the
316 LiDAR-derived vegetation cover, vegetation cover derived from the BD TOPO database is overestimated
317 everywhere with the exception of some small reaches (Figure 5). The median overestimation is 35% upstream of
318 river km 160 and 22% downstream. This overestimation rises to more than 39% for 20% of the reaches.

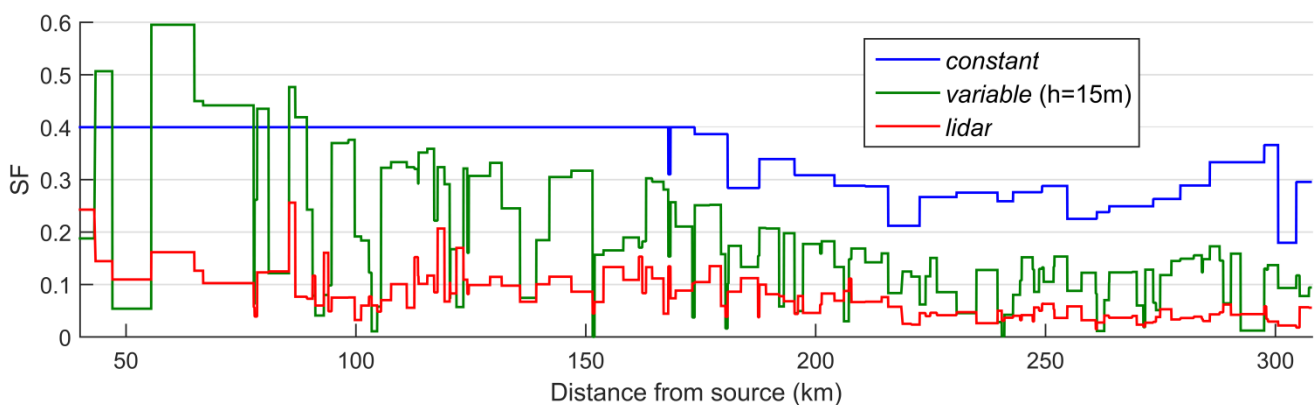


319
320 **Figure 5: Characterisation of riparian vegetation for each T-NET reach (a) comparison of vegetation cover derived from the BD TOPO**
321 **database (Valette et al., 2012) and LiDAR datasets (buffer of 10 m on both sides of the river polygons) (b) median and 3rd quartile**
322 **vegetation heights from LiDAR data**
323

324 3.2. Variation in riparian shading computed with the three methods

325 In the Loir catchment, direct and diffuse radiation comprise ~70% and ~30% respectively of the incoming solar
326 radiation received at the river surface between 8 and 16h (period 2007-2014). This means that shadow factor
327 has a greater impact on water temperature than view factor.

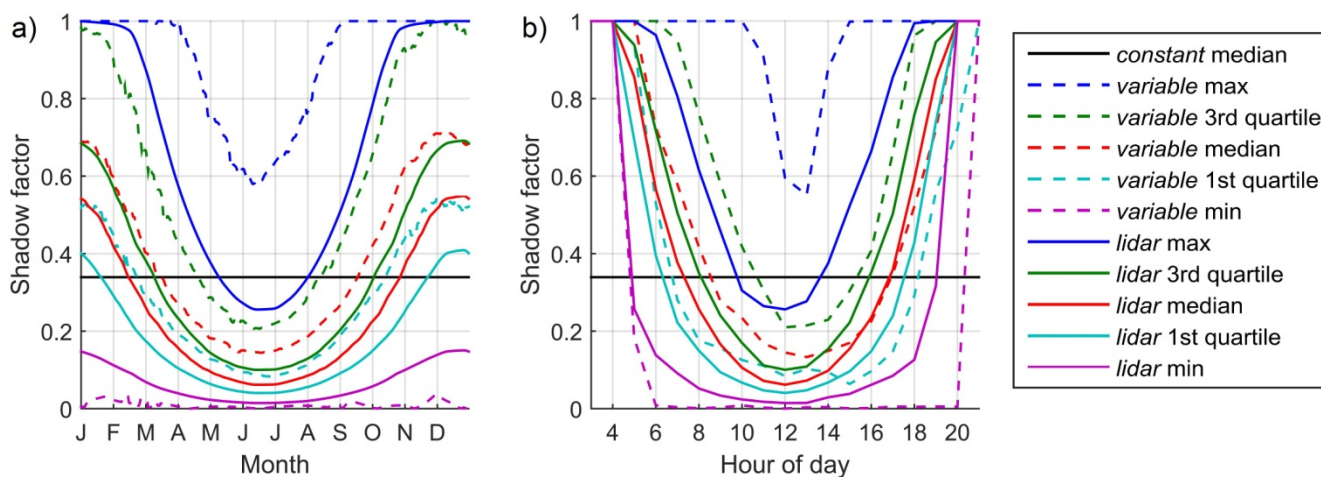
328 Figure 6 shows the longitudinal profile of SF on the Loir River for the three methods at midday on the summer
329 solstice, when solar radiation is strongest. For the *constant* method, the reaches covered by LiDAR data have a
330 uniform Strahler order of 5, so that the weighting coefficient k in this area is always equal to 0.4 (see section
331 2.3). The variation of SF is thus only dependent on the vegetation cover. The *variable* method varies strongly as
332 a function of reach azimuth, even though the sun is at its highest elevation, while the *lidar* method shows
333 smaller variations. The *lidar* method is thus less sensitive to reach azimuth, compared to the *variable* method.



