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

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Abstract

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 r~~R~~iver 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 m^3/s) than during summer (5.3 m^3/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 net solar radiation, air temperature and~~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, Fullerton et al., 2015); and 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). 3 pixels is usually considered to be the absolute minimum (Torgersen et al., 2001). 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 timerequire 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 modellling (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; and 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).

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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}~~m^3/s~~, and the average flow rates in August and January ~~is~~ were 95 m^3.s^{-1}~~m^3/s and the average flow in January is~~ and 553 m^3.s^{-1} ~~m^3/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 pixels (180 m) threshold~~(180 m). However, during low flow periods (i.e. below 100 m^3.s^{-1}), 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 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.

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~~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 90^{th} 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 km^2, (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}$$m^3/s$ and 478 $m^3.s^{-1}$$m^3/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 (345 $m^3.s^{-1}$).

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3.2 ~~From the TIR satellite TIR images to~~Extraction of 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.

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

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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~~ used for two different purposes~~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 based on- ~~heat~~ hHeat budgett ~~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 dDescription 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

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winter, based on 292 measurements from the ADES database (www.ades.eaufrance.fr) conducted in the vicinity of the Loire River, over the 1991-2011 period (). Over 80% of the temperature measurements were comprisedincluded in the interval mean mean plus plus or minus +1.4°Cmean minu means. F_{net} [W.m^{-2}] stands for the atmospheric heat fluxes 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 isThis value was therefore probably somewhat underestimated, as images pixels composed of both water and land are not consideredwere 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 fluxes ($F\ net$) 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 radiations, RS the solar radiations, RE the emitted radiations, CV the conduction, and CE the condensation/evaporation.

The atmospheric parameters extracted from the SAFRAN database (Système d'Analyse Fournissant des Renseignements Adaptés à la Nivologie) database from Météo France (Quintana-Segui et al., 2008) were averaged along the successive Loire River sections consideredin 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

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~~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.

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

3.4 Groundwater discharge estimation based on~~–~~ g~~groundwater G~~roundwater ~~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} [m³. 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.:

$$q_{sa} = k_{riv}(h_g - h_r) \tag{5}$$

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.

$$k_{riv} = f k_H L \tag{6}$$

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:

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

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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) 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~~ in groundwater discharge estimation ~~– Heat budget~~

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

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

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

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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 (i.e. $T_{i_{new}}$) 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~~ ~~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}).

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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

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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 (

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 +-2 km ~~that~~which was applied to the data ~~is~~was therefore useful in ~~lowering~~reducing the uncertainty.

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~~4.3~~4.2 Longitudinal temperature profiles

Among the ~~7~~ seven longitudinal temperature profiles, ~~3~~ three main profile types can be observed: ~~2~~ two in summer~~time~~ and one in winter (Figure 4a; Figure 4b)~~time~~.

In summer~~time~~, 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 (Figure 4b). 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 3~~Figure 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 of~~after~~ river kilometer 690 (29/05/2003, 19/07/2010 and 20/08/2010), or upstream ofbefore river kilometer 690 (24/08/2000 and 29/07/2002) and be then was followed by a rise in the temperature.

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

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 arewere comprised between 0.04°C.km^{-1} and 0.1°C.km^{-1} (mean of 0.074°C.km^{-1}). The sharpestmost marked temperature changes are therefore at least one order of magnitude higher than theose 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.

4.44.3 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 modelingtwo methods (Figure 5a). We found thatT the variability of the with the heat budget iswas 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 staywas always with in the interval estimated by the heat budget. Overall, compared to the groundwater modeling, the heat budget tendsed to overestimate the groundwater discharge between river kilometers 640 and 660 in winter and to underestimate the dischargeit between river kilometers 660 and 680 in summer (Figure 5b; Figure 6a; Figure 6b).

