Quantification of the contribution of the Beauce's Aquifer Groundwater Aquifer contribution to the discharge of the Loire River/River Loire discharge using thermal infrared satellite thermal infrared imagery imaging

E. Lalot[1], F. Curie[12], V. Wawrzyniak[23], F. Baratelli[3], S. Schomburgk[44], N. Flipo[3], H. Piegay[25], F. Moatar[16]

[1,2,6]{ Laboratoire GEHCO, UFR sciences et techniques, Université François Rabelais, Tours, France }

Mis en forme : Anglais (États-Unis)

[23,5]{ Plateforme ISIG, CNRS-UMR 5600 EVS, Ecole Normale Supérieure de Lyon, Université de Lyon, Lyon, France }

[4]{ Dir. Eau Environnement et Ecotechnologies, Bureau de Recherches Géologiques et Minières (BRGM), Orléans, France }[3]{ Centre de Géosciences – Systèmes hydrologiques et Réservoirs, Mines ParisTech, Fontainebleau, France }

[4]{ Dir. Eau Environnement et Ecotechnologies, Bureau de Recherches Géologiques et Minières (BRGM), Orléans, France }

Correspondence to: E. Lalot (eric.lalot@gmail.com)

Abstract

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Seven Landsat t~~T~~hermal i~~I~~nfrar~~R~~ed (TIR) images~~,~~ taken over the period 2000-2010~~,~~ were used to establish longitudinal temperature profiles of the middle Loire River~~,~~ where it flows above the Beauce aquifer. The groundwater discharge along the River course was quantified for each identified groundwater catchment area~~s~~ using a heat budget based on ~~the~~ temperature variations of the Loire River ~~temperature variations,~~ estimated from the TIR images. The r~~R~~esults showed that 75% of the temperature differences, between *in situ* observations and TIR image based estimations, remained within the ±1°C interval. ~~The groundwater discharge along the River course was quantified for each identified groundwater catchment areas using a heat budget based on the Loire River temperature variations, estimated from the TIR images.~~ The main discharge area of the Beauce aquifer into the Loire River was located between river kilometers 630 and 650, ~~with~~where there was a temperature drop of around 1°C to 1.5°C in the summer and a ~~temperature~~ rise of about 0.5°C in winter. According to the heat budgets, groundwater discharge ~~i~~was higher during the winter period (13.5 $m^3.s^{-1}$) than during the summer period (5.3 $m^3.s^{-1}$). These findings are in ~~agreement~~line with the results of both a groundwater budget and a process-based distributed hydrogeological model. Groundwater input was also found to be higher during the Loire's flow recession periods~~/ receding flow periods of the Loire River~~. ~~This result confirms what was obtained using a groundwater budget and spatially locates groundwater input within the Middle sector of the Loire River. According to the heat budgets, groundwater discharge is higher during winter period (13.5 m³/s) than during summer (5.3 m³/s). Groundwater input is also higher during the flow recession periods of the Loire River.~~

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1 Introduction

Water temperature is a key factor for aquatic fauna (Ward, 1992; Caissie, 2006). For instance, it controls oxygen~~'s~~ dissolution, ~~a key parameter~~essential for aquatic organisms. River temperature is controlled by many factors such as solar radiation, air temperature or groundwater discharge (Webb and Zhang, 1997, 1999; Hannah et al., 2004). However, quantifying the respective influence of these factors is often difficult, since temperature profiles of the river course have first to be established.

Since the late 1990's t~~T~~hermal i~~I~~nfrar~~R~~ed images (TIR) have been used to determine river water temperature along sections ranging from tens to hundreds of kilometers (Torgersen et al., 2001; Handcock et al., 2006 and 2012). Until now, ~~TIR~~ these images of water courses have mainly been used ~~to~~: i) to identify cold refuges for fish in the summer~~time~~ (Belknap and Naiman, 1998; Torgersen et al., 1999; Tonolla et al., 2010; Monk et al., 2013); ii) to study the thermal variability of rivers or alluvial floodplains and locate areas of similar thermal characteristics (Smikrud et al., 2008; Tonolla et al., 2010; Wawrzyniak et al., 2012, 2013); iii) to validate river temperature models (Boyd and Kasper, 2003; Cristea and Burges, 2009).

~~However, m~~Most of these studies have been~~are~~ based on airborne TIR images, while s~~. S~~tudies based on ~~satellite~~ TIR satellite images are scarce, ~~mostly~~ mainly due to their poor ~~because the~~ spatial resolution ~~of these images is usually poor~~. In the case of the Landsat 7 satellite, one pixel of the TIR image represents 60*60 m on the ground ~~surface~~. Therefore, only a few large river courses ~~could~~ can be studied using TIR satellite images, as it is usually considered that~~it was considered that the~~ river width ~~had to~~must exceed 3 image~~s~~ pixels to ~~allow enough accuracy in~~provide an accurate estimation of water temperature ~~estimation~~ (Handcock et al., 2006; Wawrzyniak et al., 2012). However, the advantage of Landsat satellite images ~~have the advantage~~ over airborne images is that they are~~of being~~ freely available at different dates, ~~so that~~providing archives ~~are available~~ to explore inter-annual or seasonal patterns. As the surface area~~ground~~ covered by ~~one~~ a single satellite image would ~~take time~~require a long time to be covered using air transportationby air, longitudinal thermal profiles derived from TIR satellite images also show less bias due to change in water temperature during sampling time.

Although it has been shown that gGroundwater discharge has already been shown may to have a significant influence on surface water temperature (Hannah et al., 2004; Webb and Zhang, 1997, 1999), however, this influence has seldom been studied based onusing TIR images (Loheide and Gorelick, 2006; Burckholder et al., 2007; Wang et al., 2008, Danielescu et al., 2009; Mallast et al., 2014). Only one paper describes a test to quantify the groundwater discharge in a small stream, based on the longitudinal temperature profile established from the airborne TIR images (Loheide and Gorelick, 2006). To the authors'our knowledge, groundwater discharge into rivers has not never been observed or quantified before, using satellite TIR images.

The knowledge of LocatingThe location of groundwater discharge areas location is crucial to assess the vulnerability of aquatic fauna, as thesegroundwater discharge locations can act as sheltered areas (Belknap and Naiman, 1998). Understanding water temperature variations Along along the middle Loire River, where several nuclear power plants are located, the understanding of the water temperature evolution variations is an operational issue for "Electricité De France" (EDF). It has been shown that,For example, between the nuclear power plants of Dampierre and Saint – Laurent des Eaux, the Loire River temperature has been shown to beis influenced by the groundwater discharge from the Beauce aquifer and the Val d'Orléans hydrogeological system (Alberic and Lepiller, 1998; Alberic, 2004; Moatar and Gailhard, 2006). The average discharge of the Beauce aquifer has already beenwas previously quantified using hydrogeological numerical modelling (Monteil, 2011; Flipo et al., 2012) and it was found to be circahave an- inter annual average of approximately 10 $m^3.s^{-1}$$m^3/s$ on inter annual average. However, until now, field measurement data has not been used to accurately locate or quantify the groundwater discharge ~~has not been well located or quantified based on field measurement data~~.

The main ~~goals~~ aims of this study were therefore to test the ~~abilities~~ ability of ~~Landsat satellite~~ thermal infrared images from the Landsat satellite i) to accurately determine water temperature in a river ~~having~~ with a width ~~under~~ of less than 180 m; ii) to characterize the ~~evolution~~ longitudinal and temporal variations of temperature along a 135 km section of the middle Loire River overlying the Beauce aquifer between Dampierre and Blois; iii) to locate and quantify the contribution of the Beauce aquifer groundwater discharge~~'s contribution of the Beauce aquifer~~ into the Loire River.

2 Study area

The study site ~~is~~ was the Loire River between Gien and Blois (a 135 km reach), which overlies the Beauce aquifer (Figure 1). The catchment area of the Loire ~~River~~ at Gien is 35,000 km^2 and river slope is 0.4 m.~~/~~km^{-1} in the studied section (Latapie et al., 2014).

The river flow rate is measured daily in Gien, Orléans ~~,~~ and Blois, respectively at river kilometers 560, 635 and 695 (Banque HYDRO: www.hydro.eaufrance.fr). Over the 1964~~-~~ to 2011 period, in Orléans the average flow rate ~~in Orléans is~~ was 345 m^3.s^{-1}~~m³/s~~, and the average flow rates in August and January ~~is~~ were 95 m^3.s^{-1}~~m³/s and the average flow in January is~~ and 553 m^3.s^{-1}~~m³/s~~respectively.

The width of the wet section of the middle Loire River ranges between 200 m and 450 m (Latapie et al., 2014), which is higher than the three image pixel~~s (180 m)~~ threshold(180 m). However, during low flow periods, the Loire River ~~locally~~ forms several branches locally and the ~~river~~ main branch width can be as low as 50 m. During ~~low flow~~these periods, the average river depth is about 1 m in ~~this these sections~~the studied reach. ~~The main weirs (natural and~~

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~~artificial) along~~Along the Loire River, the main natural and artificial weirs are located at river kilometers 571, 603, 635, 661, and 670, where the ~~river~~ water level shows a drop of just over 1 m ~~at~~ during low flow periods.

~~On t~~The climate of the study area ~~the climate~~ is temperate. The mean annual air temperature in Orléans is 11°C. The cold season lasts from mid-November to early March, with an average air temperature of 4.0°C (data from Météo France at Orléans station for the period 1961-1990). The warm season lasts from late May to early September, with an average air temperature of 17.2°C.

The water temperature of the Loire River is influenced by several factors: i) atmospheric heat fluxes from direct solar radiation~~s~~, diffuse solar radiation, latent heat exchange, conduction and water emitted radiation~~s~~; ii) groundwater discharge from the Beauce aquifer and Val d'Orléans hydrosystem (Alberic, 2004; Gutierrez and Binet, 2010);~~-~~ iii) warm water originating from the cooling systems of the nuclear power plants of Dampierre and Saint-Laurent des Eaux (average discharge of 2 $m^3.s^{-1}$~~m^3/s~~ ~~by~~ from nuclear reactors). However, ~~the influence of~~ the nuclear power plants only ~~on~~have a slight -influence on the ~~Loire River~~ temperature of the river~~is low~~, as the cooling towers ~~the heat being~~ remove much of the~~d~~ heat~~through cooling towers~~. The median temperature rise ~~of the Loire River~~ between the upstream and downstream sections~~parts~~ of the nuclear power plants is 0.1°C with a 90th percentile of 0.3°C (Bustillo et al., 2014). The greatest increase in ~~the Loire R~~river temperature due to the ~~nuclear~~ power plants ~~in the Loire River temperature~~ is observed in winter, ~~at~~ during low flow periods (<1°C); iv) in~~-~~flows from the tributaries. The catchment area of the Loire River between Gien and Blois is around 5,600 km², (a 16% increase ~~of~~ in the ~~Loire River~~ catchment area over the 135 km reach). The influence of the tributaries on the ~~Loire River~~river temperature is considered negligible in this section ~~of the Loire River~~, since the water temperature of the tributaries is usually close to that of the Loire

River itself temperature (Moatar and Gailhard, 2006) and the flow rates of the tributaries flows are smallis low (less than 1 $m^3.s^{-1}$). However, in this section the main tributary of the Loire River in this section, is the Loiret River,which drains water originating from both the Beauce aquifer and the Loire River (Alberic, 2004; Binet et al., 2011) and is very short (6 km). The influence from of the Loiret River is therefore difficult to separate fromcan therefore be mergedincluded with that of the Beauce aquifer.

