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Stream temperature estimated in situ from thermal-infrared images: best estimate and uncertainty

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Abstract. The paper aims to show a technique to estimate in situ the stream temperature from thermal-infrared images deepening its best estimate and uncertainty. Stream temperature is an important indicator of water quality and nowadays its assessment is important particularly for thermal pollution monitoring in water bodies. Stream temperature changes are especially due to the anthropogenic heat input from urban wastewater and from water used as a coolant by power plants and industrial manufacturers. The stream temperatures assessment using ordinary techniques (e.g. appropriate thermometers) is limited by sparse sampling in space due to a spatial discretization necessarily punctual. Latest and most advanced techniques assess the stream temperature using thermal-infrared remote sensing based on thermal imagers placed usually on aircrafts or using satellite images. These techniques assess only the surface water temperature and they are suitable to detect the temperature of vast water bodies but do not allow a detailed and precise surface water temperature assessment in limited areas of the water body. The technique shown in this research is based on the assessment of thermal-infrared images obtained in situ via portable thermal imager. As in all thermographic techniques, also in this technique, it is possible to estimate only the surface water temperature. A stream with the presence of a discharge of urban wastewater is proposed as case study to validate the technique and to show its application limits. Since the technique analyzes limited areas in extension of the water body, it allows a detailed and precise assessment of the water temperature. In general, the punctual and average stream temperatures are respectively uncorrected and corrected. An appropriate statistical method that minimizes the errors in the average stream temperature is proposed. The correct measurement of this temperature through the assessment of thermal-infrared images obtained in situ via portable thermal imager is confirmed by the direct measurement of stream temperature using an ordinary technique based on an appropriate thermometer.

1. Introduction

Today large quantities of water are artificially brought into urban watersheds via water works and hydraulic systems and consumed to maintain the various and common urban activities. Therefore, vast quantities of urban wastewater are discharged into the local water system, in general at different temperatures from the naturally occurring water. Stream temperature is an important indicator of water quality. Into water bodies, most chemical and biological activities are a function of temperature. The fish habitat in particular is sensitive to water temperature. Water bodies temperature is affected by various environmental process, both natural and anthropogenic. Human activities can affect stream temperature through global climate change [1], regional land-use alteration [2-3], heated effluents from power generation plants [4-5] and summertime urban stormwater runoff [6]. Disentangling the various effects is not easy. Stream temperature changes are especially due to the anthropogenic heat input from urban wastewater and from water used as a coolant by power plants and industrial manufacturers. Wastewater from municipal treatment plants is probably the largest anthropogenic heat source for urban streams. Its effect on stream temperature depends on the temperature and volume of wastewater added to the stream [7]. The increase in stream temperature related to anthropogenic heat input from urban wastewater is described in [8].

Nowadays, the water temperature assessment is important particularly for thermal pollution monitoring of the water bodies (including streams, rivers, lakes and reservoirs). In Italy, [9] regulates the stream temperature changes due to heat input from a discharging. The regulation regards the limited area of the water body near the discharging. Therefore, it is necessary an appropriate and suited technique to estimate the water temperature. It is note that stream temperatures assessment using ordinary techniques (e.g. appropriate thermometers) is limited by sparse sampling in space due to a spatial discretization necessarily punctual. These techniques are limited due to the necessary entrance of the temperature measuring instruments into the water body. On the contrary of the ordinary techniques, latest and most advanced techniques assess the water temperature in distant way from the water body. These innovative techniques estimate the stream temperature using thermal-infrared remote sensing based on thermal imagers placed on aircrafts [10-12] or using satellite images [13-15]. Recently, portable thermal imager is used to estimate in situ the stream temperature from thermal-infrared images [16-17]. These techniques are based on infrared (IR) thermography. In fact, they assess the thermal images based on the radiant power output of the surface of the water body; it is possible, therefore, to estimate only the surface water temperature. On the contrary of the thermal images taken over in situ via portable thermal imager, those taken over from aircrafts or satellites are suitable to detect the temperature of vast water bodies but do not allow a detailed and precise surface water temperature assessment in limited areas of the water body. In fact, the thermal images taken over from aircraft or satellite have a low resolution, so they do not distinguish the thermal fields of stream water respect anomalous thermal fields generate by foreign matter to the water. On the contrary, the thermal images taken over in situ via portable thermal imager have an high resolution, therefore the thermal anomalies are evident. The thermographic technique in situ is based on the sampling, from appropriate thermal images, of measuring points of the water temperature and to process, with suitable statistical methods, the temperature data to minimized the negative effects of thermal anomalies. The paper aims to review the technique to estimate in situ the stream temperature from thermal-infrared images via portable thermal imager deepening its best estimate and uncertainty and to show a method to assess the thermal pollution of the stream itself. A stream with the presence of a surface discharge of urban wastewater is proposed as case study to validate the technique and to show its limits. Since the technique analyzes limited areas in extension of the water body, it allows a detailed and precise assessment of the water temperature. In general, the punctual and average stream temperatures are respectively uncorrected and corrected. An appropriate statistical method that minimizes the errors in the average stream temperature, due to the thermal anomalies, is proposed. The correct measurement of the average stream temperature through the assessment of thermal-infrared images obtained in situ via portable thermal imager is confirmed by the direct measurement of stream temperature via an ordinary technique based on an appropriate thermometer.

