Thermal-infrared remote sensing of surface water–groundwater exchanges in a restored anastomosing channel (Upper Rhine River, France)

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Funding information
European Community, Grant/Award Number: LIFE08 NAT/F/00471; City of Strasbourg; University of Strasbourg and French National Center for Scientific Research (IDEX-CNRS) 2014 MODELROH project, specific CNRS applications; ZAEU (Zone Atelier Environnementale Urbaine – LTER).

Abstract
Ecological processes are a key element to consider in functional river restorations. In the framework of a LIFE+ European restoration program, we have investigated the potential for airborne thermal-infrared remote sensing to map surface water–groundwater exchanges and to identify their driving factors. We focused our attention on anastomosing channels on an artificial island of the Upper Rhine River (Rohrschollen), where a new channel was excavated from the floodplain to reconnect an older channel in its upstream part. These hydraulic engineering works led to an increased inflow from the Rhine Canal. Here, we propose an original data treatment chain to (a) georeference the thermal-infrared images in geographic information system based on visible images, (b) detect and correct data errors, and (c) identify and locate thermal anomalies attributed to groundwater inputs and hyporheic upwellings. Our results, which have been compared to morpho-sedimentary data, show that groundwater upwelling in the new channel is controlled by riffle–pool sequences and bars. This channel is characterized by large bedload transport and morphodynamic activity, forming riffles and bars. In the old channel, where riffle–pool sequences no longer exist, due to impacts of engineering works and insufficient morphodynamic effects of the restoration, thermal anomalies appeared to be less pronounced. Groundwater inputs seem to be controlled by former gravel bars outcropping on the banks, as well as by local thinning of the low-permeability clogging layer on the channel bed.

KEYWORDS
airborne thermal-infrared (TIR) remote sensing, functional restoration, hydromorphology, hyporheic processes, Upper Rhine anastomosing channel

1 INTRODUCTION

Stream temperature is a key parameter in many river studies for characterizing the ecological functioning of fluvial systems (Angilletta, 2009; Magnuson, Crowder, & Medwick, 1979; Ward, 1992; Webb, Hannah, Moore, Brown, & Nobilis, 2008). The thermal regime of fluvial systems is driven by heat flow between solar radiation, channel water, sediments, groundwater, and riparian vegetation modified by air temperature, humidity, and wind speed (Caissie, 2006; Poole & Berman, 2001; Poole, Stanford, Frissell, & Running, 2002). Longitudinal stream temperature patterns are generally linked to climate gradients, channel size, and riparian vegetation-induced shadow patches (Acuña & Tockner, 2009; Bornette, Amoros, & Lamouroux, 1998; Hancock et al., 2006; Malard, Mangin, Uehlinger, & Ward, 2001; Poole & Berman, 2001; Torgersen, Price, Li, & McIntosh, 1999; Verneaux, 1977). This explains why, in most cases, tributaries feed relatively cold water into larger channels (Dugdale, Bergeron, & St-Hilaire, 2013; Wawrzyniak et al., 2016).

At a finer spatial scale, geomorphically controlled features of surface water–groundwater exchanges and riparian shade (Broadmeadow, Jones, Langford, Shaw, & Nisbet, 2011; Namour et al., 2015) induce thermal heterogeneities of surface water that control the spatial distribution of thermal habitats and the diversity of ecological functioning (Bernt & Dodds, 2005; Breil, Lafont, Vivier, Namour, & Schmitt, 2007; Hannah, Malcolm, & Bradley, 2009; Lafont, 2001; Schmitt et al., 2011; Stanford, Hauer, & Ward, 1988).
Groundwater inputs are generally confined to sections of gravel bars and downstream sections of riffles or steps, in riffle–pool or step–pool sequences, respectively (commonly referred to hyporheic upwelling when used at this scale; Boulton, Findlay, Marmonier, Stanley, & Valett, 1998). Groundwater inputs can also be enhanced in channel banks and/or bottoms by the presence of coarse sediments, where hydraulic conductivity is relatively high (Brunke & Gonser, 1997; Cardenas, Wilson, & Zlotnik, 2004; Packman & MacKay, 2003; Poole, Stanford, Running, & Frissell, 2006). Temporal dynamics of groundwater inputs are linked to the hydrological cycle, including the relative variations between groundwater and surface water levels (Burkholder, Grant, Haggerty, Khangaoankar, & Wampler, 2008; Constantz, Thomas, & Zellweger, 1994; Westhoff et al., 2007).