3 Material and methods

3.1 Data

Seven satellite images from the Landsat 7 ETM+, presenting cloud cover under 10 %, were extracted from the period 1999-2010 (http://earthexplorer.usgs.gov/). (Table 1). 5 Five images were available in the warm season and 2 two in the cold season. They were taken at 12h30 (local hours)LT in summertime and 11h30 (local hours) LT in wintertime. Each image covered the entire course of the Loire River course between Gien and Blois.

Water temperatures of the Loire River are monitored by EDF upstream of the nuclear power plant of Dampierre (river kilometer 571) and Saint-Laurent des Eaux (river kilometer 670) on an hourly basis. In the cold season, tThe average observed daily water temperature observed, on the days when the images were taken, was 5.2°C in the cold season and. 23.7°C In in the warm season, it was 23.7°C.

River discharge/ flow ratesflows measured in Orléans, on the days the images were taken, were comprised between 61 $m^3.s^{-1}$m³/s and 478 $m^3.s^{-1}$m³/s. On 6 six out of the 7 seven dates for which the images were taken, the Loire River flow discharge/ flow rate was lower than the average mean annual flow.

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3.2 From the TIR satellite ~~TIR~~ images to the ~~the Loire River~~ longitudinal temperature ~~longitudinal~~ profiles of the Loire River

The first step was to locate pixels corresponding to ~~TIR image pixels corresponding solely to~~ water only ~~pixels~~. To ~~do so~~this end, ~~were first identified using~~ a threshold based on the TM 8 band of the Landsat images (0.52 to 0.9 µm; USGS, 2013) was used and~~. O~~ only ~~pixel~~ values below the threshold were kept. The aerial images in the visible range from ~~BD~~ the Ortho database, ~~from~~ of the "Institut National de l'information Géographique et forestière" (IGN), were used to set the threshold value for each image by comparing the TM 8 band to the Loire water course in ~~places where it was~~ known locations and where it did not alter~~ed~~ with time. The Carthage database from the IGN, which maps all the French watercourses ~~in the form of~~as lines, enabled ~~the further separation of~~ the water pixels belonging to the Loire River to be separated from ~~the pixels~~~~ones~~those belonging to other water bodies. As shade resulting from the clouds merges with the water pixel, it was removed manually using the same TM 8 band. The main advantage of using the TM8 band to detect water is that its ~~the~~ spatial resolution ~~of the TM8 band~~ (15 m) is much higher than ~~the spatial resolution~~that of the TM 61 band (60 m resolution, subsampled at 30 m; 10.4 to 12.5 µm) ~~that~~which is used to estimate water temperature.

~~In a~~A previous study (Handcock et al. 2006), ~~it was found~~demonstrated that river temperatures should be estimated using only pure water pixels (i.e. ~~that are water pixels situated more than a pixel away~~separated from the river banks by at least another water pixel). However, in the case of the middle Loire River, pure water pixels ~~it was not possible to find~~could not be found ~~pure water pixels~~ along the entire river course, especially at low flow rates. Therefore, all water pixels were kept~~. .~~, ~~but~~ Pixels~~,~~ composed of land and water~~,~~ were considered as land pixels.

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In order to detect the water pixels from the TM 61 infrared band, a neighborhood analysis was therefore conducted, based on the water and land pixels already identified from the TM 8 band. Only pixels from the TM 61 band situated further than 60 m away from the already identified land pixels (using the TM 8 band) were kept. To detect pure water pixels, a 120 m buffer zone was used.

~~Then~~The~~,~~ temperature was then calculated for these identified Loire pixels from the radiance values extracted from the TM61 band of the Landsat images ~~(10.4 to 12.5 µm)~~ using Planck's law (Chander et al., 2009). A value of 0.98 was used for ~~the~~ water emissivity. No atmospheric correction was taken into account, ~~considering the fact that~~since the study area was included in a single LANDSAT image and ~~that~~ atmospheric conditions were homogeneous within the study area (~~under~~with less than 10% of cloud cover). Finally, temperature values for~~of~~ these pixels were projected orthogonally on the longitudinal profile of the Loire ~~River~~ extracted from the Carthage database. The average temperature ~~was then~~for 200m long~~averaged by~~ sections ~~of 200 m in length~~was then calculated. ~~This~~ A distance of 200 m ~~value~~ was chosen to be ~~, so that it is~~similar ~~close from~~ to the width of the Loire River ~~width~~. After this, a~~A~~ moving average ~~over~~ for 10 consecutive temperature values along the water course (2 km) was ~~further conducted~~calculated to smooth the temperature profile.

The temperature profiles extracted from the TIR images were then exploited in two different ways: i) the accuracy and uncertainty of the temperatures estimated from the TIR images was tested ~~through a~~by comparing them~~– comparison~~ with the hourly *in situ* measurements conducted by EDF at Dampierre and Saint-Laurent des Eaux; ii) a heat budget method, based on the temperature estimated from the TIR images, was used along successive sections of the Loire River ~~in order~~ to quantify the groundwater discharge for each section. The r~~R~~esults were then compared with the ~~inter-annual~~ groundwater discharge ~~(period 1998-2007)~~ calculated ~~by~~ using a deterministic process~~-~~-based groundwater ~~budget method~~model applied over the whole Loire River basin. Calculated groundwater discharge~~s~~ estimations were compared over successive groundwater catchment areas along the Loire River~~corresponding to the respective River sections~~.

3.3 Groundwater discharge estimation - ~~heat~~ Heat budget based on TIR images

The middle Loire River was divided into 11 sections, so that ~~on~~ for each section there was only one groundwater catchment area on each side of the river. The groundwater catchment areas were delineated using available piezometric maps, or elevation data (surface water catchment area) when the ~~piezometric~~ maps were missing. A d~~D~~escription of the method can be found in Schomburgk et al. (2012). The first section begins at river kilometer 560 where the flow rate is ~~known~~ measured (Gien). The groundwater discharge was estimated on each section using a heat budget based on the temperatures derived from the TIR images.

The heat budget equilibrium can be written as (Moatar and Gailhard, 2006):

$$\rho.C.Q_{i-1}.T_{i-1}+F_{net}.S+\rho.C.Q_{gw}.T_{gw}=\rho.C.Q_i.T_i \qquad (1)$$

$$Q_{i-1}+Q_{gw}=Q_i \qquad (2)$$

The groundwater discharge in the section (Q_{gw}) can be deduced:

$$\frac{\rho.C.Q_{i-1}.(T_{i-1}-T_i)+F_{net}.S}{\rho.C.(T_i-T_{gw})}=Q_{gw} \qquad (3)$$

Q_{i-1} [$m^3.s^{-1}$] is the upstream flow rate of the section at ~~the~~ temperature T_{i-1} [°C], Q_i [$m^3.s^{-1}$] is the downstream flow rate of the section at ~~the~~ temperature T_i [°C]. Q_{gw} [$m^3.s^{-1}$] is the groundwater flow rate at ~~the~~ temperature T_{gw} [°C]. ~~At~~ For each section, the flow entering the section is equal to the flow entering the previous section plus the groundwater discharge estimated over the previous section (only taken into account if the estimated discharge ~~is~~ was positive). The groundwater temperature was considered to be 12.6°C in summer and 12.1°C in winter, based on 292 measurements from the ADES database (www.ades.eaufrance.fr)

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conducted in the vicinity of the Loire River, over the 1991-2011 period ~~()~~. Over 80% of the temperature measurements were ~~comprised~~included in the interval mean ~~mean plus~~ plus or minus ~~±~~1.4°C~~mean minu~~ ~~means.~~ F_{net} [W.m^{-2}] stands for the atmospheric heat flux~~es~~ and S [m^{2}] is the surface area covered by the Loire River on the section. S was estimated ~~by adding up~~ for each section by adding the ~~surfaces~~ surface areas of all the water pixels identified on the satellite images from the TM 61 band. ~~It is~~This value was therefore ~~probably~~ somewhat underestimated, as images pixels composed of both water and land ~~are not considered~~were not included~~, but tests on some Loire River sections showed that this underestimation did not exceed 20 %~~. ρ is the water density [kg.m^{-3}]~~,~~ and C [J.kg^{-1}.K^{-1}] is the ~~water~~ specific heat of water.

The heat flux~~es~~ ($F\ net$) between the Loire River and the atmosphere ~~were~~ was estimated as follows (Salencon and Thébault, 1997; Chapra, 1997; Table 2):

$$F\ net = RA + RS - RE - CV - CE \qquad (4)$$

Where RA is ~~the~~ atmospheric radiation~~s~~, RS ~~the~~ solar radiation~~s~~, RE ~~the~~ emitted radiation~~s~~, CV the conduction~~,~~ and CE the condensation/evaporation.

The atmospheric parameters extracted from the SAFRAN database from Météo France (Quintana-Segui et al., 2008) were averaged along the successive Loire River sections ~~considered~~~~in the study~~. ~~Every~~ All the atmospheric factors ~~was~~ were averaged over the 24 h period preceding the ~~taking~~ acquisition of the infrared image. This choice is questionable as the water temperature in the Loire River may be influenced by changes in atmospheric factors over a longer time period. However, ~~water~~ the travel time of water between Gien and Blois ~~is~~ was ~~about~~ between 1 to 1.5 days on the dates when the images were taken. Atmospheric parameters ~~should~~ were therefore not ~~be~~ integrated over a period exceeding a day.

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As the Loire River course is ~~large~~wide, no shading from the alluvial forest was taken into account.

3.4 Groundwater discharge estimation – ~~groundwater~~ Groundwater ~~budget~~modeling

~~Average groundwater discharge into the Loire River was calculated using groundwater budget per groundwater catchment areas over the 1998-2007 period. Effective rainfall was then calculated for each catchment area using Turc formulae. The useable ground reserves are available at the municipality scale and 1000 weather stations were considered in order to spatialize the atmospheric parameters. Effective rainfall was further separated between infiltration to the groundwater and surface runoff using the IDPR index (Mardhel et al., 2004; Putot and Bichot, 2007). Known groundwater withdrawals, obtained from the Water Agencies, were then removed from the calculated infiltrated water. In steady state condition, the average infiltration rate in the aquifers corresponds to the groundwater discharge into the Loire River.~~

The Eau-Dyssée model was used to determine the groundwater discharge along the Loire River. Eau-Dyssée is an integrated, distributed, process-based model that allows the simulation of the main components of the water cycle in a~~n~~ hydrosystem. Detailed descriptions of the model can be found in Flipo et al. (2012) and Saleh et al. (2011). This model has been applied to basins of different scales and hydrogeological settings, e.g., the Oise basin (4,000 km^2; Saleh et al., 2011), the Rhône basin (86,500 km^2; Habets et al., 1999; Etchevers et al., 2001), the Seine basin (65,000 km^2; Ledoux et al., 2007; Pryet et al., 2015) and the Loire basin (120,000 km^2; Monteil, 2011).