2. Approach

2.1. *Case study*

For the IR thermographic applications in situ, the studied surface water body is the Aterno River in urban area of L'Aquila Municipality (Italy). A surface discharge of urban type is present in the analyzed situ. The discharge is characterized by an average wastewater hydraulics flow rate of 0,06 m^3/s during the thermographic experimental period. In the vicinity of the input point of the discharge wastewater, the Aterno River is characterized by an average hydraulics flow rate of 3,8 m^3/s and a river channel width of 20 m about. Thermal-infrared images are taken over via portable thermal imager in no. 3 areas of limited extension: close to the input point of discharge, upstream and downstream areas of discharge (60 m about is the distance from each other).

2.2. Thermographic experimentation: equipment and boundary conditions

Thermal-infrared images are taken over by a FLIR Systems S65 HS portable thermal imager that measures a range of the electromagnetic radiation spectrum between 7,5 and 13 μm wavelengths. The portable thermal imager has an average incidence angle, respect to surface of the water body, of 30° close to the input point area and in the downstream area of the discharge, of 90° in the upstream area of the discharge. The measurement days have been 21st, 22nd and 23rd November 2011. The measurement hours have been 9 am, 1 pm and 8 pm. During the measurement days, the maximum and minimum air temperatures have been 0 °C and 15 °C respectively. The average inclination of the solar rays to the ground has been 27,60° about. The water of the Aterno River is physically modelled as an opaque body having a constant emissivity coefficient 0,96 [16].

2.3. Image processing

Image processing was conducted using ThermaCAM Researcher Pro 2.8 software, distributed by FLIR Systems. Thermal-infrared images taken over by a portable thermal imager can take over only an area of the river channel with a very limited extension. Therefore, in order to have thermographic images that can estimate the stream temperature of an area with suitable extension of the water body, it is necessary to take over a suitable number of thermal images and to combine them with an appropriate and specific software. Visually, some cross-sections of the river channel are studied (no. 8 in total: no. 2 upstream, no. 2 in the vicinity and no. 4 downstream of the discharge). From these fluvial cross-sections, punctual temperatures are extrapolated from thermal images through a specific software. These punctual thermal data are analyzed for each measurement carried out in a specific day and in a specific hour. For each fluvial cross-section: the spatial distribution of punctual temperatures is determined; the arithmetic average temperatures and their variances are calculated. In figures 1, 2 and 3 are reported some examples of the taken over and assessed thermal-infrared images.

3. Sources of uncertainty

In figures 1, 2 and 3 the thermal images present several anomalous thermal fields (i.e. uncertainties) generated by foreign matters to the water and contamination from atmospheric effects. Sources of uncertainty include thermal scattering from the near-bank environment, the role of shade, surface effects such as surface roughness and viewing geometry, i.e. the observation angle. The near-bank environment includes objects with a wide variety of temperatures and emissivities, including bark, branches, dead grasses, leaves, soil, sand and rocks, that are exposed during the period of the thermographic measurements due to the low water levels of the river, and that have commonly different temperatures from those of the river water. Some of the IR radiation emitted by objects in the near-bank environment will reach the stream surface, either directly or through multiple scattering from objects near and in the water river. IR radiation emitted from near-bank objects may also pass directly into the path of the sensor of the portable thermal imager or be multiply scattered or reflected from other surfaces into the sensor, both of which will increase the observed temperature. However, this effects is small compared to the temperature of the water. The IR radiation emitted by objects depends by the observation angle; in fact this angle can be a source of uncertainty [18].

