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# Open water swimming in urban areas E. coli distribution with TELEMAC-3D

# Open water swimming in urban areas
# *E. coli* distribution with TELEMAC-3D

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*Abstract* – **Swimming in urban open waters is increasingly popular. In Paris, a bathing area is open during summer in La Villette Basin, our study site. To control sanitary risks, the European Bathing Water Directive (2006/7/EC) classifies the water quality according to thresholds of indicators of pathogenic microorganisms, the faecal indicator bacteria (FIB), such as *E. coli*. The reference FIB enumeration methods take more than 24 h.**

**To obtain, in due time, information on the sanitary conditions in the bathing area, in this study, two issues were considered.**

**On the one hand, for assessing more rapidly the microbiological level, a relationship between bacterial activity and fluorescent dissolved organic matter (FDOM) can be used. Here, *E. coli* was estimated from a relationship with tryptophan-like fluorescence (TLF) established for La Villette system.**

**On the other hand, the thermal stratification of the water column observed during summer heat waves can impact the spatiotemporal distribution of FIB, in water bodies with low current speed. The three-dimensional hydrodynamic model TELEMAC-3D was run to predict the space and time evolution of *E. coli*. To reproduce the thermal stratification in the basin, WAQTEL thermal process was activated. TLF data measured upstream were used as an input for the simulations.**

**Two periods of ten days were simulated. In the first period (12-22 September 2021), including a heavy rain event, five field measurements of *E. coli* were available. The model results were converted from TFL to *E. coli* and then compared to field data. There was a good agreement between them (RMSE = 197 MPN/100mL, $r^2$ = 0.74). The regulatory threshold was exceeded during four days and the bathing area would have had to be closed during this period.**

**The same *E. coli* input was used for a second simulation run during a heat wave period (13-23 July 2022). The thermal stratification was correctly reproduced. A slight lateral heterogeneity of *E. coli* distribution between left and right bank of the basin was simulated.**

**These preliminary results indicate the good capability of a warning system combining upstream continuous TLF monitoring with hydrodynamic modelling. It would support a better assessment of sanitary conditions in a bathing area and improve the accuracy on the duration of the regulatory threshold exceedance.**

***Keywords***: thermal stratification, sanitary risk, bathing, open water, *E. coli*, faecal contamination, TELEMAC-3D.

## I. INTRODUCTION

Open water sport events are increasingly popular in urban areas. Some open water competitions of the International Federation of Swimming are performed in urban freshwater bodies (FINA https://www.fina.org/open-water). For example, in July 2022, the second phase of Marathon Swim World Series took place in Paris, at the Ourcq Canal.

The prefectural decree of 1923, banning public swimming in the Seine River, is still in force today. An exception in Paris region, since 2017, is the public swimming area installed in La Villette Basin during summer.

Reintroducing urban bathing is part of environmental policies aimed at recovering the ecological quality of the river in wider Paris. Urban bathing mitigates the urban heat island effects of Paris and reduces the heat wave impact on the population. Furthermore, it is a way of reclaiming public space and reinforcing the links of the city dwellers with nature.

However, open water swimming can cause waterborne diseases. To control the sanitary risks, the European Directive of Bathing Waters 2006/7/EC [1] classifies the water quality in function of the concentrations of indicators of faecal contamination known as faecal indicator bacteria (FIB). Two bacteria are used as reference parameters in the European classification: *Escherichia coli* (*E. coli*) and intestinal enterococci (IE). For inland waters, the threshold for a sufficient water quality for bathing is 900 MPN/100mL for *E. coli* and 330 MPN/100mL for IE, both values based upon a 90-percentile evaluation. In this study, *E. coli* was used as a representative indicator of FIB. The reference method for *E. coli* enumeration, in the laboratory, has a long response time, taking from 24h to 48h [2].

In some watercourses, the analysis of the microbiological water quality is performed on a daily basis, upstream of the bathing area, in order to anticipate the decision of a closure of the bathing area. To improve the accuracy of the decision making and reduce the risk of having undetected contamination between two measurements, a more frequent monitoring time step is required.