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Eau-Dyssée ~~conceptually~~ divides a~~n~~ hydrosystem conceptually into three interacting compartments: a surface, an unsaturated zone and a saturated zone. Specifically, the model couples different modules, which simulate the mass balance of surface water ~~mass balance~~, the runoff, the river flow rate~~/ discharge~~, the fluctuations of in-stream water levels~~ fluctuations~~, the flow rate in the unsaturated and saturated zones.

The water flux~~es~~ q_{sa} [m^3. s^{-1}] at the stream-aquifer interface ~~are~~is computed ~~with~~using a conductance model, i.e., ~~they are~~it is proportional to the difference between the piezometric [m], and the in-stream water level, h_r [m], i.e.:

$$q_{sa} = k_{riv}\left(h_g - h_r\right) \qquad (5)$$

Where the proportionality constant k_{riv} [m^2. s^{-1}] is the conductance of the stream-aquifer interface. Rushton (2007) showed that the main factor controlling this coefficient is the horizontal hydraulic conductivity k_H [m. s^{-1}] of the underlying aquifer.

$$k_{riv} = f k_H L \qquad (6)$$

Where f [-] is an adjustable correction factor, generally ranging between 0.9 and 1.2 (Rushton, 2007), and L [m] is the length of the river in the aquifer mesh.

Eau-Dyssée was applied to the Loire basin by Monteil (2011). In-stream water levels were assumed to be constant. This work has been improved by simulating the time variability of in-stream water levels with a Manning-Strickler approach (Chow, 1959). Under the assumptions that the river section is rectangular and that its width is much greater than its depth, h_r is given by:

$$h_r = b + \left(\frac{Q}{\alpha\, \kappa\, W\, S^{1/2}}\right)^{5/3} \qquad (7)$$

Where b [m] is the riverbed elevation, Q [m^3. s^{-1}] is the discharge, α = 1 m$^{1/3}$. s^{-1}, κ [-] is the Strickler's coefficient, W [m] is the river width, S [-] is the slope of the riverbed.

Details on the input data and model calibration can be found in Monteil (2011). The morphological parameters of the Loire River (river width and riverbed elevation and slope)

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were estimated from several cross sections surveyed with an average spacing of 1.6 km (Latapie et al., 2014). The Strickler's coefficient was calibrated against observed hydrographs at ~~6~~six stations along the Loire River, ~~3~~three of which are located on the Beauce aquifer.

The stream-aquifer exchanges were simulated in the period 1996-2013 at a daily time step for the river network at a 1 km resolution. Groundwater discharge was then calculated for the 11 Loire River sections selected for the heat budget.

3.5 Uncertainty estimation – Heat budget

Equation (3) was used to estimate the uncertainty associated with the calculated groundwater discharge. The absolute uncertainty of the calculated groundwater discharge ΔQ_{gw} can be computed as:

$$\Delta Q_{gw} = \left|\frac{\rho.C.(T_{i-1}-T_i)}{\rho.C.(T_i-T_{gw})}\right|.\Delta Q_{i-1} + \left|\frac{\rho.C.Q_{i-1}}{\rho.C.(T_i-T_{gw})}\right|.\Delta(T_{i-1}-T_i) + \left|\frac{F_{net}}{\rho.C.(T_i-T_{gw})}\right|.\Delta S +$$

$$\left|\frac{(\rho.C.Q_{i-1}.(T_{i-1}-T_i)+F_{net}.S)}{\rho.C.(T_i-T_{gw})^2}\right|.\Delta(T_i-T_{gw}) \qquad (8)$$

ΔQ_{i-1} is the absolute uncertainty in the river flow rate. A 10% uncertainty in the flow estimation is considered: $\Delta Q_{i-1} = 0.1.Q_{i-1}$ (9)

$\Delta(T_{i-1}-T_i)$ is the absolute uncertainty in the river temperature variations over the corresponding river section. It is computed, based on the known spatial variation between Dampierre and Saint-Laurent des Eaux of the ~~shift~~difference ~~disparity~~between the temperature estimated from the TIR images and th~~ate temperature~~ estimated from in-situ measurements. At each date, a ~~shift~~difference~~sparity~~ by river kilometer~~s~~ and ~~finally~~then by river section~~s~~ ~~i~~was calculated. The value of this ~~shift is~~difference~~disparity~~ was added to T_i to estimate the variation in surface water temperature that could be caused by uncertainties in the measurements: $(T_{i_{new}} - T_i)$.

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$$\Delta(T_{i-1} - T_i) = \left|(T_{i-1} - T_{i_{new}}) - (T_{i-1} - T_i)\right| \qquad (10)$$

ΔS is the absolute uncertainty in the water surface estimate. It ~~is~~was computed based on the difference between the water surface estimated from the TM 61 band and from the TM 8 band of the Landsat satellite. ΔS ~~i~~was calculated at each date for every study section of the Loire ~~River sections~~ (11 sections).

$\Delta(T_i - T_{gw})$ is the absolute uncertainty of the difference between the river temperature and the groundwater temperature. It ~~is~~ was considered to be equal to 2°C in order to take into account both groundwater temperature variability and surface water temperature accuracy.

4 Results

4.1 Temperature accuracy and temperature uncertainty

Temperature accuracy is the average difference between the temperature estimated from the TIR images and the temperature measured in-situ (Handcock et al., 2012). The comparison between the *in situ* and TIR derived temperatures shows that, on average, the TIR images tend to overestimate the Loire River water temperature in winter (+ 0.3°C) and to underestimate it in summer (- 1°C).

Over 75% of the TIR derived temperatures ~~are~~ were ~~comprised~~ between ± 1°C of the temperature measured directly in~~to~~ the river (11 times out of 14: Figure 2). ~~But~~ However, the temperature difference ~~exceeds~~ exceeded 1.5°C on 29/05/2003 and on 29/07/2002 at the Dampierre station and on 29/07/2002 at Saint-Laurent des Eaux.

Temperature uncertainty can be ~~associated~~linked to the repeatability of the measurement (Handcock et al., 2012). The study of the longitudinal ~~evolution~~changes of the difference between TIR image~~s~~ based temperature and in-situ measurements may give ~~some~~an idea~~s~~

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~~about~~of the degree of –uncertainty (Figure 2). On average, the variation in temperature difference ~~variation~~ remain~~s~~ed below 0.8°C over the 100 km reach from Dampierre– to Saint-Laurent-des-Eaux, except on the 29/07/~~th of July~~ 2002 (1.3°C) and on the 29/05/~~th of May~~ 2003 (2.3°C). The variation of the temperature difference ~~is~~was ~~comprised~~ between 0.0004°C.km^{-1} and 0.02°C.km^{-1} (mean of 0.007°C.km^{-1}).

Tests were carried out ~~To~~ to assess the influence of the nature of the water pixels (pure or non-pure) on the estimated temperature~~, tests were carried out~~. For the 200-m long sections of the Loire River ~~In the case~~ where~~, for a 200 m long section of the Loire River,~~ pure water pixels exist, temperature was estimated for both pure ~~water pixels~~ and non-pure water pixels. ~~The~~ A linear regression was conducted for ~~between~~ the temperature estimated with pure water pixels and ~~temperature~~ that estimated with non-pure water pixels~~ was drawn~~. ~~and the standard deviation of the residuals of the regression line was calculated. The standard deviation is found to be comprised between 0.18°C and 0.21°C and the slope of the regression line is comprised between 0.98 and 1.01.~~Taking into account the data from all the dates, the slope of the regression line is 1, while it is 0.98 when summer alone is consider~~ing~~ed ~~summer only~~ and 0.72 ~~considering~~for winter ~~only~~alone (Figure 3a; Figure 3b). The difference between the temperatures estimated from pure and non-pure water pixels ~~usually~~generally remain~~s~~ed in the +-0.5°C interval (over 98% of the time), which corresponds to the approximate resolution of the satellite sensors. Therefore, taking into account non-pure water pixels does not seem to ~~induce an important~~cause a large bias in the case of the Loire River.

However, when the number of water pixels in a 200-m section of the Loire River decreases ~~(small~~due to the river being narrower~~ river width),~~ the standard deviation of the observed temperature increases notably (

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Table 3). Peak temperature values along the longitudinal temperature/thermal profile may appear in places where the main river branch is particularly narrow. This phenomenon is mostly due to the uncertainties inherent to in the satellite sensor. Uncertainty is can be reduced by averaging and as the number of. The more pixels are considered over a section increases, the lower the uncertainty decreases is. The moving average over 1 2 km thatwhich was applied to the data iswas therefore useful in loweringreducing the uncertainty.

4.34.2 Longitudinal temperature profiles

Among the 7 seven longitudinal temperature profiles, 3 three main profile types can be observed: 2 two in summertime and one in wintertime.

In summertime, a mean decrease of in the temperature between 0.8°C and 1.5°C can be observed on all the profiles between the river kilometers 620 and 650. A local temperature minimum is observed on every profile at river kilometer 645, close to the town La Chapelle-Saint-Mesmin. The river temperature increases increased again from river kilometer 660 to 680 and then remains remained constant or decreases decreased once more after river kilometer 680.

However, the temperature profiles differ between river kilometers 560 and 620, since the water temperature can either increased (29/05/2003 and 19/07/2010; Figure 3Figure 4b) or decreased (24/08/2000, 29/07/2002 and 20/08/2010; Figure 3

Figure 3b). Another difference appears between river kilometers 650 and 660, with either a temperature drop (29/05/2003 and 19/07/2010) or a temperature rise (29/07/2002). Then, from river kilometers 680 to 700 the temperature dropped can appear downstream ofafter river

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kilometer 690 (29/05/2003, 19/07/2010 and 20/08/2010), or upstream of~~before~~ river kilometer 690 (24/08/2000 and 29/07/2002) and ~~be~~ then was followed by a rise in the temperature.

In winter~~time~~ the temperature ~~tends~~ tended to increase sharply by around 0.5°C between river kilometers 630 and 650 ~~by around 0.5°C~~ (Figure 4a).

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Sharp temperature changes in the longitudinal profile need to be compared with the uncertainty and not with the accuracy. The sharpest temperature changes observed on the longitudinal profiles ~~are~~were ~~comprised~~ between 0.04°C.km^{-1} and 0.1°C.km^{-1} (mean of 0.074°C.km^{-1}). The ~~sharpest~~most marked temperature changes are therefore at least one order of magnitude higher than th~~e~~ose ~~changes that are to be~~ expected from the uncertainty (0.0072°C.km^{-1}). They are therefore likely to be meaningful in terms of physical processes.