334
335 **Figure 6: Longitudinal profile of shadow factor provided by the 3 methods on the Loir River**
336 **at the summer solstice (21st June) at 12h UTC.**
337

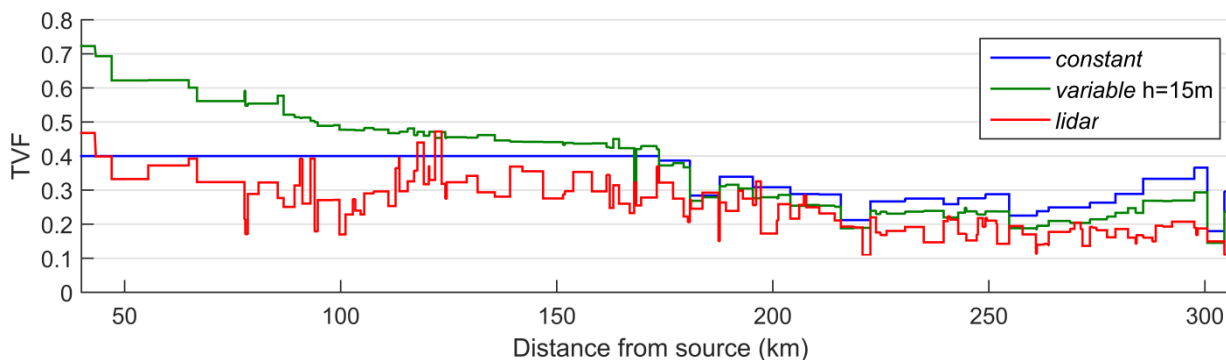
338 At noon, the Loir's SF computed with the *lidar* method lies between 0 and 0.3 in June (median=0.1; Figure 7a
339 solid lines) and between 0.1 and 1 in December (median=0.5). There is thus more variability in winter than in
340 summer, because reach azimuth has a much greater impact when the sun is low in the sky. Seasonal variability

341 in SF exhibits strong annual cyclicality, with SF minima centred on the summer solstice for every reach. Highest SF
 342 values are found on a reach located 85 km from the source, flowing East-West and bordered by persistent
 343 riparian forest cover (>20 m tall). Lowest SF values are found on a North-South oriented reach located 271 km
 344 from the source, explaining the weak annual cycle at noon (Figure 7a, pink solid line). Figure 7b shows the daily
 345 cycles at the summer solstice. The hour of minimum SF in a day is not always centred on noon because it
 346 depends on the reach orientation. SF obtained from the *variable* method is usually higher than that provided by
 347 the *lidar* method, except in winter and at noon for North-South oriented reaches (Figure 7a, dashed pink line).
 348 At the summer solstice, between 6 and 18h, the *variable* method yields higher SF than the *lidar* method 74% of
 349 the time, especially in the upstream parts of the watershed. Indeed, the *variable* method yields 184 occurrences
 350 of SF values equal to 1, while it only occurs 3 times with the *lidar* method.