High groundwater discharge rates (0.31~~55~~ 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 ~~i~~were~~s~~ 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 a~~was 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 method~~modeling (between 0.6~~5~~ and 0.9 m^{3}.s^{-1}.km^{-1}). Both methods showed a high~~The~~ 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 ~~T~~the results of the two methods ~~give~~were 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 (Handcock 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~~ i.e.~~–~~ 1.33 $l.s^{-1}.km^{-2}$). Temperature from the Loire River were under-estimated at this date. One possible explanation of this ~~shift~~ would be that high ~~water~~ evaporation at this date le~~a~~ds 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

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sensors low resolution can also play~~s~~ a role, particularly ~~especially~~ in narrow parts ~~where~~ of the Loire~~ River which areis particularly narrow~~.

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 (Bur~~c~~kholder 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 0.01~~10~~ m^3~~l~~.~~/~~s^{-1}) and using high precision aerial images (Loheide and Gorelick, 2006).

This work is new ~~in that~~because firstly, groundwater discharge ~~is~~ was estimated on a large river, ~~based on~~through ~~satellite~~ TIR satellite images and secondly the results were compared~~. The comparison~~ with~~ the groundwater discharge~~ estimations obtained~~ed~~ using ~~a groundwater budget~~groundwater 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 section~~s~~ 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 from~~in 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 remained~~s mainly~~ below 0.4 m^3.s^{-1}.km^{-1}, which

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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~~. F~~actors such as bed friction, heat conduction through the river bed, or hyporheic exchange ~~are not considered~~are 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 u~~U~~ncertainties ~~are also attached~~linked ~~–~~to using groundwater modeling to calculate the groundwater discharge ~~calculated using with the groundwater budget modeling~~. Nevertheless, t~~T~~he modeling of the Loire River flow in Blois, Orléeans and Gien over the 1996-2013 period ~~works well nevertheless~~provided 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.~~ D~~D~~espite all the uncertainties, the groundwater discharge estimated using the heat budget ~~stays~~ remained within the same order of magnitude as~~of~~ ~~the discharge~~that calculated ~~with the groundwater budget~~using groundwater modeling.~~At maximum, the groundwater discharge rate, estimated with the heat budget, overestimates, or underestimates, by less than~~ It was always below ± 1

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$m^3.s^{-1}.km^{-1}$ of the discharge calculated by using the groundwater budgetmodeling. The average groundwater discharge calculated by using the groundwater budgetgroundwater modeling for 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 $r^2 = 0.782$).

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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 636~~5~~ 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~~

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TIR satellite images allow to locateenable the main groundwater discharge area to be located 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).

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 (Figure 5). This difference may be explained by the limitations of the heat budget employed, since a drop in water temperature is observed on all summer thermal profiles. However, this drop does not start at the same location depending on dates. The main groundwater outlet location seems to change with time and to be located on the downstream part of the section considered (near Blois).

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 3~~Figure 4a; Figure 4b), ~~but~~ however, the temperature rise ~~begins~~ of the power plant.

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 km~~a 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 t~~T~~hermal i~~I~~nfrar~~R~~ed (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~~s~~ 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

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seriously underestimated at low flow rates and ~~when~~ high water temperatures ~~is high~~ (differences of over 2°C).

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 ~~areis 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 m³./s⁻¹)~~ than in summer~~time~~ (13.5 m^3.s^{-1} and 5.3 m^3.s^{-1} respectively~~5.3 m³.s⁻¹m³/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 model~~l~~ing of both the groundwater discharge and ~~the~~ stream temperature.

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Mis en forme : Police :(Par défaut) Times New Roman, 12 pt, Couleur de police : Noir

Mis en forme : Anglais (États-Unis)

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Mis en forme : Anglais (États-Unis)

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	5.8~~75~~	5.6~~5~~
22/02/2003	478	4.2~~15~~	5.5~~5~~	12.7~~65~~
Summer				
29/05/2003	89~~8.6~~	22.8~~5~~	20.1~~05~~	25.5~~5~~
19/07/2010	112	23.4	23.1	28.3~~25~~
20/08/2010	78~~7.9~~	21.8	20.9~~5~~	28.3~~29~~
24/08/2000	83~~.3~~	24.0	22.5~~5~~	30.4~~5~~
29/07/2002	61~~.1~~	28.3	26.0	32.5