~~4.4~~4.3 Groundwater discharge estimation - Heat ~~and groundwater~~ budget and groundwater modeling

The groundwater discharge ~~is~~ was estimated at ~~7~~ seven dates (winter and summer) along the same successive 11 sections of the Loire ~~River sections~~, using ~~respectively the~~ both heat budget and groundwater modeling~~two methods~~ (Figure 5a). ~~We found that~~T~~t~~he variability of the with the heat budget ~~is~~was much higher than that ~~the variability of the groundwater discharge~~ estimated using groundwater modeling (with ~~respective~~ maximum standards deviations of 0.6 m^3.s^{-1}.km^{-1} and 0.11 m^3.s^{-1}.km^{-1} respectively). Nevertheless, the modeled groundwater discharge ~~always stay~~was always with~~-~~in the interval estimated by the heat budget. Overall, compared to ~~the~~ groundwater modeling, the heat budget tend~~s~~ed to overestimate the groundwater discharge between river kilometers 640 and 660 in winter and to underestimate ~~the discharge~~it between river kilometers 660 and 680 in summer (Figure 5b; Figure 6a; Figure 6b).

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High groundwater discharge rates (0.3155 m^3.s^{-1}.km^{-1}) on average) are were calculated with the groundwater heat budget method between river kilometers 563 and 565 and they also showed a noticeable increase in the standard deviation (0.6 m^3.s^{-1}.km^{-1}). It corresponds to a section where the groundwater discharge, estimated using the river heat budget, shows a noticeable increase in the standard deviation (0.6 m^3.s^{-1}.km^{-1}). However, these high discharge rates and high standard deviation iweres not observed using the groundwater modeling.

Between river kilometers 570 and 630, the average estimated groundwater discharge using both methods is low (respectively less than 0.3 m^3.s^{-1}.km^{-1}) and less than 0.1 m^3.s^{-1}.km^{-1} respectively) and the standard deviation it shows awas also low standard deviation (respectively less than 0.4 m^3.s^{-1}.km^{-1}) and less than 0.05 m^3.s^{-1}.km^{-1} respectively)..

Further downstream, according to both methods, the groundwater discharge shows showed a marked peak in the section located between river kilometers 630 and 660. At river kilometer 640, the groundwater discharge estimated with the heat budget is was positive at each date (comprised between 0.3 and 1.5 m^3.s^{-1}.km^{-1}) and it also corresponds corresponded to the location where the groundwater discharge is was maximum maximal according to the groundwater budget methodmodeling (between 0.65 and 0.9 m^3.s^{-1}.km^{-1}). Both methods showed a highThe standard deviation of the groundwater discharge is high according to both methods (respectively 0.4 and 0.1 m^3.s^{-1}.km^{-1} respectively).

From river kilometers 640 to 690, the standard deviation of the estimated discharge is comprised between 0.4 and 0.5 m^3.s^{-1}.km^{-1}, which is higher than between river kilometers 560 and 630. For river kilometers 660 to 680 Tthe results of the two methods givewere different, results from river kilometers 660 to 680 with a negative discharge estimated by the heat budget

(-0.24 $m^3.s^{-1}.km^{-1}$ on average) and a positive discharge calculated by groundwater modeling (0.12 $m^3.s^{-1}.km^{-1}$ on average).

Negative flow values ~~are~~ were estimated ~~by~~ using the heat budget method. Theoretically, the estimated groundwater discharge should not be negative. However, in summer~~time~~, negative discharge values are ~~especially~~ computed when water temperature increases but when this increase cannot be explained by ~~the~~ atmospheric heat flux~~es~~. In winter~~time~~, negative discharge values can also be obtained when water temperature shows a decrease that cannot be explained by ~~the~~ atmospheric heat flux~~es~~.

The absolute uncertainty in the groundwater discharge estimated by the heat budget remained~~s~~ ~~under~~below 0.4 $m^3.s^{-1}.km^{-1}$ ~~over~~for more than 75% of the time. Taking into account the uncertainty, ~~we found that~~ in the Loire River section between river kilometers 636 and 645 at all the dates the estimated groundwater discharge was always above 0.03 $m^3.s^{-1}.km^{-1}$ ~~in the Loire River section comprised between river kilometers 636 and 645 the estimated groundwater discharge remains at all dates over 0.03 $m^3.s^{-1}.km^{-1}$~~ and ~~is~~was therefore significant. On this river section, the groundwater discharge estimated with the heat budget ~~is comprised~~was between 2.8 $m^3.s^{-1}$ and 13.7 $m^3.s^{-1}$, while ~~the groundwater discharge~~that estimated ~~through~~using groundwater modeling varie~~s~~d between 5.2 $m^3.s^{-1}$ and 8.6 $m^3.s^{-1}$.

5 Discussion

5.1 Temperature accuracy and ~~temperature~~ uncertainty

There are many factors that can contribute to the accuracy or ~~to~~ the ~~uncertainty~~ uncertainty of the temperature estimation using ~~the~~ TIR satellite ~~TIR~~ images. ~~Main sources of uncertainty~~

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~~come from~~The main factors are the satellite sensors, the atmospheric influence on the transmitted radiation~~s~~ (Kay et al., 2005; Chander et al., 2009; Lamaro et al., 2013), the change in water emissivity with time and along the water course, the existing correlation between radiation~~s~~ estimated at neighboring pixels (Handcock et al., 2006) and the thermal stratification of water temperature (Robinson et al., 1984; Cardenas et al., 2008). The TIR images only measure the temperature ~~from~~of~~of~~ the upper 100 µm of the water body (skin layer), which may differ from the temperature ~~from~~of~~of~~ the entire water body (Torgersen et al., 2001).

The average difference between the temperature estimated from the TIR satellite ~~TIR~~ images and the temperature~~one~~ observed *in situ* ~~is~~ was – 0.51°C. On average, it is found that temperature estimated using TIR images tends to underestimate real water temperature.

However, t~~T~~he opposite ~~phenomenon~~ has also ~~regularly~~ been regularly observed.~~-using TIR satellite images.with this method;~~ Wawrzyniak et al. (2012) found that TIR images overestimated the Rhône River temperature by + 0.5°C on average. Another study was conducted over several water courses of the Pacific Northwest rivers of the United-States (Handcok et al., 2006). A mean temperature difference of + 1.2°C ~~mean temperature difference~~ was found, when the water course width was over three image pixels and ~~a~~ of + 2.2°C ~~mean temperature difference~~ when the width was ~~comprised~~ between 1 and 3 pixels. ~~A m~~Mean temperature differences of ~~comprised~~ between +1 °C and + 1.9°C ~~was~~ were~~also~~ found in ~~another~~ four other Pacific Northwest rivers ~~of the United States~~ (Cherkauer et al., 2005).

N~~However, n~~egative biases were also found (Barsi et al., 2003). In the case of Lake Tahoe, the temperature estimated with TIR images was on average 1.5°C to 2.5°C colder ~~by 1.5°C to 2.5°C~~ than the temperature observed *in situ*. Similar results were observed on the Wenatchee River ~~of~~ in the United States (Cristea and Burges, 2009).

Satellite based TIR images can therefore lead to either ~~underestimation~~ under- or over-estimation of the water temperature. Depending on the time of the year, ~~the~~ this ~~disparity/~~difference ~~shift~~ can ~~happen~~ be either positive or negative~~in both directions~~ (Lamaro et al., 2013, De Boer, 2014).

Findings from this study confirm that water temperature can be either over- or under-estimated using TIR images ~~the TIR images can lead to either overestimation or underestimation of the water temperature~~ (Figure 2). The biggest disparity ~~shift~~ was~~is~~ observed on the 29/07/2002, when the water temperature ~~is~~ was maximum (> 26°C) and the flow rate minimum (60 $m^3.s^{-1}$~~m^3/s~~ – 1.33 $l.s^{-1}.km^{-2}$). One possible explanation of this ~~shift~~ would be that high ~~water~~ evaporation at this date lead~~s~~ to a low temperature of ~~water skin~~ surface~~temperature~~ water.

The average temperature difference between TIR images and *in situ* measurements ~~is~~ was similar to ~~what had been~~that observed in ~~the~~ previous studies (Handcock et al., 2006; Wawrzyniak et al., 2012), even though in this study non-pure water pixels ~~are kept~~were included and no atmospheric correction ~~is~~ was applied. Temperature estimation using non-pure water pixels from TIR images may therefore be more robust than ~~is~~ previously considered~~usually thought~~. However, this study also shows that differences between temperatures estimated using TIR images and temperatures observed *in situ* may locally exceed 2°C.

The temperature estimated for non-pure water pixels could be influenced by the temperature ~~from~~of the riverbanks.~~–~~ However, tests ~~that were~~ carried out show that the difference in temperatures estimated using TIR images or measured *in situ* cannot be explained only by the bias resulting from the use of the non-pure water pixels. Uncertainty resulting from the satellite sensors low resolution can also play~~s~~ a role, particularly ~~especially~~ in narrow parts ~~where~~ of the Loire ~~River which are~~~~is particularly narrow~~.

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5.2 Longitudinal temperature profiles and groundwater discharge estimations

TIR images of water courses have been used in the past to detect groundwater discharge areas and to differentiate them from hyporheic upwelling areas (Burckholder et al., 2007). The surface of the cold water plumes associated with groundwater upwelling has been shown to be correlated with the groundwater discharge rate (Danielescu et al., 2009). However, quantifying groundwater discharge using a river heat budget based on TIR images has only been done once, on a small stream (along a 1.7 km reach, with a flow of 10 l./s^{-1}) and using high precision aerial images (Loheide and Gorelick, 2006).

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This work is new in thatbecause firstly, groundwater discharge is was estimated on a large river, based onthrough satellite TIR satellite images and secondly the results were compared. The comparison with the groundwater discharge estimationions obtaineded using a groundwater budgetgroundwater modeling. over the successive catchment areas is also new, as Loheide and Gorelick (2006), on the other hand, compared their findings with groundwater discharge estimated through measurements of the stream flow over successive stream cross sections. This last technique is difficult to use for large rivers and limited sections lengths', due to the important high uncertainty in flow rate measurements (up to 20 %).