351
 352 **Figure 7: Percentiles of the SF distribution obtained with the three methods on the 135 T-NET reaches**
 353 **(a) Annual cycles at noon (b) daily cycles at the summer solstice.**
 354

355 Figure 8 shows the longitudinal profile of TVF for the three methods. Mean values are 0.34, 0.38 and 0.26 for
 356 the *constant*, *variable* and *lidar* methods respectively. TVF computed with the *lidar* method comprises values
 357 between 0.47 and 0.11. Like for the SF, there is a significant ($p < 0.01$) decreasing trend due to both the
 358 increasing width of the river and the decreasing vegetation cover. The *variable* method overestimates TVF,
 359 especially for the upstream portion of the river. Indeed, the inter-method variability in computed TVF values
 360 decreases as the influence of vegetation on TVF reduces with increasing river width.



361
 362 **Figure 8: Longitudinal profile of tree view factor provided by the 3 methods on the Loir River.**
 363 **Values from the *variable* method are averaged on 08/2007-07/2014**
 364

365 **3.3. Impact of riparian shading method on annual and seasonal river temperature simulations**

366 Results of this paper focus on the 4 temperature monitoring stations located on the Loir River, where LiDAR
 367 data are available. For the 14 other temperature monitoring stations located on the tributaries, the constant
 368 method provides a median annual RMSE on mean daily temperature at 1.69 °C (min=1.35 °C, max=2.89 °C).
 369 Seasonality in the accuracy is observed since median bias on mean daily temperature is -0.4 °C when computed
 370 for the full year but rises to 0.2 °C in summer. 67% of daily biases are comprised between ± 2 °C.

371 Biases, SDE and RMSE averaged on the four stations are shown in Table 1 for the April-September and the
 372 October-March periods. In the April-September period, the *lidar* method improves the mean bias by 0.62 °C in
 373 comparison with the *constant* method. The mean RMSE is improved by 0.22 °C although the mean SDE is
 374 increased by 0.10 °C. The three metrics show that the *constant* method provides better results than the *variable*
 375 method. During the October-March period, biases of the 3 methods are closer to zero. All criteria of the
 376 *constant* and the *lidar* methods are very similar because solar radiation is lower and vegetation transmissivity is
 377 high. However, the *variable* method is consistently colder than the other methods by ~ 0.3 °C.

378
 379

Table 1: Model performance criteria for maximum daily temperature, averaged for the 4 stations located on the Loir River from April to September and from October to March (°C)

	April to September			October to March		
	Bias	SDE	RMSE	Bias	SDE	RMSE
<i>Constant</i> method	-1.44	1.61	2.17	-0.31	2.04	2.07
<i>Variable</i> method (h=15m)	-1.86	1.65	2.55	-0.60	2.09	2.18
<i>Lidar</i> method	-0.82	1.75	1.95	-0.33	2.05	2.08

380

381 Figure 9 shows the monthly biases ($T_{sim} - T_{obs}$) of maximum daily temperature (T_{max}) computed on available
 382 measured data (see Figure 4). At the four stations, the *lidar* method provides improved biases in comparison to
 383 both the *variable* and the *constant* method from April to September. Compared to the *variable* method, the
 384 maximum improvement occurs during the spring and autumn months (2 °C at S1; 1.5 °C at S2; 0.5 °C at S3; 0.7
 385 °C at S4). Despite this improvement, the *lidar* method still underestimates river temperature by more than 1 °C
 386 during at least 2 months in summer at S1, S2 and S4. The *constant* method provides a consistently colder T_{max}
 387 than the *variable* (and *lidar*) methods at stations 3 and 4 from May to August, presumably because this method
 388 does not model the seasonal cycle of increasing and decreasing shadow length.