Mis en forme : Exposant

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

Solar radiation~~s~~	RS estimated from the SAFRAN database	Details
Atmospheric radiation~~s~~	$RA =$ $\sigma.(T_a + 273.15)^4.\left(A + 0.031.\sqrt{e_a}\right).(1 - R_L)$	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

Mis en forme : Surlignage

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

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~~**Standard deviation of water temperature (°C)**	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)~~River sections with under 20 water pixels	0.70	0.56	0.76	0.32	0.45	0.42	0.52
River sections with over 20 water pixels~~σ (n>20)~~	0.50	0.44	0.73	0.26	0.41	0.41	0.42

Mis en forme : Non Surlignage

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Mis en forme : Police :Non Gras

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).

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 and at two different sites (Dampierre and Saint-Laurent des Eaux). 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).

Mis en forme : Police :Italique

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.

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.

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.

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.

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.

Answer to reviewers

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

Response to reviewer 1:

Comment 1 - Line 20: Capitalization of "River".

The correction has been made.

Comment 2 - Lines 25 and 28: Writing style is too conversational (see "drop of around" and "in line"); this is fine in speak but is not precise enough for scientific writing.

The term “around” has been removed.

Comment 3 - Line 50: May want to cite http://onlinelibrary.wiley.com/doi/10.1002/hyp.10506/abstract "Rethinking the longitudinal stream temperature paradigm: region-wide comparison of thermal infrared imagery reveals unexpected complexity of river temperatures".

The reference has been added (line 45).

Comment 4 - Line 51: Note that 3 pixels across the stream width is the absolute minimum. Realistically, it should be greater than 5 pixels. I think that Torgersen et al. (2001) recommended 10 pixels in width based on their quantitative analysis. It would be appropriate here and/or in the discussion to stress that 3 pixels in width is the absolute minimum and other papers have recommended a greater number of pixels across the stream width.

The reference to Torgersen et al. (2001) has been added (lines 52-53).

Comment 5 - Line 93: Again, 3 pixels across the stream in most cases is not sufficient. Thus, to call it a "threshold" is not appropriate. The "threshold" should be "> 3 pixels" in order to have any confidence in the temperature measurements. Furthermore, this study was not designed to rigorously test the "3 pixel" recommendation. In order to do that, you would need more locations in the stream where you measured kinetic water temperature. Thus, it is important to not make strong statements about 3 pixels being sufficient.

The term “threshold” has been removed.

Comment 6 - Line 136: It is unusual to start a heading with "From". This heading is confusing.

The heading has been modified.

Comment 7 - Line 170: I don't understand the use of "exploited" here.

The phrase has been modified and the term “exploited” has been removed (lines 168-169).

Comment 8 - Line 179: The punctuation of this heading is confusing. In fact, the heading itself is difficult to understand.

The heading has been modified.

Comment 9 - Line 220: The two parts of this heading are redundant.

The heading has been modified.

Comment 10 - Line 259: Again, this kind of punctuation for a heading is confusing.

The heading has been modified.

Comment 11 - Line 319: Need to refer to a figure or figures. Do not break the paragraph after this sentence.

References have been added.

Comment 12- Line 341: Again, this is an awkward way to write and punctuate a heading.

The heading has been modified.

Comment 13 - Line 397: Check spelling.

“Handcok” has been modified to “Handcock”.

Comment 14 - Line 406: Specify the seasons during which it will be positive or negative.

Results from the previous studies were different. It is therefore not possible to specify a season during which the difference is necessarily going to be positive or negative.

Comment 15 - Line 411: Need to clarify this comment. Help the reader by stating whether the in situ temperature was higher or lower than the TIR temperature and why.

A phrase has been added to clarify the comment (lines 405-406).

Comment 16 - Line 434: This paragraph is too long. Divide it into two paragraphs for clarity.