There are several sources of uncertainty in the groundwater discharge estimation using the heat budget. First, there is the an uncertainty coming fromin the estimation of water temperature water temperature estimation. As a result, important uncertainties are attached to the estimated groundwater discharge when the length of the river section considered is small, at the river surface and of the river flow rate. In general in the present study,We found that the resulting uncertainty in groundwater discharge estimate remaineds mainly below 0.4 m^3.s^{-1}.km^{-1}, which is quite high in case of low groundwater discharge. Then, there There are also uncertainties inherent to in the heat budget method used as f. Factors such as bed friction, heat conduction

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through the river bed, or hyporheic exchange are not consideredare not included. However, for that kind of the type of slow flowing river studied, the influence of bed friction is assumed to be low, especially particularly in summer (Evans et al., 1998). Similarly, heat conduction through the bed usually plays a minor role in the global overall river heat budget (Hannah et al., 2008). The effect of heat conduction and hyporheic flows can be confused with the groundwater discharge, which probably leads to a small overestimation of the groundwater discharge. The water travel time for water to travel along the river is not taken into account in the heat budget either. As a result the river temperature tends to be slightly overestimated due to, the influence of the local atmospheric conditions over the river temperature tends to be slightly overestimated. There are also uUncertainties are also attachedlinked –to using groundwater modeling to calculate the groundwater discharge calculated usingwith the groundwater budgetmodeling. Nevertheless, tThe modeling of the Loire River flow in Blois, Orléeans and Gien over the 1996-2013 period works well neverthelessprovided good results (Nash criteria of 0.98, correlation of 0.99 and relative bias of 0.01 $m^3.s^{-1}$). Then, the groundwater discharge estimate given by the groundwater budget method is an average value over a 10 year period. In contrast, only 7 TIR images are taken into account in this study and the average discharge estimated using these images is therefore related to the sampling date. It may suffice to explain the difference between the average estimated groundwater flow using the heat budget and the flow calculated by the groundwater budget method. DDespite all the uncertainties, the groundwater discharge estimated using the heat budget stays remained within the same order of magnitude asof the dischargethat calculated with the groundwater budgetusing groundwater modeling. At maximum, the groundwater discharge rate, estimated with the heat budget, overestimates, or underestimates, by less than It was always below ± 1 $m^3.s^{-1}.km^{-1}$ of the discharge calculated by using the groundwater budgetmodeling. The average groundwater discharge calculated by using the groundwater budgetgroundwater modeling for

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the inter-annual period is was always within the range of variation of the groundwater discharge estimated using the river heat budget. The shapes of the average estimated average groundwater discharge curve provided by the two methods along the Loire River is alsoare also relatively close similar to the one calculated by the groundwater budgetbetween the two methods (coefficient of determination $r^2 = 0.782$).

On the upstream part of the Loire River, i.e. from river kilometer 560 to 635, the groundwater discharge estimated from the heat budget appears to bewas small low (less than 0.3 $m^3.s^{-1}.km^{-1}$; Figure 5a), except for some dates around river kilometer 564. It is known thatThis is possibly explained by the fact that between river kilometers 610 and 625 the Loire River losesloses water through the Val d'Orléans karstic system between river kilometers 610 and 625 (Alberic, 2004; Binet et al., 2011). This is also consistentin line with the results from the groundwater modeling. It should be noted that tThe high standard deviation of the estimated discharge near river kilometer 564 may could be explained not only by both real variations of in the discharge rate, as highlighted by the groundwater budget, but and also by the bias resulting from the small length of the corresponding section. Similarly, high groundwater discharge around river kilometer 564 (0.6 $m^3.s^{-1}.km^{-1}$) was also found by the BRGM, using a groundwater budget over the successive groundwater catchment areas to calculate- the average interannual groundwater discharge over the period 1998-2007 (Schomburgk et al., 2012).A calculation of the average interannual groundwater discharge along the Loire River, over the period 1998-2007, was also carried out by the BRGM, using a groundwater budget over the successive groundwater catchment areas (Schomburgk et al., 2012). They found similarly high groundwater discharge around river kilometer 564 (0.6 $m^3.s^{-1}.km^{-1}$)

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A first thermal anomaly appears downstream of river kilometer 620. From river kilometer 6365 to river kilometer 645 the groundwater discharge estimated with the heat budget is

~~comprised~~was between 0.3 and 1.5 m^3.s^{-1}.km^{-1}. ~~We found that, t~~Taking into account the uncertainties, the groundwater discharge calculated ~~by~~through the heat budget always ~~stay~~remained positive between river kilometers 636 and 645. This river section corresponds to a known discharge area of the Beauce aquifer and the Val d'Orléans hydrosystem (Desprez and Martin, 1976; Gonzalez, 1991; Binet et al., 2011) ~~that~~ which is also identified by ~~the~~ groundwater ~~budget~~modeling (calculated discharge ~~comprised~~was between 0.6 and 0.9 m^3.s^{-1}.km^{-1}). Schomburgk et al. (2012) calculated a slightly lower~~,~~ but still significant~~,~~ groundwater discharge of 0.5 m^3.s^{-1}.km^{-1}. It is interesting to note that~~,~~ along the Loire River, the maximum estimated exchange rates ~~estimated~~ occurred at times whe~~re~~n the river flow ~~decreases~~ decreased over~~between~~ two consecutive days, while the lowest exchange rate ~~is~~ was estimated when the ~~river~~ flow ~~increases~~ increased (~~Figure 6~~Figure 7). The m~~M~~aximum groundwater discharge ~~is~~ was also estimated in winter (13.5 m^3.~~/~~s^{-1} compared to 5.3 m^3.~~/~~s^{-1} in summer), when the groundwater level was ~~is~~ at its highest. ~~It is consistent~~This is in line with the results from the groundwater modeling ~~showing~~which show an average discharge of 7.6 m^3.s^{-1} in winter~~time~~ and 6 m^3.s^{-1} in summer~~time~~. It is known that temporal changes in river water levels can lead to ~~important~~ large modifications in exchange rates and ~~exchange~~ directions (Sophocleous, 2002). During a rise in ~~river~~ the water level, water ~~from the river~~ can flow into the lateral aquifer while the opposite ~~phenomenon happens~~is true ~~at~~ during low ~~river~~ flow rates. Thus, the variation in estimated exchange rates is likely to have a physical basis. An exchange rate of 11.5 to 12.5 m^3.s^{-1}~~m^3/s~~ was calculated at la Chapelle Saint-Mesmin (river kilometer 642), using geo-chemical tracers during the summer of 1986 (Gonzalez, 1991). ~~It is~~This was higher than the maximum groundwater discharge estimated in the summer using the heat budget (7.5 m^3.~~/~~s^{-1}). Therefore, the high discharge rates estimated using the heat budget are plausible. The ~~satellite~~ TIR satellite images ~~allow to locate~~enable the main groundwater discharge area to be located

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precisely, along the right bank of the Loire River and 2 the two to 3 three kilometers upstream from of the confluence with the Loiret (Figure 7Figure 8).

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On the downstream part of the Loire River, between river kilometers 650 and 680, both heat budget and groundwater modeling estimations showed a decrease in groundwater discharge decreases according to both estimations (heat budget and groundwater budgetmodeling). Over the last 20 km downstream the heat budget would suggest a slight increase in the groundwater discharge, in line–. This is consistent with the findings from Schomburgk et al. (2012). HoweverOn the other hand, the groundwater modeling predicts a slight decrease in the groundwater discharge.Then, downstream of river kilometer 680, groundwater discharge estimated with the groundwater budget increases again. However, even though an increase in the median discharge estimated with the heat budget is observed, its value stays negative

The change in the groundwater discharge rate with over time could explain why the river temperature may either increasedrise or decreaseddrop between river kilometers 645 and 665, or between river kilometers 570 and 620. However, atmospheric factors are also likely to play a role, even though the atmospheric data available do not offer a satisfactory explanation for this phenomenon. The influence of warm water discharges discharged from the nuclear power plant on the longitudinal temperature profile is was not noticeable either, as no sudden temperature rise is was observed at the locations of the nuclear plants locations. In the case of Saint-Laurent des Eaux, discharged warm water discharges may nevertheless contribute for to a certain extent–some part to the global overall temperature rise observed between river kilometers 670 and 680 (Figure 3Figure 4a; Figure 4b), but however, the temperature rise begins of the power plant.

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Similarly, no sudden temperature variations could be explained by weirs across the river course and or changes in the river slope (less than 0.1°C change between the 1 kma kilometer up- or downstream of the structure~~ upstream and the 1 km downstream~~), although abrupt temperature changes near weirs have been observed on the Ain River in France (Wawrzyniak, 2012), based on airborne TIR images. This could be explained by the small reservoir capacity of the Loire River upstream of the weirs (Casado et al., 2013), and also due to~~probably by~~ the low spatial resolution of the TIR satellite ~~TIR~~ images. The Landsat images were ~~also~~ taken around 12~~h~~:30 LT and thermal stratification ~~may~~could be expected to be ~~more important~~greater later ~~during~~in the day.

6 Conclusion

Temperatures of the middle Loire River were estimated using Thermal InfraRed (TIR) Landsat images. Although no atmospheric correction was implemented and non-pure water pixels were taken into account~~With no atmospheric correction considered and taking into account non-pure water pixels~~, temperature differences~~, between~~ from *in situ* observations and TIR~~-~~images based estimations~~,~~ remain~~s~~ within the interval defined in previous studies (i.e. 75% of these differences being in the ±~~-~~1°C interval). Therefore, this study shows that river temperature may be studied from ~~satellite~~ TIR satellite images even when the river width falls below the three-pixel~~s'~~ width threshold (i.e. < 180 m). However, the river temperature can be seriously underestimated at low flow rates and ~~when~~ high water temperatures ~~is high~~ (differences of over 2°C).

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We demonstrate that groundwater discharge to a large river can be estimated using satellite images. The groundwater discharge was estimated along the Loire River using both ~~a~~ the heat budget based on the longitudinal temperature profiles established from the TIR images, and a groundwater ~~budget on the successive groundwater catchment areas~~model. The variations~~evolution~~ of the groundwater discharge rate along the Loire River are~~is found to~~

~~be~~were ~~-~~similar ~~according to~~with both methods. The main discharge area of the Beauce aquifer into the Loire River is located between river kilometers 636~~5~~-645 (close to la Chapelle Saint-Mesmin).

According to the TIR images, the average groundwater discharge between river kilometers 636 and 645 appears to be higher in winter~~time~~ ~~(13.5 m^3./s^{-1})~~ than in summer~~time~~ (13.5 $m^3.s$-1 and 5.3 $m^3.s^{-1}$ respectively~~5.3 $m^3.s^{-1}$~~~~m^3/s~~). ~~It is consistent~~This is in line with the results from the groundwater modeling~~-~~ which show~~ing~~ an average discharge of 7.6 $m^3.s^{-1}$ in winter~~time~~ and 6 $m^3.s^{-1}$ in summer~~time~~. ~~It~~ The groundwater discharge ~~is~~ was also ~~found to be~~ higher when the ~~Loire River~~river flow ~~decreases~~ decreased ~~between~~ over two~~2~~ consecutive days. Our TIR images ~~underline~~ highlight that instantaneous groundwater discharge can vary considerably ~~s are highly variable with~~ over time. Therefore, average discharge is not sufficient to predict the observed changes in water temperature along the river course.

To assess the consistency and robustness of these results, further studies could be conducted using more sophisticated modell~~l~~ing of both the groundwater discharge and ~~the~~ stream temperature.