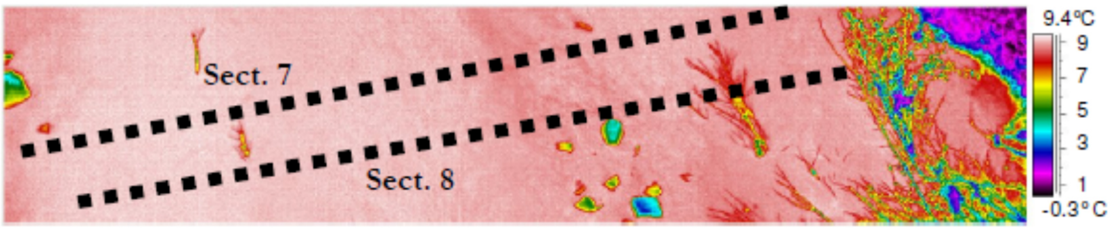

Figure 1. Example of a thermographic image of the upstream area of the discharge.

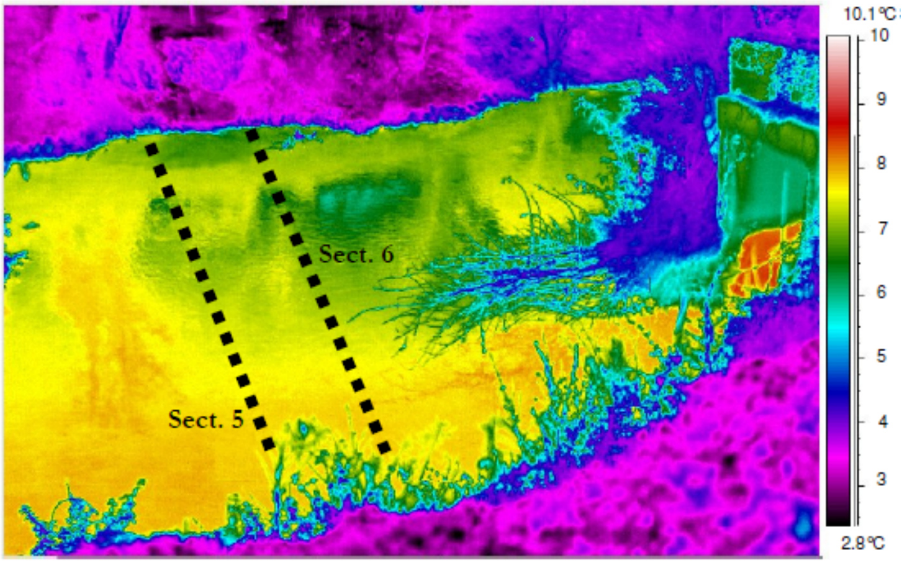

Figure 2. Example of a thermographic image of the area in the vicinity of the discharge.