For most aquifers in temperate zones, groundwater is warmer than surface water in winter and vice versa in summer (Caisse, El-Jabi, & Hebert, 2007; Lyons, Wang, & Simonson, 1996; Malard et al., 2001; Poirel, Lauters, & Desaint, 2008; Torgersen, Faux, McIntosh, Poage, & Norton, 2001). During summer, groundwater inputs may provide thermal refuges for many stenothermal coldwater species such as salmonid fish. This cooling effect is particularly important for these species during heat waves (Burkholder et al., 2008; Dugdale, Bergeron, & St-Hilaire, 2015; Tockner, Paetzold, Karais, Claret, & Zettel, 2006; Tonolla, Acuña, Uehlinger, Frank, & Tockner, 2010; Torgersen et al., 1999). Cool thermal refuges are therefore increasingly important in the context of future climate change (Arnell & Reynard, 1996; van Vliet, Ludwig, Zwolsman, Weedon, & Kabat, 2011).

Conventional stream temperature surveys are based on in situ thermal sensors. Although they are well suited to monitor surface water temperature over time (Broadmeadow et al., 2011; Pfister, McDonnell, Hisler, & Hoffmann, 2010; Torgersen et al., 1999), they reflect rather poorly spatial heterogeneities in surface water temperature (Cardenas, Harvey, Packman, & Durelle, 2008; Tonolla et al., 2010). To overcome this spatial limitation, we use airborne thermal-infrared (TIR) remote sensing for nearly 2 decades on river stretches extending up to 60 km (Torgersen et al., 2001). This approach is increasingly used in ecology and hydrology, notably to infer groundwater inputs (Loheide & Gorelick, 2006) from thermal anomalies. The latter can be natural, like thermal refuges driven by groundwater inputs (Dugdale et al., 2013, 2015; Torgersen et al., 1999; Wawrzyniak, Piégay, Allemand, Vaudor, & Grandjean, 2013; Wawrzyniak et al., 2016), or induced by human activities like inputs of warm water by nuclear power plants (Chen, Shi, & Mao, 2003; Fricke & Baschek, 2015). In order to exploit the full potential of TIR imagery, we develop specific data processing techniques for extracting, spatializing, and assessing the uncertainty of the generated datasets (Handcock et al., 2006).

Most airborne TIR-based studies have focused on main river channels that were typically between 20 and 500 m wide (Dugdale et al., 2013; Handcock et al., 2006; Wawrzyniak et al., 2016). Although tributaries of large rivers are commonly assumed to be thermal refuges in summer, their detailed longitudinal stream temperature patterns remain poorly documented. For small-sized aquatic environments (20–30 m), such as anastomosing channels corresponding to an old disconnected channel with a high-clogging rate and low-morphodynamic activity (Makaske, 2001; Makaske et al., 2009; Schmitt et al., 2016), it is necessary to develop specific methods for dealing with shadow induced by riparian vegetation, as well as disturbance caused by logjams.

Ecohydrological processes are a key element in functional river restoration projects (Descloix, Datry, Philippe, & Marmonier, 2010; Johnson, 2005). However, studies on surface–groundwater exchanges in post-restoration monitoring programs are rather scarce (e.g., Poole & Berman, 2001). Here, we present results from a European LIFE+ restoration program (European’s financial instrument supporting environmental, nature conservation, and climate action projects) of an anastomosing channel network of the Upper Rhine River. The floodplain was excavated to create a “new channel” upstream of an “old channel,” leading to an increased inflow from the Rhine Canal.

We target a better mechanistic understanding of the spatial distribution of groundwater inputs (which refers to both groundwater and hyporheic upwellings). More specifically, we hypothesize that (a) in the new channel, groundwater inputs are induced by riffles and bars; (b) in the old channel, they are controlled by former gravel bars outcropping on the banks as well as local thinning of the clogging layer at the channel bottom. To test these hypotheses, we searched for thermal anomalies along the studied channels and investigated how their spatial distribution maps the hypothesized controlling factors. We compared and discussed the spatial distribution of groundwater inputs between (a) the new channel, characterized by active morphodynamics, bedload transport or deposition, and a high-geomorphological diversity (bars and riffles), and (b) the old channel, which is marked by relatively inactive morphodynamics, a sediment-clogged channel bed, and a poor geomorphological diversity due to impacts of engineering works.