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Table 1. Loire River temperature, air temperature and river flow rate at the date and hour time when satellite images where taken.

Date	Daily river flow in Orléans (m^{3}./s^{-1})	Hourly mean water temperature in Dampierre (°C)	Hourly mean water temperature in Saint-Laurent des Eaux (°C)	Hourly air temperature in Orléans (°C)
Winter				
15/11/2001	182	5.2	5.875	5.65
22/02/2003	478	4.215	5.55	12.765
Summer				
29/05/2003	898.6	22.85	20.105	25.55
19/07/2010	112	23.4	23.1	28.325
20/08/2010	787.9	21.8	20.95	28.329
24/08/2000	83.3	24.0	22.55	30.45
29/07/2002	61.1	28.3	26.0	32.5

Code de champ modifié

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Table 2. Details of the atmospheric heat flux~~es~~ calculations.

Solar radiation~~s~~	RS estimated from the SAFRAN database	
Atmospheric radiation~~s~~	$RA = \sigma.(T_a + 273.15)^4.(A + 0.031.\sqrt{e_a}).(1 - R_L)$	T_a (°C) is the air temperature estimated from the SAFRAN database from Météo France $\sigma = 4.9 * 10^{-3}\ J.m^{-2}.d^{-1}.K^{-4}$ is the Stefan-Boltzman constant $A = 0.6$ $R_L = 0.03$ — are attenuation and reflection coefficients $e_a = 1.22 * Q_a$ is the air vapour pressure Qa in $g.kg^{-1}$ is the ~~air~~ specific humidity of air estimated from the SAFRAN database
Emitted radiation~~s~~	$RE = \varepsilon.\sigma.(T_w + 273.15)^4$	$\varepsilon = 0.98$ is the water emissivity T_w (°C) is the mean water temperature on the section estimated from the longitudinal ~~thermal~~temperature ~~longitudinal~~ profiles
Conduction	$CV = \rho_a.C_a.e(V).(T_w - T_a)$	$\rho_a = 1.293.(\frac{273.15}{T})$ air density in $kg.m^{-3}$ is the function of air temperature T (K) estimated from the SAFRAN database $C_a = 1002\ J.kg^{-1}.C^{\circ -1}$ is the ~~air~~ specific heat of air $e(V) = 0.0025 * (1 + V_2)$ is the function of the wind 2 m above the ground V_2 $(m^3.s^{-1})$ $V_2 = V_{10}.(\frac{2}{10})^{0.11}$ is used to estimate the wind 2 m above the ground as a function of the wind 10 m above the ground, itself estimated from the SAFRAN database
Condensation / Evaporation	$CE = L(T_w).\rho_a.e(V).(Qw - Qa)$	$L(T_w) = (2500.9 - 2.365.T_w).10^3 J.kg^{-1}$ i~~I~~s the latent evaporation heat

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		$$Qw = \frac{4.596.e^{\frac{237.3*T_w}{237.3+T_w}}}{1.22}$$ Qw in $g.kg^{-1}$ is the specific humidity of ~~the~~ saturated air at the -water temperature

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Table 3. Standard deviation of water temperature (°C) estimated on all the 200-m sections of the Loire River.~~,~~ Standard deviations were~~ is~~ calculated at sections with~~ either~~ under 20 water pixels ~~in the section ~~and~~or~~ over 20 water pixels.~~??~~

Date	24/08/2000	15/11/2001	29/07/2002	22/02/2003	29/05/2003	19/07/2010	20/08/2010
σ (n<20)	0.70	0.56	0.76	0.32	0.45	0.42	0.52
σ (n>20)	0.50	0.44	0.73	0.26	0.41	0.41	0.42

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Figure 1. Map of the study area. The delineation of the Beauce aquifer comes from the BDLISA database from the Bureau de Recherches Géologiques et Minières (BRGM).

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Figure 2. –Differences between TIR derived temperatures extracted from the longitudinal temperature profile and *in situ* measurements (at the same date and ~~hour~~time) ~~at~~ for each date. The dates are classified according to the air temperature at the time when the images ~~are~~ were taken (air temperature ~~rises~~ rose from ~~the~~ 15/11/2001 to ~~the~~ 29/07/2002).

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Figure 3.~~ Loire temperature profiles in summertime. For each profile data were centered, so that the average temperature appears to be 0°C~~ A: ~~.~~Relationship between the temperatures extracted from the non-pure water pixels and ~~the temperatures extracted~~those from the pure water pixels. Temperature values of both pixel types ~~are~~were averaged over the successive 200-m sections where pure water pixels existed. Summer temperatures are represented. B: Relationship between the temperatures extracted from the non-pure water pixels and ~~the temperatures extracted~~ from the pure water pixels. The t~~T~~emperatures~~ values~~ of both pixel types ~~are~~were averaged over the successive 200–m sections where pure water pixels existed. Winter temperatures are represented.

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Figure 4. A: Loire temperature profiles in winter~~time~~ extracted from the TIR images.~~ For each profile data were centered, so that the average temperature appears to be 0°C.~~ B: Loire temperature profiles in summer~~time~~ extracted from the TIR images. For each profile data were centered.

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Figure 5. A: Groundwater discharge per section~~s~~ of the Loire River estimated at the different dates using the heat budget based on the TIR images (black points), and calculated by ~~the~~ groundwater ~~budget method~~modeling (~~grey triangles~~grey line), as a function of the river kilometers. B: Absolute value of the difference between groundwater discharges estimated by groundwater modeling and ~~with~~ the heat budget.

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Figure 6. A: Calculated groundwater discharge along the Loire River in 20/08/2010 using groundwater modeling and the heat budget. B: Calculated groundwater discharge along the Loire River in 15/11/2001 using groundwater modeling and the heat budget.

Figure ~~6~~7. Groundwater discharge rate as a function of the variation in river flow in the 48 h ~~preceding the taking of~~ before the TIR image was taken.

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Figure ~~7~~8. Temperatures measured in the Loire River in the vicinity of La Chapelle Saint-Mesmin on the 29/07/2002. Groundwater discharge is visible along the right bank (north side) of the Loire River as a cold patch between river kilometers 642 and 644.

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Answer to Reviewers

The line numbers mentioned correspond to the line numbers of the revised manuscript (not of the marked-up manuscript).

Response to reviewer 1 :

1. "Quantification of the Beauce's Groundwater Contribution to the Loire River Discharge Using Satellite Infrared Imagery" uses Landsat TIR images to determine groundwater contributions to the Loire River using a simple energy budget approach and compares this to a groundwater budget approach. A method for determining groundwater contributions to rivers over space and time is presented, however there were many different assumptions and acknowledged errors in data utilized, calculations completed, or comparisons made that undermine the potential impact of the study. "

Despite the uncertainties, this study shows that extracted temperature profiles nevertheless remain in agreement with known areas of groundwater discharge along the Loire River.

A quantification of the uncertainty associated to the heat budget method has been added to the revised version of the manuscript (part 3.5 – revised manuscript). We show that uncertainties are not very likely to undermine the major findings of this study.

We also choose to present in the revised version of the manuscript a deterministic process-based hydrogeological model of the Loire River basin (part 3.4 – revised manuscript). This model allows the quantification of the daily groundwater discharge along the Loire River. It is therefore better suited to the comparison with the heat budget than the groundwater budget previously used. We find that both methods (groundwater budget and hydrogeological model) give similar results and that they are in agreement with the heat budget.

2. Number of pixels spanning the channel that were included within the analysis. In general, there were 3 pixels spanning the channel, but at times these were mixed pixels (water and land). The mixed pixels were still included within the analysis (2053 line 3-7).

We do not use mixed pixels in the study (i.e. composed of land and water). All the pixels used are water pixels only. However, the number of water pixels across the stream is variable and at times lower than 3. That means, we do use pixels that are not pure (i.e adjacent to mixed pixels but still composed of water only). In our terminology, pure water pixels stands for water pixels that are situated more than a pixel away from any mixed pixels. The manuscript has been clarified in this regard (lines 150-159 – revised manuscript).

3. No atmospheric corrections of the satellite TIR (2053 line 11) and shade influences from clouds were removed (2053 line 1-2). There was no explanation of how cloud influences were removed.

No atmospheric corrections are done in this study. However, this is mostly an issue when considering temperature variations over distances covering several satellite images (Handcock et al., 2012). In the current study, the studied river length is only 135 km and included in a single image. The river flows over a flat landscape. On the days when the images are taken, the sky was clear over the whole area and atmospheric conditions were therefore expected to be homogeneous. Furthermore, the Loire River is discretized in sections that do not exceed 30 km in length. It is therefore expected that atmospheric influences over the infrared radiations emitted from the water do not play a significant role in explaining the temperature variations observed along each river section. A comment was added in the manuscript in this regard (lines 162-164 – revised manuscript).

It is nevertheless true that a global shift of each Loire temperature longitudinal profile by a constant value is to be expected after taking into account atmospheric corrections (Handcock et al., 2012). However, this shift is likely to be small (<1°C), since the average difference between temperature measured in-situ and temperature estimated from the non-atmospherically corrected TIR images does not exceed 1°C. Overall, the error made on the groundwater discharge estimate while not taking into account atmospheric correction is therefore of the same order of magnitude as the error made while not taking into account groundwater temperature variability, i.e. 10 to 30% (see response to comment 7). The uncertainty due to the river temperature estimate has been taken into account in the calculation of the global uncertainty (part 3.5 – revised manuscript).

Clouds and their shades on the ground surface are detected visually using the TM8 band and the corresponding pixels from the TM6 band are removed manually from the analysis (lines 145-147 – revised manuscript). Overall, clouds are few as only images with under 10% of cloud cover are selected.

4. Tributaries and power plant influences were considered negligible even though their influence was difficult to separate (2051 line 24-25) and can be close to 1_C in the winter (2051 line 10-16).

No warming of the Loire River temperature was observed downstream of Dampierre and Saint-Laurent des Eaux, based on the TIR images (lines 506-512 – revised manuscript). We do not possess in-situ measurements of the water warming in the vicinity of the power stations. Reports from EDF show that, at Dampierre, in July 2010, the mean temperature increase is 0.1°C, while the maximum temperature increase is 0.18°C. Such a low temperature increase can not necessarily be identified with the satellite TIR images. EDF uses cooling towers to reduce the temperature of the water that is released into the Loire River. A 1°C maximum temperature increase was reported in winter, but only at low flow (i.e. well below 100 m^3/s). Such flows were not observed during the acquisition period of the TIR images, in winter. The choice was therefore made not to take into account the influence from the power plants, as the induced water temperature changes are small.

