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Modélisation hydrodynamique 3D pour l'évaluation de la qualité de l'eau en milieu urbain – application au Bassin de La Villette (Paris, France)

3D hydrodynamic modelling for the assessment of water quality in urban waterbodies – application to Bassin de La Villette (Paris, France)

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RÉSUMÉ

La distribution spatio-temporelle des contaminants dans les cours d'eau doit être prise en compte, notamment pour les prises de décision visant à réduire les risques sanitaires. Les variations de débit et la stratification thermique ont un impact sur cette distribution spatio-temporelle, entre un point de surveillance en amont et une zone d'intérêt en aval. Dans notre site d'étude, le Bassin de La Villette (Paris, France), un modèle hydrodynamique tridimensionnel (TELEMAC-3D) a été utilisé pour estimer l'impact des conditions hydro-météorologiques sur le transport d'une contamination microbiologique de l'amont vers l'aval, où une zone de baignade est ouverte en été. Le modèle a été validé en comparant les résultats de simulation de la température de l'eau et de la conductivité électrique avec des données de terrain à haute fréquence. Deux périodes estivales chaudes, et deux périodes montrant de grandes variations de conductivité ont été simulées. Les résultats de modélisation de la température de l'eau et de la conductivité ont montré un bon accord avec les données de terrain. Enfin, une période de contamination bactérienne survenant après un épisode de pluie a été simulée pour illustrer la capacité du modèle à reproduire le transport de la contamination.

MOTS CLÉS

Temps de pluie, risques sanitaires, TELEMAC-3D, stratification thermique, baignade urbaine

ABSTRACT

The spatiotemporal distribution of contaminants in watercourses is an important aspect to consider, particularly to anticipate decision-making for sanitary risk management. Discharge variation and thermal stratification impact this spatiotemporal distribution between an upstream monitoring point and a downstream area of interest. In our study site, Bassin de La Villette (Paris, France), a three-dimensional hydrodynamic model (TELEMAC-3D) was used to estimate the impact of hydro-meteorological conditions on the transport of a microbiological contamination from upstream to downstream, where a bathing area is open during Summer. The model was validated by comparing simulation results with high-frequency field data of water temperature and electrical conductivity. Two different periods of hot weather, and two with large conductivity variations were simulated. The modelling results of water temperature and conductivity were in good agreement with field data. Finally, a period of bacterial contamination following a rain episode was simulated to illustrate the model capability to reproduce the contamination transport.

KEYWORDS

Rainfall events, sanitary risks, TELEMAC-3D, thermal stratification, urban bathing

1 INTRODUCTION

The conventional monitoring of water quality consists of discrete measurement or grab sampling upstream of an area of interest in order to anticipate an adequate decision-making. However, a contamination occurring between two measurements can be undetected. To reduce this risk, a high-frequency monitoring should be performed.

An important aspect to consider is the spatiotemporal distribution of contaminants in the waterbody. Hydro-meteorological conditions, such as flowrate variation and thermal stratification, impact the transfer time between an upstream monitoring point and a downstream area of interest. Due to climate change, heat waves occur more frequently in Summer, causing vertical thermal stratification. During these episodes, flow velocity vertical differences impact the spatiotemporal distribution of contaminants. A hydrodynamic model would allow to estimate the impact of hydro-meteorological conditions.

The main objective of this paper was to show the relevance of a 3D hydrodynamic model implementation to simulate the impact of hydro-meteorological conditions on the waterbody hydrodynamics. The study site was Bassin de La Villette (Paris, France), where a bathing area, open during summertime, needs an assessment of sanitary risk. Field data were obtained from a continuous monitoring system of water temperature at three depths and electrical conductivity, installed at upstream and downstream of Bassin de La Villette.

To validate the hydrodynamic model, two hot weather periods (7-12 August 2020 and 13-23 July 2022) and two periods with large conductivity variation (1-10 June 2021 and 3-23 September 2022) were considered. Finally, we illustrated how a bacterial contamination event (12-22 September 2021) can be simulated by using this hydrodynamic model.