2 | STUDY AREA

The Rohrschollen is an artificial island and wildlife park that is located 8 km southeast of the city of Strasbourg (Figure 1a). It has been built and reshaped through three successive engineering projects (consisting of correction, regularization, and canalization) that first started at the beginning of the 19th century (Zimmermann, 2012; Figure 1b and 1c). The third and last project as of today was carried out in the vicinity of our study area in 1970. It consisted of the construction of a diversion dam and an artificial channel (Rhine Canal) with a hydropower plant and a lock (Figure 1c). Most of the discharge is diverted into the Rhine Canal, except when floods exceed 1,550 m³·s⁻¹. In that case, the discharge surplus is directed to the normally by-passed old Rhine River (250 m width). As a consequence of the canalization, the main anastomosing channel of the island, whose width is about 30 m, is disconnected upstream. An agricultural dam was built in 1984 on the old Rhine River in order to raise the groundwater level for agricultural irrigation (top of Figure 1c). Moreover, the dam is also used for flood retention purposes when the discharge exceeds 2,800 m³·s⁻¹ (i.e., 2-year peak discharge). The backwater of this dam fills both the old Rhine River and the old channel. The water level is consequently
very stable in this channel. Groundwater inputs estimated by flow accretion gauging reach 0.1 m$^3\cdot$s$^{-1}$. In this context, aquatic and riparian habitats were heavily impacted and alluvial communities (floodplain vegetation, aquatic macrophytes, and macroinvertebrates) were on the decline on the island, as well as in numerous other side channels of the Rhine (Meyer, Combroux, Schmitt, & Trémolières, 2013).

In 2012, the city of Strasbourg started a European LIFE+ project to restore specific fluvial biocenosis, hydromorphological, and ecological processes, such as bedload transport, channel dynamics, surface water–groundwater exchanges, and renewal of pioneer alluvial ecosystems. For us to achieve these objectives, the old channel was reconnected to the Rhine Canal by a large floodgate (8 m wide), and a new upstream channel (900 m long) was excavated on the southern part of the island (Figure 1c). Water inflow to the new channel ranges between 2 and 80 m$^3\cdot$s$^{-1}$, depending on the discharge of the Rhine River. A scientific monitoring program focusing on hydraulics, hydrology, fluvial morphology, hydrogeology, and ecology has been designed in order to assess the effectiveness and the sustainability of the restoration measures. Although the results of TIR remote sensing are presented and discussed below, other pre- and post-restoration monitoring is not shown.
3 | MATERIAL AND METHODS

3.1 | Historical analysis

We used historical maps to reconstruct the temporal evolution of our study site. We coupled this information with a sedimentological survey to improve the understanding of current morpho-sedimentary characteristics and assess the potential benefits of the restoration in the future. We used the 1838 map to locate former gravel bars that partially compose the current banks of the old channel (Figure 1b). Some bars of coarse sediment have probably been deposited on the downstream section of the old channel during an 1852 flood (Champion, 1863; Conrad, 2011; 300-year peak discharge).

3.2 | Image acquisition

Airborne TIR images were acquired over the new and old channels using a FLIR b425 infrared camera. This device is composed of two lenses operating respectively in the 7.5–13 μm wavebands and in the standard RGB bands. The camera was fixed under a powered paraglider to acquire images close to the nadir and reduce reflected radiation from the surrounding terrestrial environment. Visible images (2048 × 1536 pixels) covered a ground area two times larger than TIR images (360 × 240 pixels) with a 25° × 19° field of view. The thermal sensor was calibrated using the water emissivity, the atmospheric conditions, and the height above the river channel. The FLIR thermal system accuracy is ±2% of temperature measurement with a sensitivity less than 0.05 °C at 30 °C. Thermal and visible images were recorded at a rate of 20 s/frame.

The aerial survey took place January 22, 2015, when the tree canopy extension was minimal and a high-thermal contrast prevailed between surface water (~4 °C) and groundwater (~10 °C). The flight was scheduled between 12:40 (start) and 13:30 (end), when air temperature was highest (2.8 °C). Due to atmospheric turbulence near the canopy, the powered paraglider had an altitudinal operating range of 250 m above the river and an average speed of 30 km/h. According to the flight parameters and trigger frequency of the thermal camera (3 pictures/min), the expected image overlap of 30% could not be achieved. For us to avoid any loss of data, two flyovers targeted each of the 3.8 km stretches of the two channels. The sensor provided ground pixel resolutions of 5.4 cm for the visual images and 34.6 cm for the thermal imagery.

3.3 | Image processing

Our image-processing chain (Figure 2) consisted of converting and validating TIR data, thermal mapping of the water surface, removing contaminated thermal pixels, and finally identifying and locating thermal anomalies.

We converted radiance values of each TIR pixel to temperature using Planck’s law within FLIR ThermaCAM Researcher software (FLIR, 2010). We extracted radiant temperatures from the TIR image frames and exported them as an array of thermal values. Next, we used a MATLAB script (MathWorks, R, 2011b) to transform the exported files (.mat) in raster format (.tiff), suitable for georeferencing in a geographic information system (GIS; ESRI ArcMap v.10.3). In order to validate the remotely sensed water surface temperatures, we compare the TIR image-derived radiant water temperatures to in situ measurements of water temperature obtained from instruments deployed for hydraulic and hydrogeologic monitoring purposes.