It is true that influence from the tributaries was not considered in this study (lines 115-120 – revised manuscript). In the case of the main tributary, the Loiret River, its influence is not separated from that of the groundwater because it is very short in length (less than 10 km) and its water is mainly of groundwater origin. Thus, we consider the Loiret discharge as groundwater discharge. Temperature variations along the Loire River, which can be attributed to the main groundwater discharge area (close to La Chapelle Saint-Mesmin), start upstream of the confluence with the Loiret River (see Figure 7). This shows that the Loiret River is not the only reason behind the temperature variations observed around river kilometer 635. All the other tributaries have flows under 1 m^3/s and temperatures close to the Loire River temperature. Their influences on the Loire River temperature profile is therefore expected to be small and were not observed on the TIR images.

5. Weir influences along the river (2050 line 25-27) were not accounted for.

Weirs influences were discussed briefly in the discussion part of the manuscript (lines 513-520 – revised manuscript). Temperature differences between the 1 km upstream reach and the 1 km downstream reach of the main weirs remain small (less than 0.1°C). It is therefore concluded that no significant temperature change along the water course could be related to a weir, based on the TIR images.

6. Surface area estimates within the heat budget calculations were based on the pixels selected for the analysis. These did not cover the entire channel surface area (2054 line 18-22). The potential 20% error in surface area translates into increased error in heat budget calculations because this value scales all surface flux estimates (S in eqn. 3).

The choice was made to consider the water pixels from the TM61 band of the LANDSAT images to estimate the Loire River surface area (lines 201-204 – revised manuscript), since we do not possess aerial images of finer spatial resolution at the date of the satellite images. This technique allows taking into account variations in the extent of the Loire River with time. The error in the surface estimate we discussed about is estimated by comparing, over each Loire River section, the area calculated using the water pixels from the TM 61 band (30 m) and the area calculated using the TM 8 band with a better spatial resolution (15 m). A description of this comparison has been added in the manuscript (lines 275-278 – revised manuscript). The uncertainty due to the surface estimate has been taken into account in the calculation of the global uncertainty (part 3.5 – revised manuscript).

7. Groundwater temperatures were assigned for summer and winter based on a data base (2054 line 16). No information was provided regarding the data or variability in these values.

ADES is a French database on groundwater data. It notably gathers most of the groundwater temperature measurements carried out by the different surveying agencies and water companies. The temperatures are measured irregularly over time. The precision of the temperature measurements is +-0.1°C. Data from the piezometers situated close to the Loire River is gathered for the period 1991-2011 (292 measurements). Looking at the measured temperatures, it appears that 80% of the temperatures are comprised between 11.5°C and 14°C in summer and between 11°C and 13.5°C in winter. These details have been added in the manuscript (lines 196-200 – revised manuscript).

The influence on the computed groundwater discharge of such a variability in the groundwater temperature can be assessed, considering that surface water temperatures varies between 4.5°C and 6°C in winter and between 20°C and 26°C in summer. Taking into account these temperature variations, we found that the groundwater discharge can fluctuate between 90% and 130% of the previously computed groundwater flow, based on mean groundwater temperatures. The highest errors in the calculation of the groundwater discharge are likely to occur in winter, when the river temperature is high and when the difference between surface water temperature and groundwater temperature is therefore low. The uncertainty due to the groundwater temperature estimate has been taken into account the calculation of the global uncertainty (part 3.5 – revised manuscript).

8. Inaccurate estimates of river temperature from TIR when compared to river temperatures. At times differences were > 3 _C different (Figure 2) and on average they were +0.3 _C in winter and -1 _C in summer (2056 line 5). Some of the “sharp” changes in temperature used to estimate groundwater influences were 0.5 _C (2057 line 19), which is a small or possibly insignificant change relative to the errors observed. Longitudinal temperature profiles varied less than 2 _C when the variability was at its highest (Figure 3).

Temperature accuracy (bias) should be differentiated from temperature uncertainty (Handcock et al., 2012). This has been clarified in the manuscript (lines 285-299 – revised manuscript).

Temperature accuracy is the average difference between the temperature estimated from the TIR images and the temperature measured in-situ. Temperature accuracy from the TIR images is 1°C on average in summer and 0.3°C on average in winter.

Temperature uncertainty is the temperature variability observed in an area that should have a homogeneous temperature (i.e. repeatability of measurement). Temperature uncertainty is therefore reduced, by averaging temperature over 200 m long sections and by using a moving average to smooth the temperature profile. The study of the longitudinal evolution of the difference between TIR images based temperature and in-situ measurements may give some ideas about the uncertainty (lines 267-274 – revised manuscript; see Figure 2). On average, the temperature difference variation remains below 0.8°C over the 100 km reach Dampierre – Saint-Laurent-des-Eaux (mean variation of the temperature difference of 0.0072°C/km). Sharp temperature changes need to be compared with the uncertainty and not with the accuracy. The sharpest temperature changes observed on the longitudinal profiles are comprised between 0.04°C/km and 0.1°C/km (mean of 0.074°C/km). The sharpest temperature changes are therefore at least one order of magnitude higher than the changes that are to be expected from the uncertainty. They are therefore likely to be meaningful in terms of physical processes (lines 335-340 – revised manuscript).

9. The overarching concern with these combined assumptions and errors are the influences on the findings within the paper. It is unclear if there is enough

variability in the longitudinal temperatures to confidently back out groundwater influences and needs to be further investigated. There are many questions and concerns regarding the influence of the assumptions or treatment of data. What are the errors in the satellite based TIR data and what is the influence of not correcting for atmospheric conditions that will vary throughout the study reach and over different times of year? Torgersen et al. 2001 states that 10 pixels are required to avoid the influences of banks emission and to get accurate river temperatures. It does not seem that 3 pixels are adequate, particularly when they are mixed pixels. Given these issues and additional uncertainty in other foundational data used in the heat balance approach (e.g., assumed groundwater temperature and incorrect surface area estimates), the confidence in groundwater estimates are likely low.

We previously discussed the influence atmospheric corrections would have on our study. It would have an influence on the temperature accuracy but not on the temperature uncertainty.

Torgersen et al. (2001) chose arbitrarily 10 pixels in each thermal image and took the median temperature value. Temperature longitudinal profiles were then drawn using these median values. This method can only be employed when using multiple images (mostly for airborne campaign). However, our method is similar in that we average river temperatures by sections of 200 m to draw the longitudinal profiles. This is a spatial extent of the same order of magnitude as the usual ground coverage of a TIR image taken from an airborne campaign. The advantage of our method is that we consider all the water pixels from the water course. There could therefore be more than 10 pixels in the 200 m sections. Then, uncertainty is further reduced through a moving average smoothing of the data over +-2 km.

We carried out sensitivity tests to estimate the overall uncertainty in our groundwater discharge estimation using the heat budget. Details about these tests have been added in the new manuscript (lines 373-379 – revised manuscript). One figure is added in the manuscript to show the confidence interval of the groundwater discharge estimation at two dates, one in summer and one in winter (Figure 6).

10. The current comparison with the groundwater budget that has long averaging times, similar uncertainties, and is vaguely described does not provide the type of validation needed to illustrate the potential of this approach. In order for this paper to have an impact within the remote sensing and groundwater communities, more information regarding a quantitative understanding of the accuracy of the proposed methodologies is necessary. Some additional information that validate the findings is also needed.

To validate further the findings, we replace the groundwater discharge calculated using the groundwater budget by the groundwater discharge calculated using a deterministic process based groundwater model over the entire Loire River basin. Using this model, the groundwater discharge to the Loire River can be calculated at each date and at every river kilometers. Uncertainty in the model prediction of the Loire River flow is known and low (Nash criteria of 0.98). Details about the uncertainty in the groundwater discharge estimated through modeling have been added in the manuscript (lines 452-454 – revised manuscript). The groundwater model was developed by Fulvia Baratelli and Nicola Flipo. They are included in the new authors list of the manuscript.

We found that the newly calculated groundwater discharge remains in agreement with the groundwater discharge previously calculated with the groundwater budget (see Figure A below). The highest groundwater discharges calculated by both methods are situated between river kilometers 620 and 660. However, on average, groundwater discharge rates calculated using groundwater modeling are higher than the groundwater discharge rates estimated with the groundwater budget. Higher groundwater discharge rates are also estimated in winter than in summer, which is in agreement with what was found using the heat budget. This remark has been added to the manuscript (lines 484-487 – revised manuscript).

Two figures are added in the manuscript to show the groundwater discharge calculated by the groundwater model (Figure 5; Figure 6).

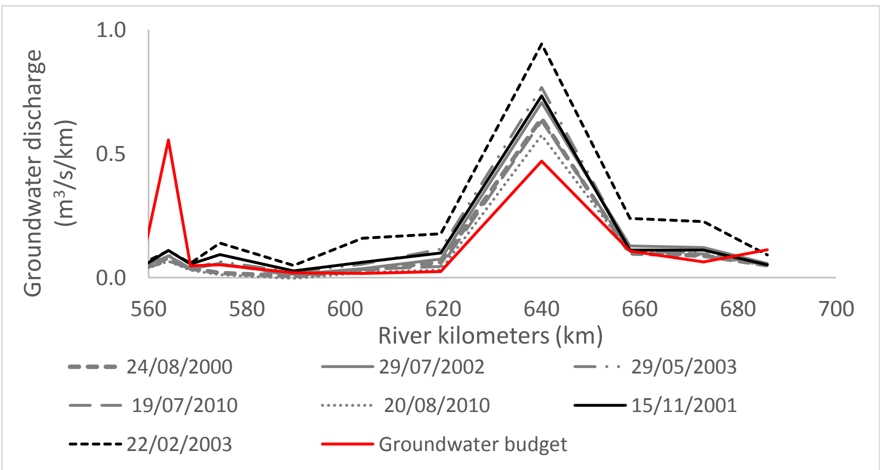

Figure A: Groundwater discharge estimated using a groundwater budget over successive Loire River groundwater catchment areas and using groundwater modeling over the entire Loire River basin.

Response to reviewer 2 :

11. This manuscript presents interesting results on how Landsat imagery in the TIR band can be used to map water temperature in a large river synoptically over hundreds of kilometers. This approach has been used in other large rivers, but the Loire River is particularly interesting because it is influenced by relatively high-volume groundwater inputs and is quite narrow (in places) for using satellite TIR imagery. Furthermore, the seasonal differences in river temperature provide an important perspective on thermal heterogeneity experienced by riverine biota. The paper could significantly improve our understanding of riverine thermal regimes and spatial patterns at broad scales, and it could be a useful contribution to the literature on thermal remote sensing of rivers, but unfortunately its presentation is quite poor. It is confusingly written from the standpoint of scientific English, and its organization requires significant revision to highlight the strengths and weaknesses of the study. For example, the data on the accuracy assessment need to be presented in more detail. The only data presented on the accuracy of the method are in Figure 2, which only presents means, which are not very useful. The authors need to present box and whisker plots perhaps to show the reader how variable the differences were. Furthermore, the authors mention that linear regression was used to evaluate kinetic and radiant temperatures, but these linear regressions and their statistics are not shown or reported. It would seem that the remote sensing part of this study would alone be a nice contribution but would require more more detail for the reader to truly evaluate the data. I am not qualified to evaluate the methods for estimating groundwater discharge, but it appears that this part of the manuscript is poorly developed. The main objectives of the paper pertain to the TIR data and how they can be used to locate thermal anomalies associated with groundwater at different times of the year. The authors may wish to reconsider how important the actual calculations of discharge are for this paper.