2 MATERIALS AND METHODS

2.1 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 at upstream that widens to a basin of 75 m wide and 700 m long downstream, where the bathing area is located (Figure 1). The whole system is 1500 m long, has a mean depth of 3 m and a mean flowrate of 2 m³/s.

The continuous monitoring system includes two measurement points. The upstream point (A) is in the inlet of the canal, and point B is 1000 m downstream (Figure 1). Both points are equipped with a conductivity sensor (OTT MS5 and OTT DS5 at points A and B, respectively) and a vertical chain of temperature sensors at three depths (Campbell Scientific). Additionally, point A is equipped with a water level sensor (CP5240 Hitec). The timestep of all measurements is 20 min.

For assessing microbiological contamination, the relationship between fluorescent dissolved organic matter (FDOM) and microbiological activity was used. Sub-surface water samples were collected at point C (Figure 1) for *E. coli* and FDOM measurements. A total of 10 samples were collected between June and end of September 2021. Samples were collected at an hourly time step by an automatic sampler for 24h, from 9AM to 9AM the day after. The samples were manually mixed to obtain daily mean samples. In addition, during a rainfall event (12-22 September 2021), 9 samples were collected at point A (0.40 m depth) for FDOM measurements.

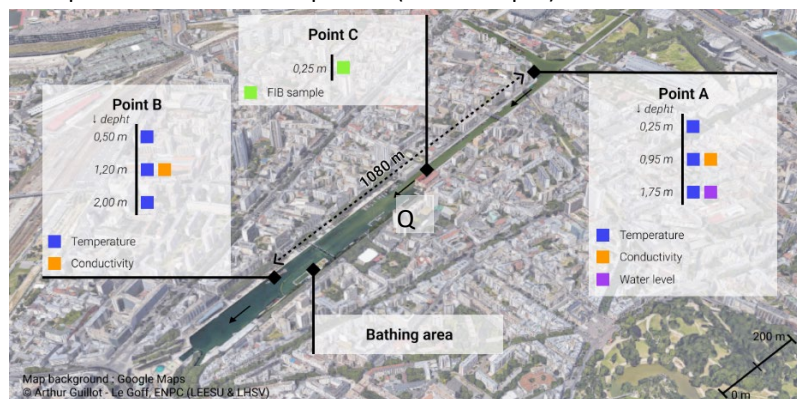


Figure 1. Location of measuring stations at La Villette

E. coli was enumerated according to ISO 9308-3 method. The FDOM measurements were performed in the laboratory, on a Cary Eclipse Fluorescence Spectrophotometer (Agilent Technologies). The absorbance at 254 nm

was obtained by using a Lambda 35 spectrophotometer (PerkinElmer). The processing of the excitation-emission matrix (EEM) spectra was conducted according to (Murphy et al., 2013), using the drEEM toolbox for Matlab R2022b. Fluorescence intensities are expressed in Raman Units (RU) according to Lawaetz and Stedmon (2009). Tryptophan-like fluorescence (peak T) is associated to microbiological activity (Coble, 2007). It is centred on ex/em 275/340 nm. The range of FDOM and *E. coli* measurements was 0.13-0.75 RU and 98-1400 MPN/100mL, respectively. The obtained relationship between FDOM and *E. coli* ($r^2 = 0.64$, $p\text{-value} < 0.001$) was defined according to Equation 1, with [*E.coli*] in MPN/100mL and peak T in RU.

$$[E.coli] = 1381 \cdot peak T \quad (Eq. 1)$$

2.2 Hydrodynamic model

The hydrodynamic 3D model TELEMAC-3D (v8p3 for Linux), from the open-source TELEMAC-MASCARET (<http://www.opentelemac.org/>) was used. The 3D grid was composed by 10 layers of 0.30 m depth, with an edge length of around 5 m. The upstream boundary condition was defined as an open boundary with prescribed surface water level, water temperature and tracer values. Downstream, an open boundary was defined with prescribed flowrate. The lateral boundaries were defined as solid walls.