Seven OTT Orpheus Mini water level loggers measuring water temperature at 5 min intervals with ±0.05% accuracy were installed at fixed intervals along each transect of the old channel. The loggers were put on the left bank at a depth of 0.7 m ± 0.1 m, depending on local and technical constraints. Temperature data recorded during the airborne survey were downloaded and compared to the river surface temperature extracted from the corresponding images. Due to the low-flow conditions (~2 m³·s⁻¹) and the absence of turbulences required to mix water in the old channel, a vertical thermal stratification of the water column prevailed during our survey. TIR data were 2.3 °C ± 0.3 °C cooler than water temperatures measured by in-stream loggers. Even if absolute temperatures are significantly different, we used a linear regression to assess the relationship between TIR and in situ data. A good correlation was observed with an $R^2$ value of 0.86 ($n = 9$).

We georeferenced the images taken in the visible range by using the ground control targets (Figure 2a) and additional control points identified on aerial photos from the BD ORTHO® base layer (BD ORTHO® 2013 from the National Geographical Institute). Coordinates of the center of these targets were measured using a real-time global navigation satellite system (RTK-GNSS) with an accuracy of 2–3 cm. During post-flight image processing, thermal and visible image pairs were automatically overlain in GIS. Applying an affine transformation, geographical coordinates of the TIR images were calculated in a MATLAB script using coordinates for the corresponding visible images. The computer program was calibrated by superimposing a thermal image over a visible image above the hydropower plant of Strasbourg, which has characteristic heat sources. The water temperature increased during the aerial survey, and we observed thermal contrasts between overlapped images triggered at different times. In order to extract a longitudinal temperature profile independent of temporal thermal variations, we separate TIR data into four groups corresponding to each overflight.

3.4 | Image analysis

We used visible images to digitize terrestrial objects (bank vegetation, logjams, and bars) and to isolate water pixels on TIR images. The proportion of mixed pixels contaminated by terrestrial objects depends on TIR pixel sizes and stream widths (Handcock et al., 2006). The surface water temperature accuracy is degraded when the number of pixels across the river width is less than 10 (Torgersen et al., 2001; Figure 2a). In order to discriminate “pure” water pixels, a buffer zone of 1 m (~3 pixels) around terrestrial objects was created (Figure 2b).

By this procedure, we discarded mixed pixels and eliminated narrow river sections (i.e., ≤7 pixels).

Longitudinal temperature profiles were extracted from TIR images (Figure 2c) by selecting the pixels with highest temperatures along the channels (Figures 3a and 5a). This helped minimizing the influence of lateral temperature evolution that depends of the number of “pure” water pixel. To take into account the temporal stream...
temperature increase during the survey (0.60 °C in the new channel and 0.76 °C in the old one), we extracted a longitudinal temperature profile for each overflight image sequences. In order to compensate for missing data, we manually matched the four temperature curves with a MATLAB graphic user interface. The first flyover served as a thermal profile reference, from which temperature differences with the three other flyovers were subtracted. This script was developed to compare stream temperature variations with hydrological, morphological, and sedimentological data. For us to improve this comparison, a thermal baseline was drawn by connecting mean temperature on the upstream part of the new channel with the mean temperature on the downstream part (Figure 3b). On the old channel, the mean temperature recorded over the lentic sector upstream of the confluence with the new channel was considered without temperature disturbance (e.g., inputs from the new channel), and the thermal baseline was extrapolated all along this channel (Figure 5b).

Links with the new channel morphodynamics are also enhanced by taking into account the thalweg longitudinal evolution from 2014 to 2015 (Figure 3b) and bedload transport that was tracked with passive integrated transponders (Lamarre, Mac Vicar, & Roy, 2005; Figure 3c). Statistical distribution of thermal pixels was analyzed using the histograms of pixel frequency to discriminate positive thermal anomalies (Wawrzyniak et al., 2013). Thermal images have been color coded to visually enhance spatial patterns of water temperature, and the identified thermal anomalies were digitalized in a GIS.

3.5 | Statistical analysis

To highlight the relationship between the rise in surface water temperature near bars and riffles, we calculated the residuals between the mean temperature curve of the four flyovers and the straight trend line (Figure 4). As bars and riffles are located on the same reaches, we grouped them in a single geomorphic unit called “bar/riffle” (Figure 4). The assumption of the nonrandom distribution between the residuals and the presence or absence of bar/riffle has been analyzed by the nonparametric Wald-Wolfowitz Runs Test (Wald & Wolfowitz, 1940). The binary logistic regression was used to test the quality of the adjustment and the prediction performance. Statistical computations were performed with the software TANAGRA 1.4.50 (Rakotomalala, 2005).
RESULTS

4.1 Thermal variations in the new channel

We observed a longitudinal temperature decrease from 3.8 to 2.5 °C (Figure 3b). This overall cooling trend exhibits four relatively important and regular thermal variations (of about 0.6 and 0.8 °C), which appear strongly linked to riffle geomorphic units and bars. At a more detailed spatial scale, these large thermal anomalies contain several thermal peaks, which appear to be located next to riffles and bars that are particularly large.