Many small modifications have been made to improve the readability of the manuscript. They have been made by an English speaking translator. The modifications are visible in the marked-up manuscript. They do not change the aims and scope of the manuscript.

Comments on the accuracy and uncertainty have been added to the manuscript (see response to comment 1).

Linear regression was not used to correct radiant temperature from in-situ measurements of kinetic temperature. Linear regression does not work well, although radiant temperature tends to overestimate kinetic temperature in winter and to underestimate it in summer (see Figure 2).

Linear regression was used to compare, when this was possible, temperatures extracted from the pure water pixels and temperatures extracted from the non-pure water pixels, in order to assess the robustness of the method (see response to comment 18).

We found that the calculation of the groundwater discharge is an important part of this work. One of the findings of this study is that, despite all the uncertainties associated to the use of satellite TIR images, the main groundwater discharge area in the Loire River can still be identified. Moreover, the calculated groundwater flow remains credible in regard to what was found in previous studies and to what we find using a groundwater flow budget over the successive catchment areas and groundwater modeling. Quantification of groundwater discharge using TIR images has already been conducted in the past (Loheide and Gorelick, 2006) but it has been used on a much smaller river. It is therefore interesting to see if Landsat images could also be employed.

12. Title: Specify "thermal IR" not just IR. Also, write out Beauce Aquifer because most readers won’t know what the "Beauce" is.

The corrections have been made.

13. Page 2048, Line 20: Throughout the manuscript, the authors write "Thermal InfraRed". Just write "thermal infrared (TIR)" and use standard terminology as in the papers that are cited in the references.

The corrections have been made.

14. Page 2049: Check spelling of "Burckholder". I think it doesn’t have a "k". Also, the word "evolution" doesn’t make sense as it is used throughout this manuscript.

In fact, it should have been written “Burkholder”. It has a “k” but no “c”. The corrections have been made. The word “evolution” was replaced by “variations”.

15. Page 2050: The authors need to say something about the presence of large wood, boulders, and gravel bars because they can also be a cause for mixed pixels, not just the banks.

In the Loire River, there are no boulders, as the sediments are mostly composed of sand and gravel. The gravel and sand bars are detected using the TM 8 band from the Landsat images. They are considered in the same way as the river banks and pixels from TIR images are therefore discarded when overlapping sand bars. Trees in the water, as well as very small sand bars, are not likely to be detected due to the resolution of the TM 8 band pixels (15*15 m^2 pixels). But, it is therefore assumed that these obstacles do not cover an important area within the 60*60 m^2 water pixels from the TM 6 band.

16. Page 2052, Line 18: This is confusing because the authors refer to the near IR data before they even describe the TIR data from the satellite. In fact, the authors don't identify the spatial resolution of the IR and TIR bands in the methods. Please check your methods. They are not presented in a logical order and they need to provide more detail.

Comments have been added in the manuscript for better clarity (lines 138-159 – revised manuscript). Resolutions of the IR and TIR bands are described.

17. Page 2053: The fact that the authors use data where there are only three pixels across the width of the stream is quite surprising, given what papers have described. It is really important for these data to be fully reported. After reading this paper, I am somewhat convinced that < 3 pixel may work in certain instances, but I need more data to be convinced.

The choice to use all the water pixels was made since we could otherwise not have covered the full length of the selected river reach. However, we made sure that the resulting bias was not too important (lines 300-309 – revised manuscript).

18. Page 2056: Where are the results and plots for the regression analysis?

We add one figure in the manuscript showing the comparison between temperatures extracted from non-pure water pixels and temperatures extracted from pure water pixels, over all the 200 m sections of the Loire River where pure water pixels could be found (see Figure 3). We found that there is no significant shift between temperatures extracted from pure water pixels and temperatures extracted from non-pure water pixels. The non-pure water pixels do not particularly overestimate the water temperature in summer (Figure 3a in the manuscript), as it was expected from the high river banks temperatures. The slope of the regression line is 0.99 and the coefficient of determination is 0.98. In winter, a slight underestimation of water temperature within the non-pure water pixels could be seen (Figure 3b in the manuscript), with a slope of the regression line of 0.72. However, the coefficient of determination is quite low ($R^2 = 0.69$) and we lack data to conclude (the range of variation of water temperature is much smaller in winter than in summer). These results are added in the manuscript (lines 300-309 –

revised manuscript). Considering both summer and winter data, the slope of the regression line is 1 with a regression coefficient of 1 (see Figure B below).

The difference between temperatures extracted from pure water pixels and from non-pure water pixels usually remains in the +-0.5°C interval (for over 98% of the 200 m sections). This 0.5°C gap corresponds to the approximate sensor resolution of the satellite camera (see Figure C below).

As we consider in our analysis both pure and non-pure water pixels, and since we use a moving average over +-2 km to smooth the temperature profile, we expect the bias resulting from the use of non-pure water pixel to remain relatively low.

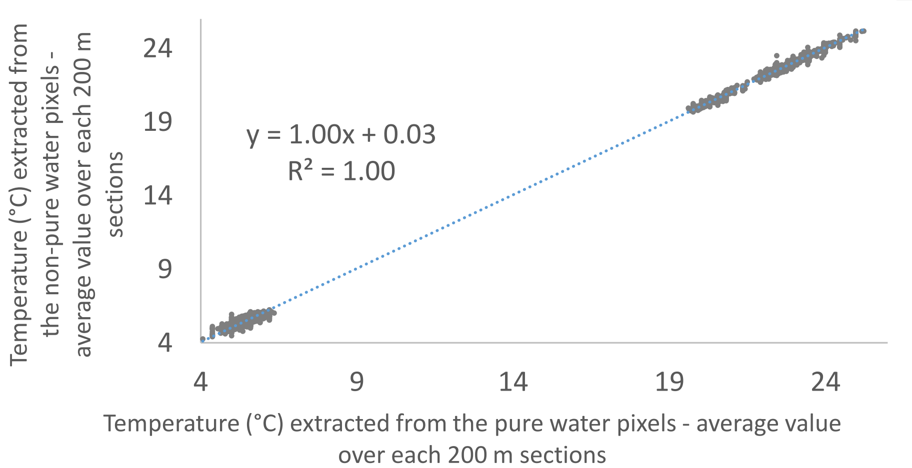

Figure B: Relation between the temperature extracted from the non-pure water pixels and the temperature extracted from the pure water pixels. Temperature values of both pixels types are averaged over the successive 200 m sections where pure water pixels exist. Both winter and summer temperature values are represented.

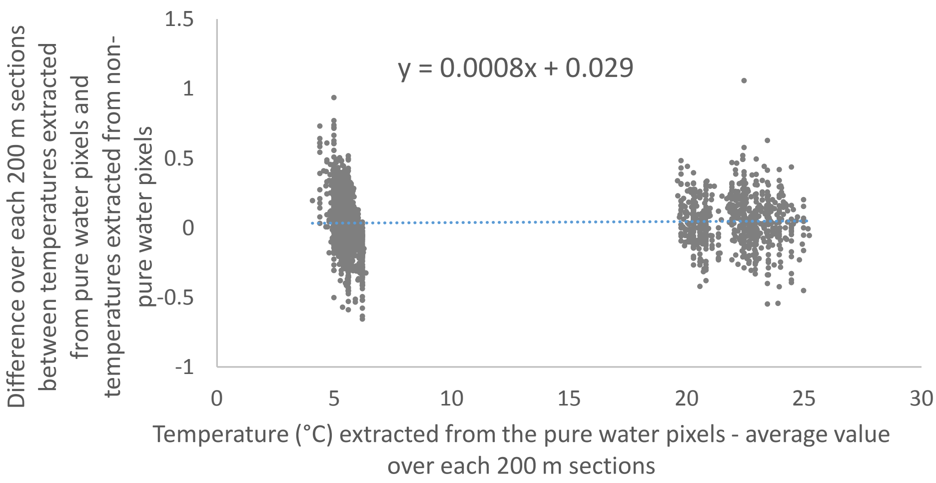

Figure C: Difference between the temperature extracted from the pure water pixels and the temperature extracted from the non-pure water pixels. Temperature values of both pixels types are averaged over the successive 200 m sections where pure water pixels exist.

19. Table 1: What time were these temperature data collected? I think it says this in the methods, but you should probably have it in the table as well. Standardize the significant digits in these numbers.

The temperatures were collected at 11:30 LT in winter and 12:30 LT in summer (lines 126-127 – revised manuscript). The significant digits have been standardized.

20. Table 3: Which sections? All sections? How many sections?

All the 200 m sections of the Loire River are included in this analysis. The legend has been modified accordingly.

21. Figure 1: The symbols on this map are difficult to see. The triangles and the crosses are too faint. Also, the river km numbers need to be moved slightly so they are not on top of other symbols. Note that the town of Saint Laurent has a symbol that gets in the way of other symbols, and it is hard to read the text of the name. The font size is generally too small throughout this figure. Need to show groundtruth locations if possible. What is the light grey area? This needs to be stated in the caption.

The map has been modified.

22. Figure 2: The y-axis label is too long. Shorten and provided clarification in the text. Don't use "ones" in the label; this is not good scientific writing. Are these mean differences? I think it would be better to have box and whisker plots of these so you can see variation.

The term "ones" has been removed from the figure.

This figure shows difference between in-situ measurements of water temperatures and temperatures estimated from the longitudinal temperature profiles obtained from the TIR images. They are therefore a kind of mean differences. The figure caption has been modified for better clarity.

We find that box and whisker plot of the temperatures extracted from TIR images in the vicinity of Dampierre and Saint-Laurent des Eaux would be harder to read. These box and whisker plots show that, in most cases, the temperature measured in-situ is comprised within the range of the temperatures observed at the neighboring water pixels from the TIR images. In these cases, temperature discrepancies between the 2 methods could easily be explained by local temperature heterogeneities in the water course or satellite sensor's resolution. However, there are 3 cases where these phenomenon may not offer an adequate explanation. It occurs on the 29/05/2003 at Dampierre and on the 29/07/2002 at Dampierre and Saint-Laurent des Eaux. This analysis is consistent with the comparison between the longitudinal temperature profiles and the in-situ temperature measurements that is shown in the manuscript. Figure 2 was therefore kept as it was in the revised manuscript.

The discrepancies between temperatures measured in-situ and TIR images derived temperatures are taken into account in the uncertainty analysis (lines 267-273 and 279-281).

23. Figure 3: State that these are derived from satellite imagery. What does "removed" mean in the y-axis label? Move the x-axis at the bottom of the figure.

The corrections have been made.

24. Figure 4: I think it would be really helpful to have Figure 3 and Figure 4 be panels in the same figure.

It has been done.