The relationship between bacterial activity and fluorescent dissolved organic matter (FDOM) may provide a high-frequency assessment of the microbiological water quality. A possible indicator of *E. coli* is a fluorescence signal known as tryptophan-like fluorescence (TLF) or peak T [3]–[5].

In water bodies of low current speeds, which is frequently the case in bathing areas, a thermal stratification is observed during summer in the water column. In turn, it impacts current speeds and, consequently, the spatiotemporal distribution of FIB [6].

This work focused on monitoring and estimating sanitary conditions in an urban bathing area, Bassin de La Villette (Paris, France), aiming to anticipate a possible closure of the site and its duration. More precisely, the objective was to predict *E. coli* concentration at the bathing area. A three-dimensional hydrodynamic model, TELEMAC-3D, was used to predict spatiotemporal distribution of *E. coli* from the upstream measurement point to the bathing area. The WAQTEL thermal module was activated to reproduce the thermal stratification on the basin. To have a few-hour forecast of the sanitary risk at the bathing area, real-time data from the upstream point were used as an input. *E. coli* values were inferred from the TLF measurements through the relationship established for La Villette system.

## II. Material and Methods

### A. *Study site and field data*

La Villette system is located in the north-east of Paris. It is composed of a canal of 25 m wide and 800 m long and a basin of 75 m wide and 700 m long, where the bathing area is located (Figure 1).

The upstream point, point A, is equipped with a vertical chain of temperature and conductivity sensors located at three depths and a water level sensor. The downstream point, point B, is also equipped with a "three depth" sensor vertical chain for temperature and conductivity measurements. The measurement time step is 20 min.

At points A and B, sampling of surface water (0.40 m depth) was performed for fluorescence measurements. From 30th June to 20th September 2021, 17 grab samples were collected at each point.

During the same period, surface water sampling for FIB and fluorescence measurements was performed at point C. Point C is located in the middle of the system, at the end of the canal (Figure 1). Five episodes were sampled, two of dry weather and three of rainy weather. Hourly samples were taken automatically for 24 hours, from 9h to 9h the day after. All the samples were then mixed to obtain mean daily samples. During the dry weather episodes, two daily samples were obtained. For the rain episodes, the duration of the first one was two days (two samples) and the duration of the other two was three days (2x3 samples). A total of ten mean daily samples were collected.

FDOM and *E. coli* concentrations in the samples were measured at the laboratory. *E. coli* was measured according to ISO 9308-3 method. The uncertainty on *E. coli* data is around 25%.

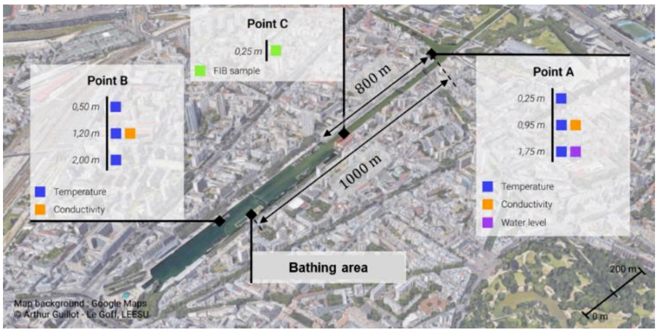


Figure 1. Location of the measuring stations at La Villette

FDOM measurements were performed on a Cary Eclipse Fluorescence Spectrophotometer (Agilent Technologies). For each sample, a simultaneous scan of excitation wavelength from 200 to 700 nm with 5-nm intervals and emission wavelength from 250 to 750 nm with 2-nm intervals was performed. The processing of the EEM spectra was conducted according to [7]. Data are expressed in Raman Units (RU) according to [8]. The TLF values, corresponding to the wavelength range 275 nm – 340 nm, respectively for Excitation and Emission wavelengths [9], were used to find a relationship with *E. coli* data.

### B. *E. coli estimation*

The relationship between TLF and *E. coli* was established through the data of the 10 samples collected between June and September 2021 in La Villette basin. The range of *E. coli* data was from 98 to 1400 MPN/100mL. The range of TLF data was from 0.13 to 0.75 RU. The obtained linear relationship ($r^2 = 0.64$, $p = 4.10^{-5}$) is given by (1).

$$[E.\ coli] = 1381 \cdot \mathrm{TLF} \quad (1)$$

[*E.coli*] in MPN/100mL and TLF in RU.