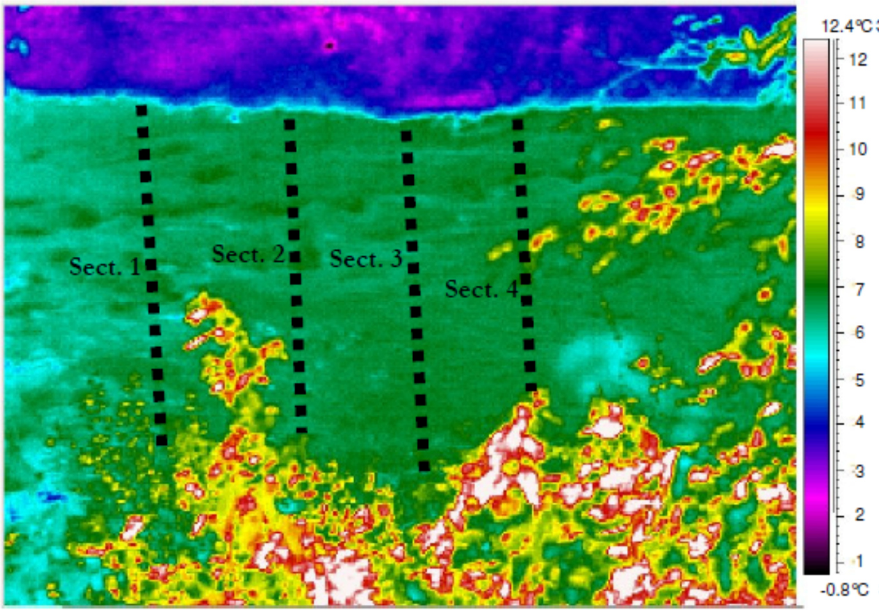

Figure 3. Example of a thermographic image of the downstream area of the discharge.

4. Best estimate of temperature

As mentioned in section 2, it is necessary to assess the average stream temperature along the fluvial cross-sections in order to limit the effects of the sources of uncertainty, i.e. to minimize the contribution of the anomalous thermal fields.

The best estimate of the average stream temperature (T_w) along a generic fluvial cross-section is assessed using the Gauss weighted average [19]. Therefore, the fluvial cross-section is idealized as discrete, i.e. composed by a series of temperature points and divided in ranges. These temperature points are grouped in a suitable number (i) of ranges and the i-th range has a determined number of points (n). For each i-th range, the arithmetic average temperature and its variance (σ^2_i) are calculated. The contribution of the quality of the i-th range to the temperature of the generic fluvial cross-section is therefore assessed by assigning a normalized weight (W_i):

$$W_i = \frac{\frac{1}{\sigma_i^2}}{\sum_{i=1}^{n} \frac{1}{\sigma_i^2}} \tag{1}$$

where ($1/\sigma^2_i$) is used in the calculation of the weight for each range so that the ranges with a great variance contribute little to the calculation of T_w. These normalized weights are used to calculate, in each fluvial cross-section, T_w as the weighted sum of arithmetic average temperatures of each i-th range (T_i):

$$T_w = \sum_{i=1}^{n} W_i T_i \tag{2}$$

5. Validation of results

In order to validate the average surface stream temperature (based on thermal-infrared images via portable thermal imager in situ) along fluvial cross-section, estimated using the Gauss weighted average (equations (1) and (2)), an ordinary technique is adopted: use of an appropriate portable thermometer. The measures using the portable thermometer are carried out in a point of the river localized at 8 m about downstream from the input point of the discharge, in each of the no. 3 hours of measurement of the no. 3 experimental days. So there are no. 9 measures with an arithmetic average of 7,6 °C. The comparison of the thermal results of equations (1) and (2) with those of the ordinary technique permits to validate the IR thermographic technique based on the use of portable thermal imager in situ.

6. Uncertainty quantification

6.1. On total thermal power taken over

In general, the total thermal power emitted by a detected object by the portable thermal imager is [20]:

$$W_{tot} = \varepsilon\tau W_{obj} + (1-\varepsilon)\tau W_{refl} + (1-\tau)W_{atm} \tag{3}$$

where ε is the emission coefficient of the detected object, τ is the atmospheric transmission coefficient, W_{obj} is the thermal power emitted by the detected object, W_{refl} is the thermal power reflected by other sources (i.e. foreign matters and bodies to the detected object) present in the environment and W_{atm} is the thermal power emitted by the atmosphere. So that, $\varepsilon\tau W_{obj}$ is the object emission, $(1 - \varepsilon)\ \tau W_{refl}$ is the environmental sources emission and $(1 - \tau)W_{atm}$ is the atmospheric emission.

