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

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Abstract

Seven Landsat tThermal iInfrarRed (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 areas using a heat budget based on the Loire River temperature variations~~,~~ estimated from the TIR images. Results 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 a temperature drop of around 1°C to 1.5°C in summer and a temperature rise of about 0.5°C in winter. According to the heat budgets, groundwater discharge is 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 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 flow recession 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.~~

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 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 tThermal iInfrarRed 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 images of water courses have mainly been used to: i) identify cold refuges for fish in summertime (Belknap and Naiman, 1998; Torgersen et al., 1999; Tonolla et al., 2010; Monk et al., 2013); ii) 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) validate river temperature models (Boyd and Kasper, 2003; Cristea and Burges, 2009).

However, most of these studies are based on airborne TIR images. Studies based on satellite TIR images are scarce, mostly 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 be studied using TIR satellite images, as it was considered that the river width had to exceed 3 images pixels to allow enough accuracy in water temperature estimation (Handcock et al., 2006; Wawrzyniak et al., 2012). However, Landsat satellite images have the advantage over airborne images of being freely available at different dates, so that archives are available to explore inter-annual or seasonal patterns. As the ground covered by one single satellite image would take time to be covered using air transportation, 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 groundwater discharge may have a significant influence on surface water temperature (Hannah et al., 2004; Webb and Zhang, 1997, 1999), this influence has seldom been studied based on 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' knowledge, groundwater discharge to rivers has not been observed or quantified before, using satellite TIR images.

The knowledge of groundwater discharge location is crucial to assess the vulnerability of aquatic fauna, as groundwater discharge locations can act as shelter areas (Belknap and Naiman, 1998). 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, between the nuclear power plant of Dampierre and Saint – Laurent des Eaux, the Loire River temperature is 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 been quantified using hydrogeological numerical model~~l~~ing (Monteil, 2011; Flipo et al., 2012) and it was found to be circa 10 $m^3.s^{-1}$~~m^3/s~~ on inter annual average. However, until now, the groundwater discharge has not been well located or quantified based on field measurement data.

The main goals of this study were to test the abilities of Landsat satellite thermal infrared images i) to accurately determine water temperature in a river having a width under 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 groundwater discharge's contribution of the Beauce aquifer into the Loire River.

2 Study area

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

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

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. However, during low flow periods, the Loire River locally forms several branches and the river main branch width can be as low as 50 m. During low flow periods, the average river depth is about 1 m in this section. The main weirs (natural and artificial) along the Loire River 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 low flow.

On 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 radiations, diffuse solar radiation, latent heat exchange, conduction and water emitted radiations; 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 system of the nuclear power plants of Dampierre and Saint-Laurent des Eaux (average discharge of 2 $m^3.s^{-1}$~~m^3/s~~ by nuclear reactors). However, the influence of the nuclear power plant on the Loire River temperature is low, the heat being removed through cooling towers. The median temperature rise of the Loire River between the upstream and downstream 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 River temperature due to nuclear power plants ~~in the Loire River temperature~~ is observed in winter, at low flow (<1°C); iv) 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 the Loire River catchment area over the 135 km reach). The influence of the tributaries on the Loire River temperature is considered negligible in this section~~ of the Loire River~~, since the water temperature of the tributaries is usually close to the Loire River temperature (Moatar and Gailhard, 2006) and the tributaries flows are small (less than 1 $m^3.s^{-1}$). However, the main tributary of the Loire River in this section, the Loiret River, 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 the Loiret River ~~is therefore difficult to separate from~~can therefore be merged 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~~Table 1~~). 5 available in the warm season and 2 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 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, the average observed daily water temperature, on the days when the images were taken, was 5.2°C. In the warm season, it was 23.7°C.

River flows 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 out of the 7 dates for which the images were taken, the Loire River flow was lower than the average mean annual flow.

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

To locate TIR image pixels corresponding solely to water, 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 first used. Only pixel values below the threshold were kept. The aerial images in the visible range from BD Ortho database, from 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 and where it did not altered with time. The Carthage database from the IGN, which maps all the French watercourses in the form of lines, enabled the further separation of the water pixels belonging to the Loire River from the pixelsones 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 the spatial resolution of the TM8 band (15 m) is much higher than the spatial resolution of the TM 61 band (60 m resolution, subsampled at 30 m; 10.4 to 12.5 µm) that is used to estimate water temperature.