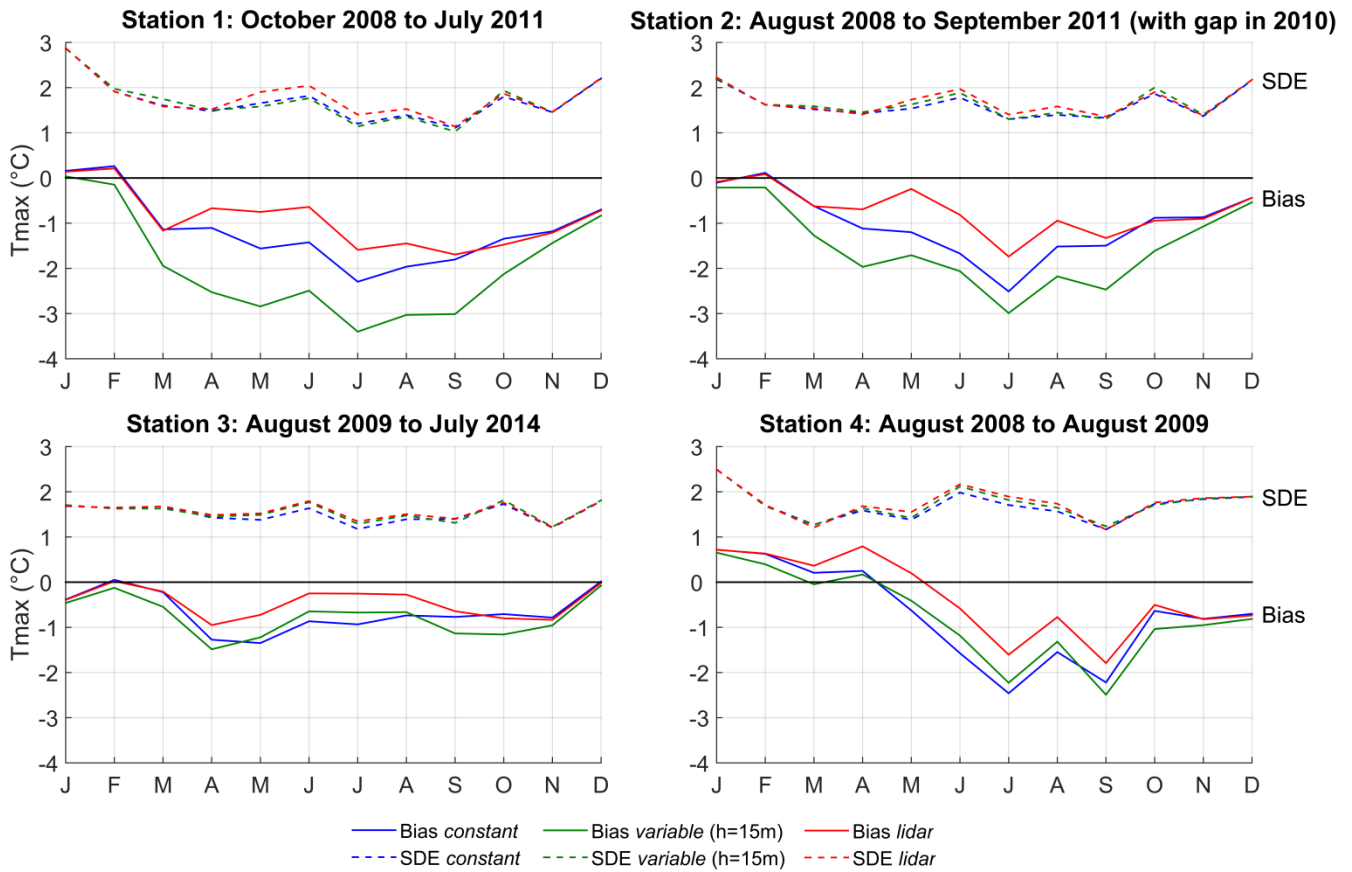


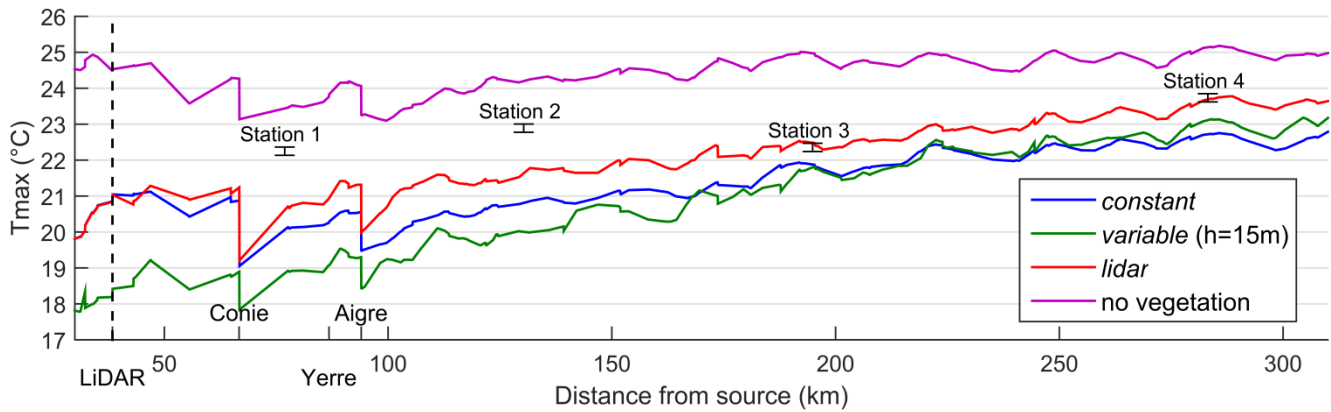
Figure 9: Monthly biases ($T_{sim}-T_{obs}$) and standard deviation of errors of maximum daily temperature provided by the 3 methods at the 4 stations (averaged annual cycles computed on available observed data)