A thermal anomaly (with a positive thermal contrast of about 0.3 to 0.4 °C) occurs over a channel section that spans from 240 to 270 m downstream. This hot spot is located in the vicinity of a large active bar that crosses almost the entire channel width. In addition, a riffle is attached to this bar (Figure 3a and 3b). The main thermal peak (observed at 255 m), with a relative temperature increase of about 0.25 °C, is located at the lower end of the riffle (Figure 3b).

Another thermal anomaly extended over a 75-m channel stretch (between downstream locations 400 and 475 m) and presents a positive thermal contrast of about 0.7 °C. In the middle of this reach, data were missing (between locations 430 and 445 m), due to pixel contaminations by bars that were reducing the channel width. We observed a first thermal peak (~0.2–0.3 °C) between locations 410 and 420 m, at the downstream part of the riffle (Figure 3b) and left of a lateral bar attached to the right bank (Figure 3a1). A second anomaly peak (0.4 °C) was located at location 455 m, just downstream of the second riffle, between bars located on each bank.

A third large thermal anomaly was observed between downstream locations 650 and 740 m, with a thermal contrast of approximately 0.5 °C. It presented several peaks located at 670 (0.35 °C), 690 (0.35 °C), 710 (0.1 °C), and 725 m (0.1 °C). The first peak
begins downstream of a convex bar. The second peak is located downstream of the main riffle and between two lateral bars. The two next peaks were located next to a lateral bar attached to the right bank (Figure 3a2).

The last large anomaly was located between 830 and 980 m downstream (Figure 3b) and presented a thermal variation of 0.8 °C. A lot of data were missing for this channel stretch due to pixel contaminations by logjams and bars that were reducing the channel width. This anomaly was located in the downstream parts of riffles and near bars. Moreover, we also observed some decreases in water surface temperature (0.1–0.15 °C) upstream of riffles at channel locations 245, 425, and 670 m (Figure 3b).

Bedload dynamics (Figure 3c) indicate that the formation of riffles and bars, which are strongly linked, is clearly induced by bedload transport and deposition. Because bedload transport took place over distances of 30 m on average, deposits (i.e., bars and riffles) were found on and just downstream of the bending reaches of the channel. At the scale of the entire new anastomosing channel, bank erosion, bedload transport, and deposition generated a general aggradation of the channel bottom (Figure 3b) and, above all, a drastic diversification of the channel morphology.

To test the hypothesis that the surface water temperature increases near bars and riffles that were due to groundwater inputs, we compare the residuals (i.e., temperature differences) with the longitudinal temperature distribution of bar/riffle reaches. Figure 4a shows that the maximum temperature is reached in the middle or in the downstream part of the bar/riffle reaches. In contrast, temperature is lower in the sector without bars and riffles. The Wald-Wolfowitz Runs Test (n = 1736) highlights the nonrandom distribution of the temperature in the channel, at a high-significance threshold of 5% (p value = 0.0075). Results of the binary logistic regression test indicate the quality of the adjustment between the presence or absence of bars and the temperature, with a good ranking rate of 59.33%. This result shows a significant relation between the temperature and the presence or absence of bar/riffle, as shown by the box plot (Figure 4b; see discussion).

4.2 Thermal variations in the old channel

The 1828 map reveals that the upstream reach of the current “old channel” corresponded to the thalweg of the Rhine River at that time (Figure 1b and 1c). The correction works that took place from 1838 to 1872 caused a substantial disconnection between the Rhine River and the old channel. Surface water–groundwater exchanges likely declined gradually as a result of sandy–silty sediment deposition and subsequent channel bed clogging and narrowing.

The longitudinal temperature profile of the old channel was less impacted by missing data than that of the new channel (Figure 5b). Unlike the new channel, the longitudinal temperature trend of the old channel presented no repeated variations correlated with the channel morphology (bars and riffles), and the thermal baseline remained relatively constant at 1 °C (except after 1,050 m). Nevertheless, the longitudinal temperature profile exhibited large contrasts that served for the definition of a thermal-based sectorization.

The first sector extended from 0 to 150 m on the upstream part of the channel and up to the confluence with the new channel (Figure 5b-I). Temperatures varied from about 1 to 2 °C. The temperature increased rapidly from 100 to 150 m due to the influence of the new channel confluence. Two thermal peaks were also identified, at the distances of 10 and 50 m, with thermal contrasts of about 0.2 to 0.4 °C.