In a previous study (Handcock et al. 2006), it was found that river temperatures should be estimated using only pure water pixels that are water pixels situated more than a pixel away from the river banks. However, in the case of the middle Loire River, it was not possible to find pure water pixels along the entire river course, especially at low flow. Therefore, all water pixels were kept. Mixed pixels, composed of land and water, were not included in the analysis.

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 was used.

Then, temperature was 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 the study area was included in a single LANDSAT image and that atmospheric conditions were homogeneous within the study area (under 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 temperature was then averaged by sections of 200 m in length. This 200 m value was chosen, so that it is close from the Loire River width. A moving average over 10 consecutive temperature values along the water course (2 km) was further conducted to smooth the temperature profile.

The temperature profiles extracted from the TIR images were then exploited in two different ways: i) the accuracy of the temperatures estimated from the TIR images was tested through a 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. Results were then compared with the ~~inter-annual~~ groundwater discharge ~~(period 1998-2007)~~ calculated by a deterministic process based groundwater ~~budget method~~model applied over the whole Loire River basin. Calculated groundwater discharges estimations were compared over successive groundwater catchment areas along the Loire River~~corresponding to the respective River sections~~.

3.3 Groundwater discharge estimation - H~~h~~eat budget based on TIR images

The middle Loire River was divided into 11 sections, so that on 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. Description of the method can be found in Schomburgk et al. (2012). The first section begins at river kilometer 560 where the flow 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 of the section at the temperature T_{i-1} [°C], Q_i [$m^3.s^{-1}$] is the downstream flow of the section at the temperature T_i [°C]. Q_{gw} [$m^3.s^{-1}$] is the groundwater flow at the temperature T_{gw} [°C]. At each section, the flow entering the section is equal to the flow entering the previous section plus the groundwater discharge estimated over the previous

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

The heat fluxes ($F\ net$) between the Loire River and the atmosphere were estimated as follows (Salencon and Thébault, 1997; Chapra, 1997; Table 2~~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 from Météo France (Quintana-Segui et al., 2008) were averaged along the successive Loire River sections considered. Every atmospheric factor was 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 travel time between Gien and Blois is about 1 to 1.5 days on the dates when the images were taken. Atmospheric parameters should therefore not be integrated over a period exceeding a day.

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

3.4 Groundwater discharge estimation – G~~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 an 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 an hydrosystem into three interacting compartments: surface, unsaturated zone and saturated zone. Specifically, the model couples different modules, which simulate the surface water mass balance, the runoff, the river flow, the in-stream water levels fluctuations, the flow in the unsaturated and saturated zones.

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

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

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.

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

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:

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

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) 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 stations along the Loire River, 3 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:

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

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 between the temperature estimated from the TIR images and the temperature estimated from in-situ measurements. At each date, a shift by river kilometers and finally by river sections is calculated. The value of this shift is added to T_i to estimate the variation in surface water temperature that could be caused by uncertainties in the measurements: $(T_{i_{new}} - T_i)$.

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

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ΔS is the absolute uncertainty in the water surface estimate. It is 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 is calculated at each date for every 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 considered to be equal to 2°C in order to take into account both groundwater temperature variability and surface water temperature uncertainty.

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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 comprised between ± 1°C of the temperature measured directly into the river (11 times out of 14: Figure 2~~Figure 2~~). But the temperature difference exceeds 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 to the repeatability of measurement (Handcock et al., 2012). 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 (Figure 2). On average, the temperature difference variation remains below 0.8°C over the 100 km reach

Dampierre – Saint-Laurent-des-Eaux, except on the 29th of July 2002 (1.29°C) and on the 29th of May 2003 (2.3°C). The variation of the temperature difference is comprised between 0.0004°C.km^{-1} and 0.023°C.km^{-1} (mean of 0.0072°C.km^{-1}).