In equation (3) it is assumed that the generic thermal power (W) emitted by a generic actual source is [21]:

$$W = \varepsilon\sigma T^4 \tag{4}$$

where ε is the emission coefficient of the source, σ is the Stefan-Boltzmann constant equal to $5{,}67 \cdot 10^{-8}$ W/m^2K^4 and T^4 fourth power of the source temperature. The equation (4) is used to estimate W_{obj}, W_{refl} and W_{atm}. In this study, the generic detected object above mentioned is the water body (i.e. Aterno River). In the present research, $\varepsilon = 0{,}96$ and $T_{obj} = 7{,}6$ °C are assumed respectively for the emission coefficient and temperature of the river water; the atmospheric transmission coefficient is assumed $\tau = 1$ [21]. In the period of the thermographic applications, there is a atmospheric (i.e. environmental) temperature T_{atm} varying between 0 °C and 15 °C. Since in the analyzed areas of the river there are not punctual heat sources, it is assumed $T_{atm} = T_{refl}$ (T_{refl} is reflected temperature) [22]. Therefore, using the equations (3) and (4) it is possible to assess the contribution of the radiation emitted by the water body, by the atmosphere and by the reflected radiation from the river respect to the total radiation taken over by the portable thermal imager. The synthetic graphic results are shown in figure 4.

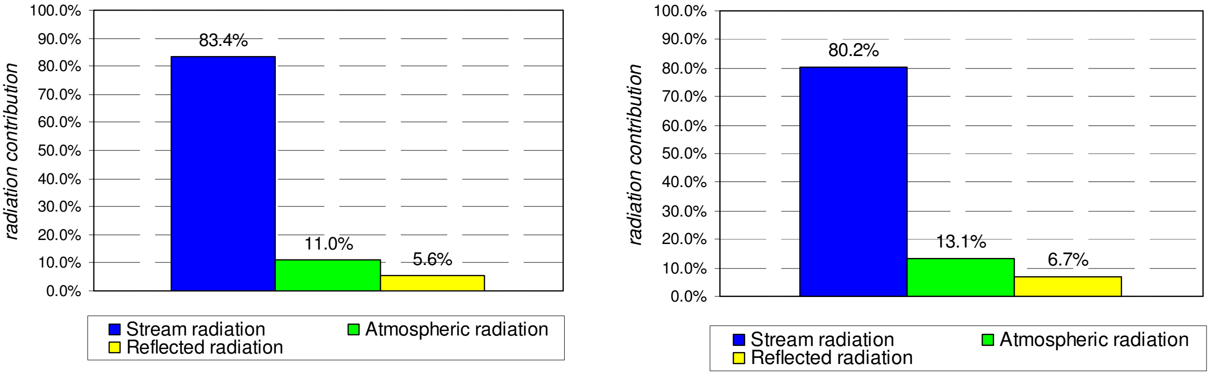

Figure 4. Radiation contribution emitted by the surface water body, by the atmosphere and by the reflected radiation on the total radiation recorded by thermal imager for emissivity and temperature of the water of the water body respectively of 0,96 and 7,6 °C, an atmospheric transmission coefficient of 1 and a reflected temperature of 0 °C (left graph) and 15 °C (right graph).

Observing the figure 4 it is possible to note that the weight, i.e. the contribution, of the water body radiation (W_{obj}), respect to the total radiation measured by the portable thermal imager (W_{tot}), decreases with the increase of the environment (T_{atm}) and reflected (T_{refl}) temperatures. Therefore, the increase of T_{atm} and T_{refl} generates consequently a growth of the noise, due to respectively atmospheric and solar radiations, on the values of stream temperature. As is shown in figure 4, the object radiation, i.e. the river water radiation, is included between the 80,2% and 83,4%, therefore the uncertainty on thermal power of the river water taken over by the portable thermal imager is 4,0%.

6.2. *On stream temperature estimated*

Considering the equation (4), it is possible to formulate the relation between the uncertainty on total thermal power taken over by the portable thermal imager (ΔW) and the uncertainty on the generic source temperature (ΔT):

$$\frac{\Delta W}{W} = 4\varepsilon\sigma T^3 \frac{\Delta T}{T} \tag{5}$$

Then for the Aterno River, since $\Delta W/W = 4{,}0\%$ and $T = 7{,}6$ °C (see section 6.1), the uncertainty on the stream temperature estimated in situ from thermal-infrared images via portable thermal imager is $\Delta T = 2{,}4$ °C, i.e. $T = \pm 1{,}2$ °C.