### C. *Hydrodynamic model*

The simulations were run using the v8p3 version of TELEMAC-3D on a Linux operating system. BlueKenue (3.3.4) was used for the preparation of geometry and mesh files and for the visualisation of the results.

#### *1)* Modelling domain

The domain goes from the canal round-about upstream to the downstream end of La Villette Basin (Figure 1). The 3D grid is composed by 10 layers of 0.30 m of depth and an average edge length of 5 m. The simulation results for the temperature and *E. coli* concentration at the surface and at the bottom layers are compared to field data at 0.5 m and 2.0 m, respectively.

The time-step of the model computation is of 20 s. The time step of the result output is 10 min

#### *2)* Hydrodynamic and heat exchange model

The thermal process was activated in WAQTEL module, considering the heat exchange of water with the atmosphere.

The lateral boundaries are defined as a solid wall. The upstream and downstream boundary conditions are defined as open boundaries, upstream with prescribed water elevation and water temperature and downstream, prescribed flowrate.

To compute the heat exchange with the atmosphere, hourly meteorological data (wind speed and direction, air temperature, atmospheric pressure, relative humidity, cloud cover, and rainfall) are required. They were obtained from Le Bourget airport station, the nearest Météo France station (around 9 km in the North-East), excepted for cloud cover which is not available at Le Bourget. We used cloud cover from the Orly meteorological station (around 17 km in the South).

For upstream boundary conditions, water temperature and water elevation measured at point A were used.

Downstream, the outlet flowrate, *Q*, was computed using the water level measurements at the upstream point (point A) according to the Manning-Strickler equation (2).

$$Q(h) = K_S \cdot S_{tot} \cdot R_H^{2/3} \cdot i^{1/2} \qquad (2)$$

Where $Q$ (m$^3$/s) is the outlet flowrate, $K_S$ (m$^{1/3}$/s) is the Strickler coefficient; $S_{tot}$ (m$^2$), the total underwater section, $R_H$ (m), the hydraulic radius, and $i$ (m/m) the hydraulic slope.

The hydraulic radius ($R_H$) and the underwater section ($S_{tot}$) were computed using the water elevation, $h$ and geometric data of the system obtained from a technical report [10]. Considering the macrophytes on the bed of the canal, a value of 2 m$^{1/3}$/s for $K_S$ was adopted.

The vertical turbulence model was Nezu and Nakagawa mixing length, with Viollet's damping function. The horizontal turbulent viscosity was considered constant. The Secchi depth was 0.9 m, derived from field data.

*3)* Microbiological input data

The TLF values obtained from the FDOM measurements at point A were linearly interpolated to an hourly time step. They were used as upstream input data, uniformly distributed on the water column, in the simulations. TLF was considered as a passive tracer.

*4)* Data processing

MATLAB (R2021b) was used for the preparation of input data and processing of simulation results. The model performance was assessed through two indicators, root mean square error (RMSE) and Pearson correlation coefficient (r).

## *D. Simulation periods*

Two simulation periods were run. The first simulated period was 12-22 September 2021. It included a rainfall episode on 14th and 15th of September, with a total rain height of 28 mm in 48 hours. The results obtained for this period will illustrate the performance of the model to simulate the microbiological contamination level.

The second simulation period was 13-23 July 2022, a period of very high air temperature. Here, the impact of thermal stratification on a possible microbial contamination will be assessed.

# III. Results and Discussion

## *A. 12-22 September 2021*

This period included a heavy rainfall episode on 14th and 15th of September, with a total rain height of 28 mm in 48 hours. Seven measurements of the microbiological indicator, TLF, were available during the period (Figure 2a). Before the rain event, the TLF level was around 0.14 RU. A value of 0.70 RU was observed on September 16th after the rain and TLF remained around 0.75 RU for 5 days, until September 20th, when it started to decrease (0.20 RU on 21st September). In parallel, 5 mean daily data of *E. coli* measured at point C were available (Figure 2b). The total number of available TLF and *E. coli* data are summarized in Table I.

To provide the upstream input of the microbiological indicator, TLF data were linearly interpolated at an hourly time step. The TLF simulation results were then converted in *E. coli* unit (MPN/100mL) using (1). Simulated *E. coli* was compared to the field data measured at point C.