The second sector extended from locations 150 to 500 m downstream (Figure 5b-II). It was characterized by relatively high temperatures (max. of 2.2 °C) downstream of the water inflow from the new channel. Downstream of a 2.1 °C thermal plateau extending from 150 to 250 m, temperatures dropped by 1.3 °C. A positive anomaly peak was located at 400–420 m downstream with a thermal contrast of 0.3 °C.
We identified a third sector located between 500 to 1,050 m downstream (Figure 5b–III). Despite a general drop in water surface temperatures from 1.3 to 1.0 °C due to the general tendency to a thermal decrease downstream, this reach presented a very high-thermal variability, as shown both by the longitudinal temperature profile and the presence of thirteen positive thermal peaks (Figure 5a) with a range of about 0.4 to 0.6 °C. A positive thermal anomaly (+0.4 to +0.5 °C) extended over a long stretch located between 520 to 840 m downstream. Thermal peaks located between 630 and 840 m were particularly well identifiable during the first flyover, with a thermal contrast of about 0.2 °C and a strong drop of about 0.3 °C (840 m).

The last sector is located between 1,050 m and the confluence with the old Rhine River (Figure 5b–IV). This sector shows a gradual increase in temperature that corresponds to a thermal-mixing zone with high temperature (up to 3 °C) contributions from the old Rhine River. Two main positive anomalies are identified at 1,100 and 1,570 m with a thermal contrast of about 0.2 °C and a strong drop of about 0.3 °C (840 m).

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The gradual decrease in surface water temperatures from 3.8 to 2.5 °C along the new channel, as shown by the thermal baseline decline (Figure 3b), is driven by heat exchanges between the water surface and the colder atmosphere. This effect had previously been reported (see, e.g., Hannah, Malcolm, Soulsby, & Youngson, 2004), but in our case, this heat dissipation is enhanced by the small size (width and depth) of the channel. At a smaller spatial scale, the heat dissipation effect was 0.03 to 0.1 °C larger upstream of certain riffles (at downstream channel locations 240 and 675 m). Around these locations, water was shallow and turbulence was high. This shallow effect has also been documented by Evans and Petts (1997).

Extensive positive thermal anomalies (from 0.3 to 0.8 °C) occurred preferentially on, or slightly downstream of, coarse sediment deposits, corresponding to riffles and lateral bars. Our statistical analysis of the

5 | DISCUSSION

5.1 Factors controlling the spatial distribution of thermal signatures along a morphodynamic anastomosing channel (new channel)

The gradual decrease in surface water temperatures from 3.8 to 2.5 °C along the new channel, as shown by the thermal baseline decline (Figure 3b), is driven by heat exchanges between the water surface and the colder atmosphere. This effect had previously been reported (see, e.g., Hannah, Malcolm, Soulsby, & Youngson, 2004), but in our case, this heat dissipation is enhanced by the small size (width and depth) of the channel. At a smaller spatial scale, the heat dissipation effect was 0.03 to 0.1 °C larger upstream of certain riffles (at downstream channel locations 240 and 675 m). Around these locations, water was shallow and turbulence was high. This shallow effect has also been documented by Evans and Petts (1997).

Extensive positive thermal anomalies (from 0.3 to 0.8 °C) occurred preferentially on, or slightly downstream of, coarse sediment deposits, corresponding to riffles and lateral bars. Our statistical analysis of the
residual data has shown that temperature rises near bars and riffles (Figure 4a). However, the box plots showed a high variability in min or max data and at 25th or 75th percentiles, especially for the bar/riffle “present” box plot (Figure 4b). This variability was probably due to the response time needed for thermal anomalies to mix and cause a warming effect at the surface of the water and (b) to the smoothing of thermal data based on temperature averages from the four flyovers.

Sediment deposition from 2014 to 2015 was fed by lateral erosion of coarse-sediment dominated banks. The diversification of the channel morphology affects the vertical dimension (higher variability of the channel bed longitudinal profile and increase of elevation amplitude between riffles and pools), as well as the nadir view dimension (formation of numerous bars and active bedload transport; Figure 3c). It appears clearly that this morphological channel diversity controls active surface-water–groundwater exchanges, which is observable by the spatial distribution of thermal anomalies (Figure 3a1, a2, a3), as it has also been noted by Acuña and Tockner (2009) and Burkholder et al. (2008).

Moreover, bars and riffles of the channel are largely composed of pebbles and gravels. These coarse sediments exhibit a rather high-hydraulic conductivity, compared to finer sediments (Burkholder et al., 2008; Evans & Petts, 1997; Namour et al., 2015; See, Armitage, & Dawson, 1999; See, Newson, & Thorne, 2003). This explains why the hyporheic fluxes are particularly large in this kind of geomorphological unit (Bencala, 2006; Cardenas et al., 2004; Evans, Greenwood, & Petts, 1995; Hannah et al., 2009; Mouw, Tappenbeck, & Stanford, 2014; Nielsen, Lise, & Ozaki, 1994; Wawrzyniak et al., 2016).