7. Stream temperature resulting

Punctual stream temperatures oscillate between 5 °C and 10 °C along upstream and downstream fluvial cross-sections, whereas in the vicinity of the discharge between 2,5 °C and 9,5 °C. Thermal peaks at low temperatures of the river water around the discharge are due to the greater presence of foreign matters to the water of the water body transported in surface by the river itself and outcropped from the river surface, with a different emission coefficient respect to that of the river water.

Average temperatures along fluvial cross-sections at 8 pm (about 8 °C) are higher and less oscillating than those at 9 am and 1 pm because of the absence of "cold" solar reflections in the infrared range.

By averaging, between all measures of each fluvial cross-section, all the weighted and arithmetic average temperatures, the Aterno River, in the detected area portion, is characterized by temperature values respectively equal to 7,2 °C and 7,3 °C. The small difference between the two temperature values is due to the preliminary choice of fluvial cross-sections little thermally disturbed, i.e. with a limited presence of anomalous thermal fields, carried out at view on the thermal images.

The thermal plume (figure 5) in the input point of the discharge in the river has a surface temperature of about 11 °C. This temperature becomes about 8 °C, i.e. equal to that of the equilibrium surface temperature of the river, through a distance of about 6 m, from the input point, in all directions including between that orthogonal and parallel at the discharge axis. In more detail, this thermal decrease has almost exponential law. Furthermore, it is maximum for the orthogonal direction at the discharge axis and minimum for that coincident with this axis. Moreover, the plume has not a symmetric spatial configuration due to the non-coincidence between the direction of the water flow of the river and the wastewater flow from the discharge, and due to the water push of the river during its natural propagation in the space.

By averaging all the weighted average temperatures in the no. 2 upstream and in the no. 4 downstream fluvial cross-sections, the stream temperatures are respectively equal to 7,7 °C and 7,3 °C. Therefore, the limits for the thermal pollution laid down by [9] are widely respected.

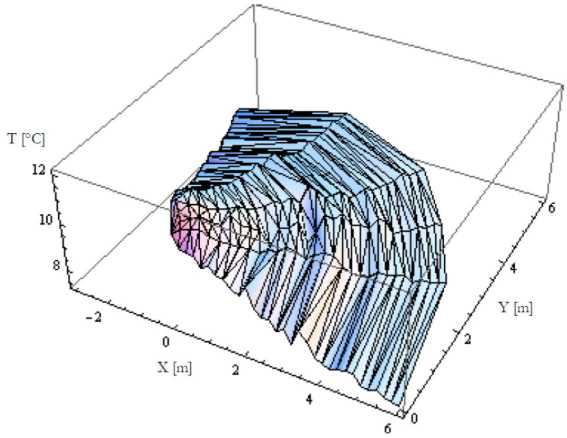

Figure 5. Spatial representation of the thermal plume.

8. Conclusions

The technique to estimate the stream temperature from thermal-infrared images in situ via portable thermal imager con be not suitable for the punctual temperatures. On the contrary, it is acceptable for the average temperatures along fluvial cross-sections; it is necessary to depurate from the calculation of these temperatures the potential errors generates, in general, by different experimental conditions of individual measurements, by the noise due to the foreign matters to the water of the water body, transported in surface by the river itself and outcropped from the river surface, highlighted from the registrations of anomalous thermal fields in the thermal images.

In according to the results and the experimental conditions characterizing this research, it is recommended to carry out the measurements with the portable thermal imager in position as possible orthogonal to the surface of the surface water body, to carry out the measurements in the evening and/or night or with overcast sky, to choose to view the sections most suitable and to use appropriate statistical methods to estimate the average surface temperatures (e.g. Gauss weighted average).

The technique analyzed in this paper allows to carry out the temperature analysis of the surface water body at a distance, without direct contact, on fairly extensive areas and to obtain rapidly numerous data readily available for subsequent and more evolved elaborations (e.g. calculation of the temperature gradients and relative heat flows).

This technique is suitable only for surface discharges and not for those submerged, since it does not allow to analyze the temperatures within the volume of the water body but only that at the surface. It allows, in addition to the assessment and monitoring of thermal pollution, also to identify sites with probable chemical pollution in place by recording of anomalous thermal fields. From the above, this technique may be of aid for government departments and public bodies responsible of the environment and land protection, for the monitoring of authorized discharges, i.e. censused, and for the identification of those abusive especially if they are not visible to the eye.