To assess the influence of the nature of the water pixels (pure or non-pure) on the estimated temperature, tests were carried out. 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 linear regression between temperature estimated with pure water pixels and temperature 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 dates, the slope of the regression line is 1, while it is 0.98 considering summer only and 0.72 considering winter only (Figure 3a; Figure 3b). The difference between the temperatures estimated from pure and non-pure water pixels usually remains 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 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 river width), the standard deviation of the observed temperature increases notably (

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Table 3Table 3). Peak temperature values along the longitudinal thermal profile may therefore in places where the main river branch is particularly narrow. This phenomenon is mostly due to the uncertainties inherent to the satellite sensor. Uncertainty is reduced by averaging. The more pixels are considered over a section, the lower the uncertainty is. The moving average over +-2 km that was applied to the data is therefore useful in lowering the uncertainty.

4.2 Longitudinal temperature profiles

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

In summertime, a mean decrease of 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 again from river kilometer 660 to 680 and then remains constant or decreases once more after river kilometer 680.

However, the temperature profiles differ between river kilometers 560 and 620, since the water temperature can either increase (29/05/2003 and 19/07/2010; Figure 3Figure 4b) or decrease (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 drop can appear downstream ofafter 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 followed by a rise in the temperature.

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

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

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

The groundwater discharge is estimated at 7 dates (winter and summer) along the same successive 11 Loire River sections, using respectively the heat budget and groundwater modeling~~two methods~~ (Figure 5~~Figure 5~~a). We found that the variability of the groundwater with the heat budget is much higher than 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}). Nevertheless, the modeled groundwater discharge always stay in the interval estimated by the heat budget. Overall, compared to the groundwater modeling, the heat budget tends to overestimate the groundwater discharge between river kilometers 640 and 660 in winter and to underestimate the discharge 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 calculated with the ~~groundwater~~ heat budget method between river kilometers 563 and 565. 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, this high discharge rate and high standard deviation is 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 $m^3.s^{-1}.km^{-1}$) and it shows a low standard deviation (respectively less than 0.4 $m^3.s^{-1}.km^{-1}$~~)~~ and less than 0.05 $m^3.s^{-1}.km^{-1}$).~~.~~

Further downstream, according to both methods, the groundwater discharge shows 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 positive at each date (comprised between 0.3 and 1.5 $m^3.s^{-1}.km^{-1}$) and it also corresponds to the location where the groundwater discharge is maximum according to the groundwater ~~budget method~~modeling (between 0.6~~5~~ and 0.9 $m^3.s^{-1}.km^{-1}$). The standard deviation of the groundwater discharge is high according to both methods (respectively 0.4 and 0.1 $m^3.s^{-1}.km^{-1}$).

~~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.~~The two methods give 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 estimated by the heat budget method. Theoretically, the estimated groundwater discharge should not be negative. However, in summertime, negative discharge values are especially computed when water temperature increases but when this increase cannot be explained by the atmospheric heat fluxes. In wintertime, negative discharge values can also be obtained when water temperature shows a decrease that cannot be explained by the atmospheric heat fluxes.

The absolute uncertainty in the groundwater discharge estimated by the heat budget remains under 0.4 $m^3.s^{-1}.km^{-1}$ over 75% of the time. Taking into account the uncertainty, we found that 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 therefore significant. On this river section, the groundwater discharge estimated with the heat budget is comprised between 2.8 $m^3.s^{-1}$ and 13.7 $m^3.s^{-1}$, while the groundwater discharge estimated through groundwater modeling varies 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 satellite TIR images. ~~Main sources of uncertainty come from~~The main factors are the satellite sensors, the atmospheric influence on the transmitted radiations (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 radiations 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~~ the upper 100 µm of the water body (skin layer), which may differ from the temperature from~~of~~ the entire water body (Torgersen et al., 2001).

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

The opposite phenomenon has regularly been observed using TIR satellite images. Wawrzyniak et al. (2012) found that TIR images overestimate 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 + 1.2°C mean temperature difference was found, when the water course width was over three image pixels and a + 2.2°C mean temperature difference when the width was comprised between 1 and 3 pixels. A mean temperature difference comprised between +1 °C and + 1.9°C was also found in another four Pacific Northwest rivers of the United States (Cherkauer et al., 2005).

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

Satellite based TIR images can therefore lead to either underestimation or overestimation of the water temperature. Depending on the time of the year, the shift can happen in both directions (Lamaro et al., 2013, De Boer, 2014).