Averaged annual cycles of SDE show little difference between methods and always stay above 1 °C (Figure 9). That means that simulated T_{max} is substantially more variable than observed data, whatever the method used.

3.4. Impact of riparian shading method on summer maximum daily temperature long profile

We analysed longitudinal profiles in summer by considering average maximum temperature between the 13th and the 31st August 2009. During this period, discharges were low ($<7 \text{ m}^3 \cdot \text{s}^{-1}$ at the downstream-most gauging station) and the averaged maximum daily air temperature in the catchment was relatively high (25.9 °C). The longitudinal profiles (Figure 10) exhibit discontinuities in the thermal signal that are driven by cool water inflows from the Conie and Aigre rivers, which drain the Beauce aquifer (Baratelli et al., 2016). Before entering the LiDAR-covered area (shown with a dashed vertical line), the *variable* method is colder than the *constant* method by more than 2.5 °C. This difference decreases slowly in a streamwise direction until it reverses and the *variable* method becomes warmer than the *constant*. Indeed, the three methods provide a persistent warming trend as a function of distance from source, but this trend is higher for the *variable* method (1.87 °C/100 km compared to 1.23 °C/100 km and 1.25 °C/100 km for the *constant* and *lidar* methods respectively). This difference in longitudinal trend persists across all summers in the 2007-2014 simulation period. On average between the 13th and 31st August 2009, the *lidar* methods provide warmer T_{max} than the two other methods all along the Loir, with biases close to zero at stations 3 and 4. However, T_{max} is still underestimated by 1.6 and 1.3 °C at stations 1 and 2. RMSE values are 1.99, 2.08, 1.43 and 1.79 °C on S1 to S4 respectively. Figure 10 also shows the simulation considering the absence of riparian vegetation. The difference between this output and the *lidar* method

412 reaches up to 3.0 °C just upstream of the Conie confluence, where sensitivity analysis shows that the *lidar*
 413 method simulation is no longer under the influence of the constant method applied upstream of the LiDAR area.
 414 This difference reaches a minimal value of 1.3 °C at the downstream-most point.



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 416
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Figure 10: Longitudinal profile of maximum daily temperature (averaged between the 13 and the 31 August 2009) provided by the 3 methods and by a vegetation-free simulation. The vertical dashed line depicts the start of LiDAR cover. Conie, Yerre and Aigre are the main tributaries.

420 4. Discussion

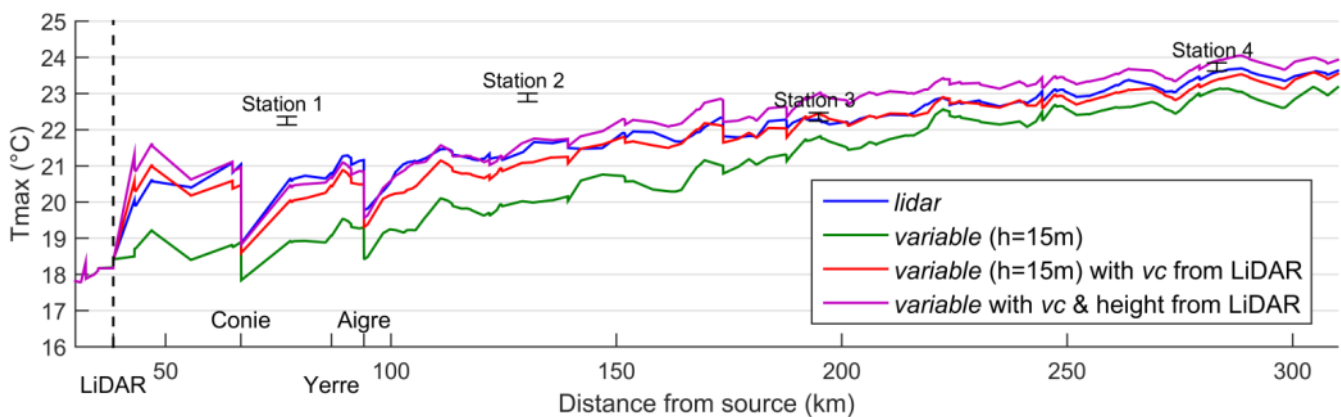
421 4.1. Discrepancies in computed SF and TVF