References

[1] Mohseni O and Stefan H G 1999 Stream temperature/air temperature relationship: a physical interpretation *Journal of Hydrology* **218** 128–141

[2] Chen Y D, Carsel R F, McCutcheon S C and Nutter W L 1998a Stream temperature simulation of forested riparian areas: I Watershed-scale model development *Journal of Environmental Engineering ASCE* **124**(4) 304–315

[3] Chen Y D, McCutcheon S C, Norton D J and Nutter W L 1998b Stream temperature simulation of forested riparian areas: II. Model application *Journal of Environmental Engineering, ASCE* **124**(4) 316–328

[4] Stefan H G and Chau V N 1976 River cooling water temperature fluctuations *Journal of Hydraulics Division ASCE* **102**(11) 1613–1627

[5] Chen C Q, Shi P and Mao Q W 2003 Application of remote sensing techniques for monitoring the thermal pollution of cooling-water discharge from nuclear power plant. *Journal of Environmental Science and Health Part A* **38**(8) 1659–1668

[6] Van Buren M A, Watt W E, Marsalek J and Anderson B C 2000 Thermal enhancement of stormwater runoff by paved surfaces *Water Research* **34**(4) 1359–1371

[7] Kinouchi T 2007 Impact of long-term water and energy consumption in Tokyo on wastewater effluent: implication for thermal degradation of urban streams *Hydrological Processes* **21**(9) 1207–1216

[8] Kinouchi T, Yagi H and Miyamoto M 2007 Increase in stream temperature related to anthropogenic heat input from urban wastewater *Journal of Hydrology* **335** 78–88

[9] Italian Legislative Decree 3rd April 2006 no. 152 – *Environmental Regulations* (in Italian)

[10] Torgersen C E, Faux R N, McIntosh B A, Poage N J and Norton D J 2001 Airborne thermal remote sensing for water temperature assessment in rivers and streams *Remote Sensing of Environmental* **763**(3) 386–398

[11] Hedger R D, Malthus T J, Folkard A M and Atkinson P M 2007 Spatial dynamics of estuarine water surface temperature from airborne remote sensing *Estuarine, Coastal and Shelf Science* **71** 608–615

[12] Marmorino G O and Smith G B 2008 Thermal remote sensing of estuarine spatial dynamics: effects of bottom-generated vertical mixing *Estuarine, Coastal and Shelf Science* **78** 587–591

[13] Bolgrien D Q and Brooks A S 1992 Analysis of thermal features of Lake-Michigan from AVHRR satellite images *Journal of Great lakes Research* **18**(2) 259–166

[14] Parkinson C L 2003 Aqua: An earth-observing satellite mission to examine water and other climate variables *IEEE Transactions on Geoscience and Remote Sensing* **41**(2) 173–183

[15] Cherkauer K A, Burges S J, Handcock R N, Kay J E, Kampf S K and Gillespie A R 2005 Assessing satellite- and aircraft-based thermal infrared remote sensing for monitoring Pacific

Northwest rivers *Journal of the American Water Resources Association* **41** 1149–1159

[16] Cardenas M B, Harvey J W, Packman A I and Scott D T 2008 Ground-based thermography of fluvial systems at low and high discharge reveals potential complex thermal heterogeneity driven by flow variation and bioroughness *Hydrological Processes* **22** 980-986

[17] Iezzi F and Todisco M T 2012 Measures of thermal pollution of the surface water bodies via IR thermographic technique *Proceedings of the XXXIII National Congress on Hydraulics and Hydraulic Constructions*, Brescia, Italy (in Italian)

[18] Handcock R N, Gillespie A R, Cherkauer K A, Kay J E, Burges S J and Kampf S K 2006 Accuracy and uncertainty of thermal-infrared remote sensing of stream temperature at multiple spatial scales *Remote Sensing of Environment* **100** 427–440

[19] Taylor J R 2000 *Introduction to Error Analysis* (Zanichelli, ed. 2, in Italian)

[20] Flir Systems 2006 *User Manual*

[21] Çengel Y A 2005 *Thermodynamics and Heat Transmission* (McGraw-Hill, ed. 2, in Italian)

[22] Testo SpA 2008 *Pocket Guide on the Thermography* (in Italian)