For water temperature, model results and field data (Figure 3) were compared at the bathing area (point B). A good agreement was obtained, with RMSE of 0.66, 0.57, 0.53 °C and r$^2$ of 0.73, 0.74, 0.79 for the surface, middle and bottom layers, respectively.

Table I Number of TLF and E. coli data at each point

| **Period** | **Point A** | | **Point C** | |
|---|---|---|---|---|
| | ***TLF*** | ***E. coli*** | ***TLF*** | ***E. coli*** |
| 12-22 September 2021 | 7 | - | 5 | 5 |

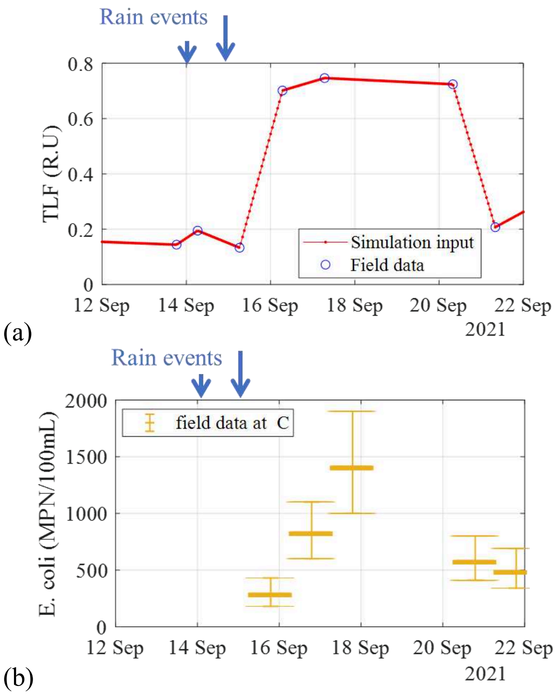


Figure 2. TLF as microbiological input at point A (a) and *E. coli* daily data at point C (b)

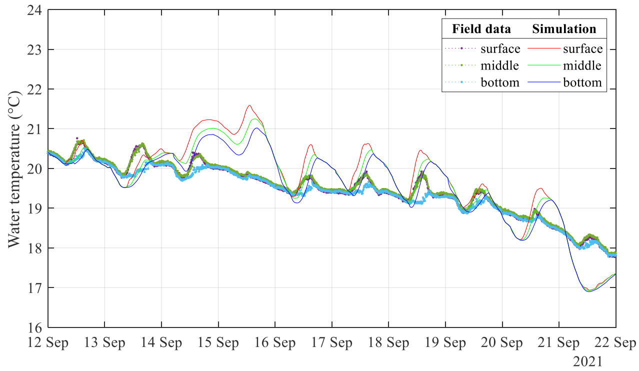


Figure 3. Water temperature at point B from 12 to 22/09/2021 – Field data and model results