422 The global overestimation of SF and TVF provided by the *variable* method compared to the *lidar* method can be
 423 explained by four key factors. First, the BD TOPO database that weights the results of the *variable* method
 424 clearly overestimates vegetation cover in relation to the LiDAR-derived values (discussed in section 3.1). Second,
 425 comparison of the wetted widths used in the *variable* method with LiDAR-derived river widths shows that the
 426 former are underestimated, especially upstream of ~150 km and downstream of ~250 km from the source.
 427 These width uncertainties drive an increase in SF (TVF) of 6% (4%) when averaged over the entire modelling
 428 period and 14% (9%) between 13th and 31st August 2009. Third, discrepancies may also arise from the fact that
 429 the *variable* method uses averaged stream azimuths while the *lidar* method intrinsically considers the position
 430 of vegetation in regard to the water surface. Indeed, reach azimuth impacts the timing of minimum SF (Li et al.
 431 2012), the hourly amount of direct solar radiation and hence the maximum daily temperature (Garner et al.,
 432 2017). In order to quantify these discrepancies, we cut the Loir river GIS line in 50 m parts and compared
 433 azimuths of these small reaches with the original T-NET reaches azimuths. The mean absolute difference is 26°
 434 and R² is 0.66. Finally, the characterisation of vegetation cover and height at high resolution with the LiDAR data
 435 may not be reproducible in the *variable* method by taking an average of these data at the reach scale. Indeed,
 436 Greenberg et al. (2012) report that 28% of the change in insolation caused by removal of riparian vegetation
 437 characterised with LiDAR data could not be explained by considering averages at the reach scale. In our case, a
 438 multiple linear regression between LiDAR-derived TVF and LiDAR-derived tree height, vegetation cover and river
 439 width averaged at the reach scale provides R²=0.83. Hence, 17% of the TVF variance cannot be explained by
 440 these three variables when averaged at the reach scale.

441
 442

442 4.2. Influence of shading routine on simulated river temperatures

443 In order to separate the influence of the *variable* method itself from the influence of the vegetation cover data
 444 used to drive it, we injected the vegetation cover computed from the LiDAR data (10 m buffers on each river
 445 bank for each reach) into the *variable* method. As a first step, tree height was kept at 15 m. The resulting
 446 longitudinal profile (13 to 31 August 2009 average) shows that, in this configuration, the *variable* method closely
 447 approximates the *lidar* method (Figure 11). The mean bias (computed against observed temperatures) between
 448 April and September is -1.19 °C, compared to -0.94 °C for the *lidar* method and to -1.86 °C for the *variable*
 449 method with the original vegetation cover. The median vegetation height computed from the LiDAR dataset was
 450 subsequently also injected into the *variable* method. In this case, mean bias is further reduced to -0.78 °C. Using
 451 the same approach with the *constant* method provides a profile that is warmer than the *lidar* method profile
 452 prior to river km 100 and colder after river km 200. Hence, a coefficient $k=0.4$ seems to be appropriate for a
 453 river width of 25-30 m, during the month of August.



454

455 **Figure 11: Longitudinal profile of maximum daily temperature (averaged between the 13 and the 31 August 2009) provided by**
 456 **injecting the *variable* method with vegetation cover (vc) and median height from LiDAR data. The vertical dashed line depicts the**
 457 **start of LiDAR cover. Conie, Yerre and Aigre are the main tributaries.**
 458