5.2 Factors controlling the spatial distribution of thermal signatures along a large stable anastomosing channel (old channel)

The old channel had less missing data than the new channel. Given that the channel is larger, only a few pixels were contaminated by bank vegetation and logs/jams. Unlike the new channel, the thermal baseline of the old channel remained at a constant level of approximately 1 °C. The heat exchange with the atmosphere was notably low because the channel has a mean width of 31 m and a mean water depth of 2 m (whereas these parameters were 7.5 and 0.29 m in the new channel, respectively). Water velocity was lower (0.04 and 0.18 m/s in the old and new channels, respectively), and little water turbulence was observed, given the absence of riffles. All of these features explain why the intensity of the thermal anomalies was less pronounced (average of 0.3 °C vs. 0.5 °C) in the old channel compared to the new channel.

Contrary to the new channel, the old one had not undergone any morphological adjustments following the restoration (such as bank erosion inducing repetitive sediment deposition of riffles and lateral bars). This is due to its considerable size, its very low slope (less than 0.1%), and the fact that during floods, a large part of the discharge is derived in the floodplain (Piasny, 2016). Furthermore, the restoration did not remove the clogging (consisting of silt, clay, and sand) at the bottom of this channel.

Considering these morphodynamic characteristics and given also the historical evolution of the channel (Figure 1b), the spatial distribution of positive thermal anomalies, representing groundwater inputs, appears to be controlled by two main morpho-sedimentary features: (a) outcropping on the channel banks of former bars composed of coarse sediments and (b) local thinning of the fine-grained sediment clogging at the channel bottom. Below, we present some additional secondary controlling factors.

As shown in Figures 1b and 5, large bars, which are composed of coarse sediments like pebbles and gravels, were deposited at the beginning of the correction works (1838) on each side of the former Rhine thalweg (corresponding to the current old channel). At some locations of the old channel banks, we observed outcrops of gravel or pebble bars. They correspond to areas characterized by higher hydraulic conductivity that enhance groundwater inputs (thermal peaks located between 630–840 and 990 m). Otherwise, thermal peaks in the first thermal-based sector (0–10 and 50 m) seem to relate to groundwater inputs from the upstream stretch of the old channel. As a consequence of the construction of the Rhine canal, the old channel is no longer visible in this area. However, a paleo-channel with its bottom composed of coarse sediments (with high-hydraulic conductivity) still exists under the Rhine Canal. Groundwater inputs increased in the upstream part of the old channel due to infiltration of water from the Rhine Canal. These different results show that groundwater fluxes are not uniform in a floodplain but are driven, among other things, by stratigraphic units of coarse sediments where hydraulic conductivity is higher than in finer sediments. These units correspond to bars and bottoms of paleo-channels. Identifiable by historical and sedimentological studies, they correspond to groundwater inputs when they are in contact with the current channel. These areas may also play an important role in river hydro-ecology (Bencala, Gooseff, & Kimball, 2011; Bolève, Revil, Janod, Mattiuzzo, & Jardani, 2007; Mouw et al., 2014; Revil, Cary, Fan, Finizola, & Trolard, 2005; Ruehl et al., 2006; Schmitt, Maire, Nobéis, & Humbert, 2007; Schmitt et al., 2011; Ward, 1989).

A second factor controlling positive thermal anomalies representing groundwater inputs in the old channel is the thickness of fine sediment clogging layer (silt, clay, and sand) at the channel bottom. Fine sediment deposition resulted from the lateral contraction of the channel after the correction works (1838 and 1872) on the Rhine River (except near the outcrops of coarse sediments mentioned above), but also from the backwater effect upstream of the agricultural dam. Indeed, during floods, it induces a deposition of the suspension load into the old channel. Channel bottom clogging is at thinnest when the gravel layer is shallow—corresponding probably to former riffles of the Rhine River that had formed prior to the correction works. These sectors present positive thermal anomalies revealing groundwater inputs, as at 400–420, 1,570, and probably 920 m. This type of link between surface water–groundwater exchanges and channel bottom clogging has also been documented by Brunke and Gonser (1997), Packman and MacKay (2003), and Poole and Berman (2001).