Findings from this study confirm that the TIR images can lead to either overestimation or underestimation of the water temperature (Figure 2~~Figure 2~~). The biggest shift is observed on 29/07/2002, when the water temperature is maximum (> 26°C) and the flow 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 leads to a low water skin temperature.

The average temperature difference between TIR images and *in situ* measurements is similar to what had been observed in the previous studies (Handcock et al., 2006; Wawrzyniak et al., 2012), even though in this study non-pure water pixels are kept and no atmospheric correction is applied. Temperature estimation using non-pure water pixels from TIR image may therefore be more robust than is usually thought. However, this study also shows that difference 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 fromof 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 also plays a role, especially in parts where the Loire River is particularly narrow.

5.2 Longitudinal temperature profile and groundwater discharge estimation

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 that groundwater discharge is estimated on a large river, based on satellite TIR images. The comparison with the groundwater discharge estimated using a groundwater budgetgroundwater modeling over the successive catchment areas is also new, as Loheide and

Gorelick (2006) 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 uncertainty in flow measurements (20 %).

There are several sources of uncertainty in the groundwater discharge estimation using the heat budget. First, there is the uncertainty coming from the estimation of 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, river surface and river flow. We found that the resulting uncertainty in groundwater discharge estimate remains mainly below 0.4 $m^3.s^{-1}.km^{-1}$. Then, there are uncertainties inherent to the heat budget method used. Factors such as bed friction, heat conduction through the river bed, or hyporheic exchange are not considered. However, for that kind of slow flowing river, the influence of bed friction is assumed to be low, especially in summer (Evans et al., 1998). Similarly, heat conduction through the bed usually plays a minor role in the global 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 along the river is not taken into account in the heat budget either. As a result, the influence of the local atmospheric conditions over the river temperature tends to be slightly overestimated. Uncertainties are also attached to the groundwater discharge calculated usingwith the groundwater budgetmodeling. The modeling of the Loire River flow in Blois, Orleans and Gien over the 1996-2013 period works well nevertheless (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

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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 in the same order of magnitude asof the discharge calculated with the groundwater budgetusing groundwater modeling. At maximum, the groundwater discharge rate, estimated with the heat budget, overestimates, or underestimates, by less than 1 $m^3.s^{-1}.km^{-1}$ the discharge calculated by the groundwater budgetmodeling. The average groundwater discharge calculated by the groundwater budgetgroundwater modeling for the inter-annual period is always within the range of variation of the groundwater discharge estimated using the river heat budget. The shape of the estimated average groundwater discharge curve along the Loire River is also relatively close 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 be small (less than 0.3 $m^3.s^{-1}.km^{-1}$; Figure 5a), except for some dates around river kilometer 564. It is known that between river kilometers 610 and 625 the Loire River losesloses water through the Val d'Orléans karstic system (Alberic, 2004; Binet et al., 2011). This is also consistent with the results from the groundwater modeling. It should be noted that the high standard deviation of the estimated discharge near river kilometer 564 may be explained not only by real variations of the discharge rate, as highlighted by the groundwater budget, but also by the bias resulting from the small length of the corresponding section. 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 $m^3.s^{-1}.km^{-1}$).

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 between 0.3 and 1.5 $m^3.s^{-1}.km^{-1}$. We found that, taking into account the uncertainties, the groundwater discharge calculated by the heat budget always stay 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 is also identified by the groundwater ~~budget~~modeling (calculated discharge comprised 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 exchange rates estimated occur at times when~~re~~ the river flow decreases between two consecutive days, while the lowest exchange rate is estimated when the river flow increases (~~Figure 6~~Figure 7). Maximum groundwater discharge is also estimated in winter (13.5 $m^3.s^{-1}$ compared to 5.3 $m^3.s^{-1}$ in summer), when groundwater level is at its highest. It is consistent with the results from the groundwater modeling showing an average discharge of 7.6 $m^3.s^{-1}$ in wintertime and 6 $m^3.s^{-1}$ in summertime. It is known that temporal changes in river water level can lead to important modifications in exchange rates and exchange directions (Sophocleous, 2002). During a rise in river water level, water from the river can flow into the lateral aquifer while the opposite phenomenon happens at low river flow. Thus, the variation in estimated exchange rates is likely to have a physical basis. An exchange rate of 11.5 to 12.5 $m^3.s^{-1}$~~m³/s~~ was calculated at la Chapelle Saint-Mesmin (river kilometer 642), using geo-chemical tracers during the summer 1986 (Gonzalez, 1991). It is higher than the maximum groundwater discharge estimated in 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 images allow to locate the main groundwater discharge area precisely, along the right bank

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of the Loire River and 2 to 3 kilometers upstream from the confluence with the Loiret (Figure 8).