458

459 **4.3. Performance of T-NET model on the Loir River**

460 Although the T-NET model of the Loir River (driven with the *lidar* method) provides relatively unbiased
 461 temperature at station 3, it still underestimates temperature at stations 1 and 2 and to a lesser extent at station
 462 4 (Figure 9). Sensitivity analyses show that uncertainty about the impact of vegetation on tributaries (because of
 463 the application of the *constant* method in areas where LiDAR data do not exist) cannot fully explain the
 464 underestimation of modelled temperatures on the Loir. Underestimation at station 1 is partly due to the
 465 underestimation of the Conie tributary. An impoundment located at the source of the river likely explains why
 466 the Conie is warmer than expected (Pedersen and Sand-Jensen, 2007; Dripps and Granger, 2013).
 467 Impoundments on several other tributaries may have the same effect and contribute to warming the Loir River
 468 and hence explain the negative biases at station 2. Station 4 is located just upstream of a small weir. There are
 469 more than 120 small weirs (height <3m) on the Loir River that may partially explain the temperature
 470 underestimation. Indeed, by increasing water depth, they increase travel time and thus sensitivity to air
 471 temperature. By decreasing water velocity, they can favour thermal stratification in summer (Torgersen et al.,
 472 2001) and since water is usually released by weir-overflow, warmer water may be selectively released. This
 473 process is not taken into account in T-NET because it only considers the longitudinal dimension. Other more
 474 complex hydrodynamic models (eg. Becker et al., 2010; Cole and Wells, 2006; Maderich et al., 2008; Deltares,

2014) would therefore be required to incorporate this process. The high temporal variability in modelled temperatures (compared to observed data) is likely due to modelled flow velocities that exceed real values. Unfortunately however, we have no observed values of travel time to compare with. Finally, it must be kept in mind that 1) computed model performances are dependent on the number of validation stations, which is limited to 4 in the current study and 2) that the T-NET model is driven with re-analysis data which are themselves subject to errors. In particular, the number of meteorological stations providing air temperature as input of the SAFRAN reanalysis in the Loir catchment is limited: approximately 10 stations are located upstream of S1 but only 2 stations located close to each other cover the rest of the basin (Quintana-Seguí et al., 2008). The density of stations is still lower for wind velocity and relative humidity but is higher for precipitations.

4.4. Implications, shading methods limitations and perspectives

Our results show that the *lidar* method has good potential for computation of SF and SVF at hourly timesteps on medium to large rivers and at large temporal and spatial scales. For small rivers (width < 10 m), whose precise location can be hard to determine using remote sensing due to obscuration by the tree canopy, the *variable* method may be more suitable, as long as it is fed with accurate vegetation cover data. Indeed, our results show that differences of modelled T_{max} can be large if the methods are used with inaccurate vegetation cover data. The quality of these input data is therefore highly important for improving stream temperature modelling. LiDAR covers of riparian zones are increasingly available, in particular because of their use for flood risk assessments. Furthermore, vegetation heights can also be obtained at the catchment scale by photogrammetric techniques (eg. Michez et al., 2017), while satellite and airborne high resolution imagery can provide accurate location of riparian vegetation (Tormos et al., 2014). These new techniques could potentially be valuable for improving future river temperature modelling efforts.

Our results show that in late August 2009, the Loir's vegetation decreases T_{max} up to 3 °C in the upstream part of the river and by 1.3 °C at the downstream-most reaches. This difference is caused by the increasing wetted width (from ~25 to ~50 m) but also by decreasing vegetation cover in the streamwise direction. These quantifications of the thermal impact of riparian vegetation are likely minimum values for two reasons. First, the impact of overhanging trees was neglected (as in all methods used in this paper) (Li et al., 2012; DeWalle, 2008). Secondly, the summer transmissivity value comes from publications studying single trees' transmissivity. However, because riparian buffers are often composed of several rows of trees, real world transmissivity values are likely to be lower, resulting in slightly cooler water temperatures (Duursma and Mäkelä, 2007; Dugdale et al., 2018). Beside this, further research is needed to validate the accuracy of shadows obtained with the *lidar* method against aerial imagery. As an example, Greenberg et al. (2012) reported an overall accuracy of 92%. Since their LiDAR data and ours were both acquired when trees were in leaf, a similar accuracy may be expected.