Many authors and especially Dugdale et al. (2013) and Wawrzyniak et al. (2016) observed the confluence effect on the thermal patterns, as shown by the effect of channel water mixing with cold water from a small lateral tributary located at 300 m in the old channel (Figure 5a). The very low flow in this lateral channel, as well as its small size, explains the low temperatures resulting from increased contact time with cold air and lower thermal inertia in this small volume of water. At the opposite, the regular thermal rise downstream of
1,050 m is induced by mixing of water from the old Rhine River with contributions from the old channel, as well as the backwater effect upstream of the agricultural dam.

Finally, a local effect controlling thermal decrease is observed on logjams (e.g., at 840 m). This can be explained by the fact that logjams locally reduce the flow velocity, which eventually favors energy exchanges with the atmosphere (Nielsen et al., 1994).

5.3 Outlook on future research avenues and methodological recommendations

Thermal heterogeneity is being increasingly surveyed by TIR remote sensing (Dugdale et al., 2013, 2015; Handcock et al., 2006; Torgersen et al., 2001; Wawrzyniak et al., 2013, 2016; Webb et al., 2008), but studies focusing on upwelling processes controlled by riffle–pool sequences (Boulton et al., 1998), particularly in small morphodynamic anastomosing channels, are scarce. Although these are of great importance in the ecological functioning of aquatic and riverine ecosystems (Descoux et al., 2010; Johnson, 2005), IR thermography is rarely carried out on restored rivers for assessing whether geomorphological restoration has stimulated active surface water-groundwater exchanges.

Mainly due to the influence of bars and riparian vegetation, understanding the fragmentation in water temperature patterns measured with airborne TIR over small rivers remains a technical challenge (Handcock et al., 2006; Torgersen et al., 2001). Although our aerial surveys took place in winter, when vegetation development and foliar cover were at their minimum, thermal measurements were influenced by riparian branches. Overhanging vegetation and bars reduced the number of pure water pixels scanned over the entire width of the channel. In the vicinity of the channel banks, the proportion of pixels influenced by tree branches increased significantly. Based on flight parameters and camera resolution, pixels located on narrow river sections (<7 pixels), where the accuracy of TIR images is reduced, were removed using a buffer zone of 1 m, which corresponds to 3.5 pixels (Handcock et al., 2006; Torgersen et al., 2001). In order to minimize data loss, we should carry out future surveys by drones under the riparian canopy, as recently documented by Wawrzyniak et al. (2016). This type of device, applied at finer spatial scales, provides continuous thermal data series. However, some sources of uncertainty, such as riparian-induced shadows, roughened water surfaces (Masuda, Takashima, & Takayama, 1988), and logjams cannot be completely avoided. To identify controlling factors of thermal anomalies distribution in fluvial systems, we have taken into account complementary data like lateral morphodynamics—including if possible bedload dynamics—riffle–pool sequences, and the location of old gravel bars outcropping in banks (Arrigoni et al., 2008; Dugdale et al., 2013).

6 Conclusion

Morpho-sedimentary diversity, gravel bar deposition, and riffle–pool sequences control the longitudinal stream temperature patterns on the new morphodynamic channel. These characteristics stem from the first floods that occurred after the restoration project. Morphological changes are particularly pronounced in the bending sectors where gravels and pebbles are remobilized by lateral erosion and are deposited as bars and riffles. Results reveal that upwelling zones are located preferentially nearby these accumulation areas of coarse sediments. In contrast, the old channel is characterized by a relatively thick clogging layer and no bars nor riffle–pool sequences. Groundwater inputs are mainly controlled by bank outcrops of former gravel bars and channel bottom-clogging thinning. These results allowed to validate our two working hypotheses: (a) in the new channel, groundwater inputs are induced by riffles and bars; (b) in the old channel, they are controlled by former gravel bars outcropping on the banks, as well as local thinning of the clogging layer at the channel bottom. Overall, IR thermography is a noninvasive surveying tool, which can be used by managers to evaluate the hyporheic processes of lateral channels and locate the spatial distribution of thermal refuges. Further research is required to gain a better understanding of groundwater input sources in small morphodynamic channels. A high-resolution survey at the scale of riffle–pool sequences and bars, as well as temporal surveys of thermal anomalies, stands as a promising avenue in this respect (especially when responding to the requirements as defined by Dugdale et al., 2013).

ACKNOWLEDGMENTS

This study has been funded by the European Community (LIFE08 NAT/F/00471), the City of Strasbourg, the University of Strasbourg (IDEX-CNRS 2014 MODELROH project), the French National Center for Scientific Research (CNRS), the ZAEU (Zone Atelier Environnementale Urbaine - LTER), the Water Rhin-Meuse Agency, the DREAL Alsace, the "Région Alsace," the "Département du Bas-Rhin," and the company "Électricité de France." We acknowledge Rodolphe Montagnon who carried out the flight by powered paraglider for the TIR survey. We also thank the two anonymous reviewers who provided very constructive comments that greatly contributed to improve the manuscript.

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