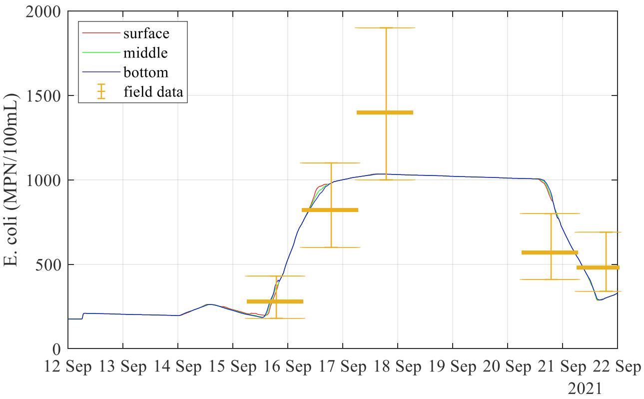


Figure 4. *E. coli* at point C – Simulation results and daily mean field data

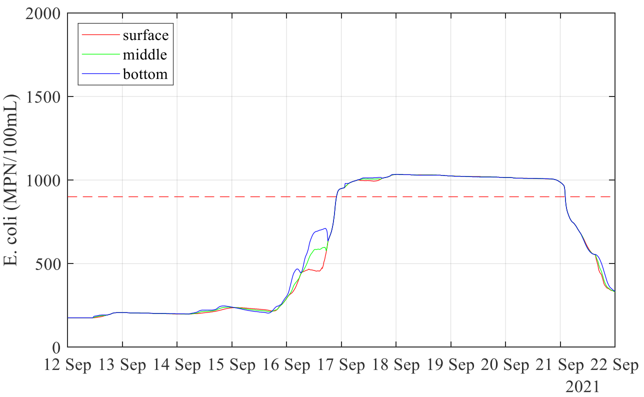


Figure 5. Simulation results of *E. coli* at point B

Over the whole period, the water column was slightly stratified during daytime, and was mixed during the night, with a temperature difference between the surface and the bottom layers of 0.21°C according to the field data and 0.34°C according to the model results.

To assess the microbiological results, the model output of TLF values were firstly converted to *E. coli* unit and then compared the field data measured at point C (Figure 4). The simulation results were within the uncertainty range of *E. coli* data. The agreement between the model results and the field data was very close, with a RMSE of 225 MPN/100mL and $r^2$ of 0.67.

The time evolution of *E. coli* at point B was then obtained from the TLF results (Figure 5) and compared to the sufficient quality threshold for bathing (900 MPN/100mL). The threshold was overpassed from the 17th to 20th September included, when the bathing area should be closed (it was the case!).

*B. 13-23 July 2022*

During this period, very high air temperature was recorded, with a maximum of 39.8 °C on 19th July. No *E. coli* data are available for this episode. For that reason, the data measured during the rain event of September 2021 were used to assess the impact of thermal stratification on *E. coli* distribution.

At the bathing area (point B), the water temperature range was [24.0 - 26.1 °C] for the field data and [22.9 - 26.8 °C] for the simulation results (Figure 6). There was a good agreement between model and data, with RMSE of 0.41, 0.47, 0.42 °C and $r^2$ of 0.70, 0.59, 0.66, respectively for the surface, middle and bottom layers.

From July 13th to 20th, the water column was stratified during daytime and mixed during the night. After July 20th, the stratification vanished. Over the stratified period, the maximum temperature difference between surface and bottom layers had a mean value of 0.97 °C for field data and of 0.91°C for model results. Over the whole period, the temperature difference between the bottom and the surface layers showed good agreement between field data and simulation results (RMSE = 0.19 °C and $r^2$ = 0.69).

The lateral heterogeneity of *E. coli* distribution at the basin area is illustrated on Figure 7. On July 17th at 13h00 (Figure 7 left), higher concentration reached earlier at left bank than at right bank. At the end of the simulated period, on July 22nd (12h00), *E. coli* spatial distribution also displayed heterogeneity between right and left banks (Figure 7 right) on July 22nd (12h00).

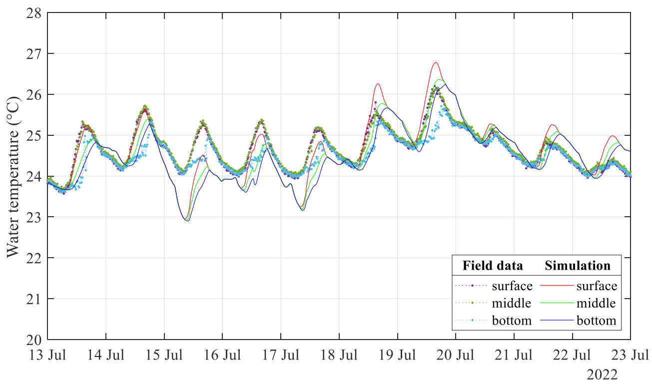


Figure 6. Water temperature at point B from 13 to 23/07/2022 – Field data and model results