On the downstream part of the Loire River, between river kilometers 650 and 680, 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. This is consistent with the findings from Schomburgk et al. (2012). However, 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 time could explain why the river temperature may either increaserise or decreasedrop 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 atmospheric data available do not offer a satisfactory explanation for this phenomenon. The influence of warm water discharges from the nuclear power plant on the longitudinal temperature profile is not noticeable either, as no sudden temperature rise is observed at the nuclear plant locations. In the case of Saint-Laurent des Eaux, warm water discharges may nevertheless contribute for some part to the global temperature rise observed between river kilometers 670 and 680 (Figure 3Figure 4a; Figure 4Figure 4b), but the temperature rise begins power plant. Similarly, no sudden temperature variations could be explained by weirs across the river course and changes in the river slope (less than 0.1°C change between the 1 km 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 probably by the low spatial resolution of the satellite TIR images. Landsat images were also taken around 12h LT and thermal stratification may be expected to be more important later during the day.

6 Conclusion

Temperatures of the middle Loire River were estimated using Thermal InfraRed (TIR) Landsat images. With no atmospheric correction considered and taking into account non-pure water pixels, temperature differences, between *in situ* observation and TIR images based estimation, 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 images even when river width falls below the three pixels' width threshold (i.e. < 180 m). However, the river temperature can be seriously underestimated at low flow and when water temperature is high (difference 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 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 similar according to 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 wintertime (13.5 m^3./s^{-1}) than in summertime (5.3 $m^3.s^{-1}$$m^3$/s). It is consistent with the results from the groundwater modeling showing an average discharge of 7.6 $m^3.s^{-1}$ in wintertime and 6 $m^3.s^{-1}$ in summertime. It The groundwater discharge is also found to be higher when the Loire River flow decreases between 2 consecutive days. Our TIR images underline that instantaneous groundwater discharges are highly variable with time. Therefore, average discharge is not sufficient to predict the observed changes in water temperature along the river course.

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To assess the consistency and robustness of the results, further studies could be conducted using more sophisticated modellling of both the groundwater discharge and the stream temperature.

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Table 1. Loire River temperature, air temperature and river flow at the date and hour 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 fluxes calculations.

Solar radiations	RS estimated from the SAFRAN database	
Atmospheric radiations	$RA =$ $\sigma.(T_a + 273.15)^4.\left(A + 0.031.\sqrt{e_a}\right).(1 - R_L)$	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 estimated from the SAFRAN database
Emitted radiations	$RE = \varepsilon.\sigma.(T_w + 273.15)^4$	$\varepsilon = 0.98$ water emissivity T_w (°C) mean water temperature on the section estimated from the thermal 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 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 $e(V) = 0.0025 * (1 + V_2)$ is 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	$CE = L(T_w).\rho_a.e(V).(Qw - Qa)$	$L(T_w) = (2500.9 - 2.365.T_w).10^3 J.kg^{-1}$ Is the latent evaporation heat

		$$Qw = \frac{4.596.\, e^{\frac{237.3*T_w}{237.3+T_w}}}{1.22}$$ 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 deviation is calculated at sections with either under 20 water pixels in the section 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

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) at each date. The dates are classified according to the air temperature at the time when the images are taken (air temperature rises from the 15/11/2001 to the 29/07/2002).

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

Figure 4. A: Loire temperature profiles in wintertime extracted from TIR images. ~~For each~~ temperature profiles in summertime extracted from the TIR images. For each profile data were centered.

Figure 5. A: Groundwater discharge per sections 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 heat budget. B: Calculated groundwater discharge along the Loire River in 15/11/2001 using groundwater modeling and 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 the TIR image.

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.