It had already been done. The first paragraph goes from line 428 to line 433.

Comment 17 - Line 523: There is no need to capitalize this words in this manner. Be consistent throughout the manuscript.

It has been modified.

Comment 18 - Table 2: The last column needs a heading.

It has been added.

Comment 19 - Table 3: The columns are not labeled correctly. Please look at examples of tables in scientific journals. Also, I wouldn't use the Greek symbol. If you label the columns correctly, you wouldn't need to use the symbol, which is awkward.

It has been modified.

Comment 20 - Figure 2: It would be helpful in the caption to state that the in situ measurements were at two different sites along the same river. Why do you have the numbers 1-7 at the top of this figure? It is clear that these are different dates. Also, the date formats are confusing in the caption and the figure. Please be consistent.

The modifications have been done.

Comment 21 - Figure 3: The way this caption is written, it is not clear what time of year the data were collected. The whole caption is redundant and very poorly worded. Please look at other scientific papers for examples of how captions should be worded for clarity. Also, I still find it quite awkward to have such long axis labels. This is not customary in scientific papers. I defer to the editor on this issue of style.

The caption and axis labels have been shortened. The summer and winter periods are defined at the beginning of the article.

Comment 22 - All figures: None of your figure axes have ticks. Please add ticks as appropriate for graphs in scientific journals.

Ticks have been added.

Comment 23 - Figure 4: I think that your x-axis label should be "River kilometer (km)" not in plural form. The same goes for all of your figures with river kilometer on the x-axis.

It has been modified.

Response to reviewer 2:

Comment 24 - P2L26-28 "….According to the heat budgets, groundwater discharge was higher during the winter period (13.5 $m^3.s^{-1}$) than during the summer period (5.3 $m^3.s^{-1}$)….." is not really a finding. What else would you expect other than groundwater discharge following the precipitation seasonality?

Previously from this study, it was not obvious that groundwater discharge would be found to be highest in winter using a heat budget based on satellite thermal infrared images.

Comment 25 - P2L29-30: This is the only place where you mention flow recession. If the connection between flow recession and groundwater input is so important, then it should be discussed in more detail.

We discuss it in the discussion part (line 477-480 – Figure 7).

Comment 26 - P2L35: net solar radiation instead? Also, "..air temperature, and groundwater discharge.." rather than "…air temperature or groundwater discharge…".

It has been modified.

Comment 27 - P2L45 “…and, (iii) to validate ………..”

It has been modified.

Comment 28 - P3L81 “…and, (iii) to locate ………..”

It has been modified.

Comment 29 - P4L94 please define low flow period. In fact, I would recommend including a figure that shows average Julian day (1-365) or monthly flow along with precipitation (if available). These additional data would help clarify the seasonality of the flow---which is surfaces repeatedly throughout the manuscript.

We already have quite a few figures. Therefore we find it better not to add another one. The term “low flow” has been precised.

Comment 30 - P5L111-112: can you provide # for temperature increase during the winter period as well?

It is provided (line 111-112).

Comment 31 - P6L120 can you show the tributaries in Figure 1?

The Loiret River is very short and would therefore not be easily visible on Figure 1. However, it can be seen on Figure 8.

Comment 32 - P6L126 what is LT? I am guessing local time?

Ye, it is local time. We were told to write LT during the first part of this manuscript review.

Comment 33 - P6L129 provide some details of the temperature sensor type (make/model) and installation (depth etc.). were temperature sensors located in the shading or in the middle of the river?

Unfortunately, we do not have such details about the sensors.

Comment 34 - P6L135 mention the mean annual flow in the parenthesis—“ mean annual flow ($345\ m^3.s^{-1}$)”

It has been added.

Comment 35 - P9L188-191: describe i (is it section id, if so the in L192 write “….rate of the section i at temperature….”). Also, should the term, F_{net}, S, Q_{gw} and T_{gw} also have the subscript i? and the equations 1-3 are time dependent?