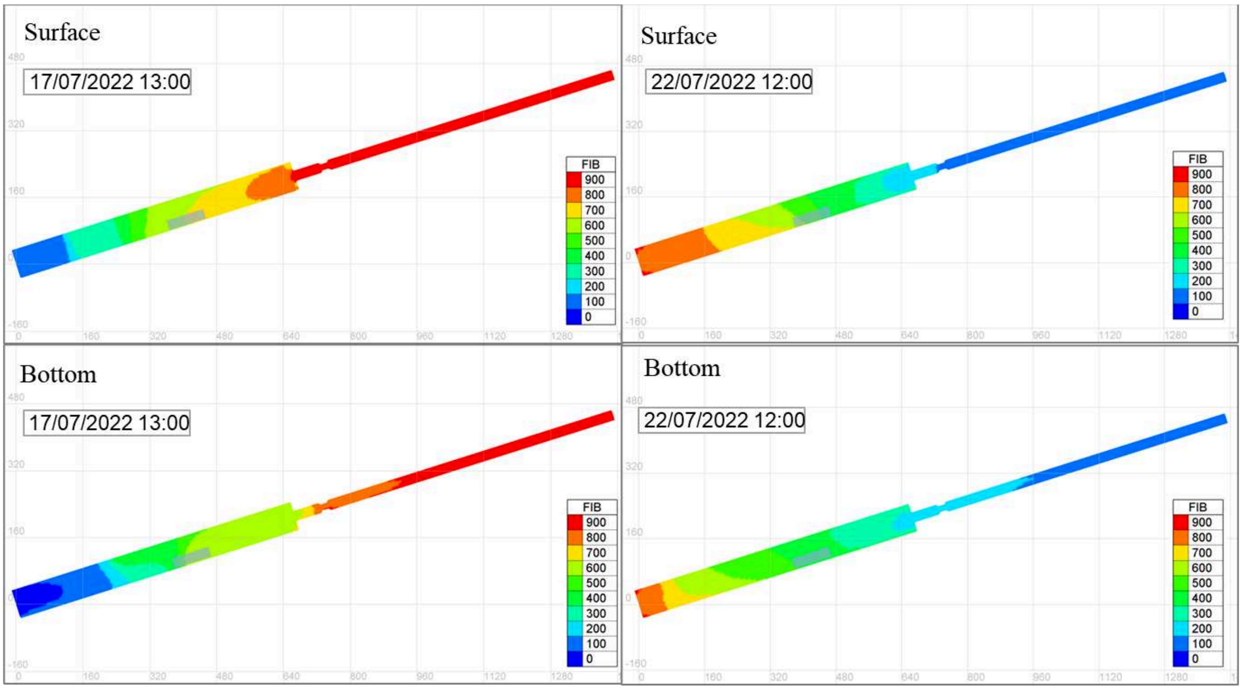


Figure 7. Spatio-temporal distribution of *E. coli* on the surface and bottom layers on July 17th at 13h00 (left) and on July 22nd at 12h00 (right)

## IV. Conclusion

A monitoring system combined with model simulations was developed for the urban bathing area of Bassin de La Villette (Paris, France). The objective was to predict the overpassing of *E. coli* threshold for sufficient bathing water quality. The three-dimensional hydrodynamic model TELEMAC-3D was used to simulate *E. coli* spatial temporal distribution, from the upstream measurement point to the bathing area. The WAQTEL thermal module was activated to reproduce the thermal stratification on the basin.

Fluorescent dissolved organic matter (FDOM) was measured in grab samples, in parallel to *E. coli* enumeration. A relationship between *E. coli* and tryptophan-like-fluorescence (TLF) was established. As it is possible to monitor FDOM *in situ*, in the future, *E. coli* could be continuously estimated in Bassin de La Villette from its relationship with TLF values.

The first simulated period (12-22 September 2021) included a heavy rain episode. The model was able to simulate adequately the time evolution of *E. coli* level: increase of the concentration after the rain and decrease five days later. The regulatory threshold was exceeded, and the bathing area would have had to be closed. According to the model results, the closure should have occurred two days earlier (September 16th) than according to the field data (September 18th).

A second simulation was run during a heat wave (13-23 July 2022). The thermal stratification was correctly reproduced. During this period, a slight lateral heterogeneity of *E. coli* distribution between left and right bank of the basin was simulated.

The transfer time between points A and B estimated by the model varied between 11h 30 min and 16h 40 min. These results indicate that combining upstream continuous TLF monitoring with hydrodynamic modelling would allow to predict the exceedance of the regulatory threshold for water quality in a downstream bathing area. It would support the decision making on the closure/opening of the bathing area.

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