A wide range of values is reported in the literature regarding the cooling effect of vegetation (Moore et al., 2005), mainly for streams narrower than 10 m, for which the response of T_{max} to clear-cutting can range from 2 to 8°C (Gomi et al., 2006). For streams wider than 10 m, a modelling approach is usually used to quantify the

512 impacts of vegetation on stream temperature. Our results are in agreement with Woltemade and Hawkins
513 (2016), who modelled a cooling effect of vegetation of approximately 2 °C for a 14 m wide North-West/South-
514 East oriented stream flowing in a mountainous catchment of California (low-flow conditions). A topographic
515 shade of 17% was considered in the deforested scenario; their result would thus be higher in an environment
516 without mountains, like the Loir catchment. Using LiDAR data, Wawrzyniak et al. (2017) modelled a cooling
517 impact of 0.4 °C on T_{max} on a 22 km-long groundwater-fed river reach with a wetted width ranging from 50 to
518 120 m. The overall NNE-SSW orientation of this river is likely to decrease the impact of riparian vegetation, in
519 comparison with the Loir, which is globally east-west orientated. Other studies show that the impact of
520 vegetation decreases steadily as wetted width increases to about 30 m (Teti, 2006), 10 m (Davies-Colley and
521 Quinn, 1998) and 17 to 43 m for East-West to North-South oriented streams (DeWalle, 2008). Our results
522 suggest that the cooling effect can remain above 1 °C even for widths larger than 40 m.

523 Potential improvements to our *lidar* method include the incorporation of wetted widths related to the
524 discharge. Although this is possible at small spatial and temporal scales by using a hydraulic model (Wawrzyniak
525 et al., 2017), modelling wetted widths at regional scales can be very complex, especially without field measures
526 of hydraulic geometry. Channel morphology from bathymetric LiDAR data may be one potential solution to this
527 issue (eg. Hilldale and Raff, 2008; Bailly et al., 2010). Another potential improvement to our methodology relates
528 to the use of Beer's law to model the extinction of solar rays through the tree canopy, as demonstrated by
529 several investigations using coarse vegetation data (Sun et al., 2015; Tung et al., 2007; Sridhar et al., 2004; Lee
530 et al., 2012). Transmission of light beneath the canopy of overhanging trees could also be modelled, but
531 requires information or hypotheses regarding the shape of trees. When aerial imagery is available, more
532 complex methods considering position of individual trees may be used in order to model the transmission of
533 light beneath the canopy (Essery et al., 2008).

534 Finally, this paper focuses on the impact of vegetation on solar radiation and hence on maximum daily
535 temperature (Johnson, 2004; Garner et al., 2017). Although the impact of vegetation on longwave radiation is
536 limited on sunny days (Leach and Moore, 2010; DeWalle, 2008), view factors computed in this paper could be
537 used to quantify the impact of vegetation on longwave fluxes at both regional scales and during a complete
538 annual cycle. LiDAR data could also be used to model the impact of vegetation on water temperature resulting
539 from decreased air temperature and wind velocity engendered by the riparian canopy. Indeed, forest canopies
540 can reduce daytime air temperature by 3 °C to more than 6 °C and wind velocity by 10-20 % in comparison with
541 open areas (Moore et al., 2005).

543 **5. Conclusion**

544 The main goal of this study was to understand the influence of using a LiDAR-derived digital surface model to
545 quantify the impact of riparian vegetation on 270 km of the Loir River. We demonstrated that the use of LiDAR
546 data improves the mean biases of simulated maximum daily temperatures (T_{max}) in summer, compared to two
547 other simpler methods for computing the effects of riparian shading at large scales. However, it did not improve

548 the standard deviation of errors on T_{max} , which is likely more influenced by the presence of weirs and
549 impoundments.

550 The monthly-averaged difference in T_{max} computed by the various shading methods can reach up to 2 °C at the
551 upstream-most station and 1 °C at the downstream-most station. However, this difference is mainly due to the
552 overestimation of vegetation cover in the dataset used to compute shadow and view factors in the non-*lidar*
553 methods. Indeed, injection of vegetation cover extracted from the LiDAR data into the shading method of
554 medium complexity (*variable method*) decreased the largest difference at the upstream-most station to 0.8 °C,
555 suggesting that this method is sufficient for the computation of SF and VF provided that it is supplied with
556 accurate (high-resolution) data pertaining to vegetation cover. Improving the quality of riparian vegetation data
557 should therefore be a priority for improving stream temperature modelling at the regional scale. The simplest
558 method (*constant method*) may be appropriate to model mean daily temperature for a given period of the year,
559 as long as vegetation cover is weighted with a coefficient depending on the river width.

560 We hope that the application and comparison of methods demonstrated in this paper will improve
561 understanding of the strengths and limitations of other existing stream temperature models. Enhancing the
562 ability of models to simulate the impact of riparian vegetation is of key importance for the development of
563 climate change adaptation measures and understanding the fundamental processes responsible for spatio-
564 temporal variability of river temperature.

565

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574

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