The terms T_i, T_{i-1}, Q_i, Q_{i-1} are explicited (lines 192-193). i stands for the upstream part of the section and i-1 for the downstream part. The other terms should therefore not have the subscript i.

To make for the time dependency, all parameters are averaged over a 24 h period.

Comment 36 - P9L201 again “………….section i.”

i stands for the upstream end of the section and not for the section.

Comment 37 - P10L211: expand “SAFRAN”

It has been done.

Comment 38 - P12L265: what is the source of the selected 10% uncertainty? Later in the manuscript you mentioned that uncertainty in flow can be up to 20% then why only 10% was considered here?

It is true that this could be confusing. On the Loire River, uncertainty in the flow rate measurement is thought to be closer to 10%, especially when there is no flood. But, a 20% uncertainty is often considered in the general case.

Comment 39 - P12L274: please describe T_{inew}

It has been done (line 270).

Comment 40 - P13L208 again how this 2°C threshold was determined?

This +-2°C threshold was determined in order to take into account both the uncertainty in the groundwater temperature (+-1°C – lines 199-200) and in the surface water temperature (+-1°C – line 289).

Comment 41 - P14L305-306: Reporting only slope of the regression is misleading when your intercept is not set to zero. Either report both slope and intercept or simply R2 and RMSE.

The intercept is written on the Figures 3a and 3b.

Comment 42 - P14L306-307: looking at the Figure 3d the difference seems to be lot higher. To be consistent with your preceding statement, you need to report the error (use ore standard term absolute bias or RMSE) for winter and summer separately. Also, what is going on with those points where non-pure pixel temperature varies a lot but pure pixel temperature is constant? This seems to be happening in both summer and winter.

The fact that non-pure pixel temperature varies more than pure pixel temperature for many point is due to the uncertainty of the satellite sensor. When few water pixels exist in a section, the number of pure water pixels is even lower.

Comment 43 - P15L333 change "….temperature tended to increase.." to "….temperature increased.." also here and few other places you only have one sentence in the paragraph.

It has been modified.

Comment 44 - P15L340 what do you mean by physical processes? can you give few examples?

It means that the temperature changes are likely to be meaningful. “Physical processes” has been removed.

Comment 45 - P17L368-369: but what is the river is losing instead of gaining? This seems to be the case between river kilometers 610 and 625 as you have stated on P21L465.

The case of a losing river was not taken into account as it is difficult to consider it in the heat budget. The uncertainties are already too important. Also, we would need to measure the flow much more regularly along the water course.

Comment 46 – P18L401-404 I don’t think bringing the lake temperature into this discussion is helpful. The vertical temperature profiles (stratified??) in lakes are very different from those in rivers.

It is true that vertical profiles are different in lakes but we would also expect temperature derived from TIR images to be warmer than those measured in-situ. Therefore, we choose to keep the reference.

Comment 47 - P18L410: check the units? There seems to be some inconsistency.

We make a distinction between the flow rate and the specific flow rate.

Comment 48 - P19L415-416: only in summer though? In winter the error is quite high.

The error appears to be quite high only at one date in summer, but not in winter.

Comment 49 - P19L430 it seems like you are using m3/s and l/s to report flow rate. Use one unit (preferably m3/s) throughout the manuscript.

It has been modified.

Comment 50 - P20L455-456: Looking at the Figure 5, I don't think this statement is fully justifiable.

We give the coefficient of determination, which is 0.7.

Comment 51 - P21L470 what is BRGM?

It is defined in the caption of Figure 1.

Comment 52 - P21L484-487 is not this what you expect? What is interesting here is the difference in error between winter and summer using the tow approaches. In winter, TIR predicts 2 times more groundwater discharge than groundwater modeling which can be attributed to the larger uncertainties (Fig 3b) in winter temperature predicted by TIR??

No, higher discrepancies observed in winter are not likely to be explained by larger uncertainties in winter temperature. However, river flows are higher in winter and flow variations are also higher. This could be part of the explanation.

Comment 53 - P24L538: check the super scripts.

It has been modified.