To compute heat exchange between water and atmosphere, the required meteorological data were air temperature, cloud coverage, wind speed and direction, atmospheric pressure, relative humidity and precipitation. The hourly data were obtained from Orly Météo-France station. The vertical turbulence model was the Nezu and Nakagawa mixing length. The horizontal turbulent viscosity was considered constant.

At the upstream inlet, water temperature, conductivity and water elevation measured at point A were used as forcing data. For the simulation of the contaminant transfer, upstream fluorescence intensity of peak T was used as forcing data. Downstream, the outlet flowrate was calculated from the Manning-Strickler equation, using the water level measured at point A.

The simulated variables were the surface water elevation, temperature, velocities and the passive tracers. The adopted tracers were the conductivity and the indicator of microbiological water quality, peak T.

2.3 Model validation

Two hot weather periods were simulated (7-12 August 2020 and 13-23 July 2022) to validate the model ability to simulate water temperature and thermal stratification. Two periods (1-10 June 2021 and 3-23 September 2022), when large variations of conductivity were observed, were simulated to validate the mean flow velocity. The transfer time from point A to point B was estimated through the lag time of conductivity variation between upstream and downstream sites.

For illustrating the model aptitude to simulate a bacterial contamination consecutive to a rainfall episode, the period of 12-22 September 2021 was considered. A total rainfall of 48 mm over 48h took occurred on September 14th and 15th. Simulated peak T was converted to *E. coli* according to Eq. 1 and compared with field data.

3 RESULTS AND DISCUSSION

In both hot weather periods of August 2020 (Figure 2-a) and July 2022 (Figure 2-b), the water temperature range was from 23 to 27°C. The water column was stratified during the day, with a difference between surface and bottom temperatures of up to 1.5 °C. At night, the water column was mixed. A good agreement between field data and simulation results of water temperature was obtained, with RMSE around 0.37°C in August 2020 and 0.26°C in July 2022 and for both periods, r^2 close to 0.8. The gap between surface and bottom temperature had similar values for both simulated and field data (RMSE around 0.2 °C). The highest temperature gaps occurred at the same time for field data and simulation results.

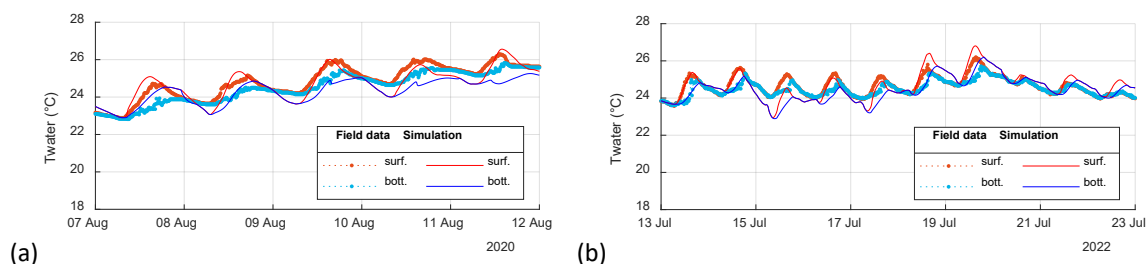


Figure 2. Measured (dotted) and simulated (line) water temperature in August 2020 (a) and July 2022 (b) at point B

In the episode of conductivity variation, in June 2021, conductivity decreased from around 800 to 600 $\mu\text{S}/\text{cm}$ in

three days and increased again to 770 $\mu\text{S}/\text{cm}$ in the following three days (Figure 3-a). In September 2022, the conductivity increased from 580 to 680 $\mu\text{S}/\text{cm}$ in three days. Variations of over 50 $\mu\text{S}/\text{cm}$ were observed during this period (Figure 3-b). Conductivity was very well reproduced by the model at downstream in both simulated periods, in June 2021 (RMSE = 8 $\mu\text{S}/\text{cm}$, $r^2 = 0.98$) and in September 2022 (RMSE = 3 $\mu\text{S}/\text{cm}$, $r^2 = 0.99$).

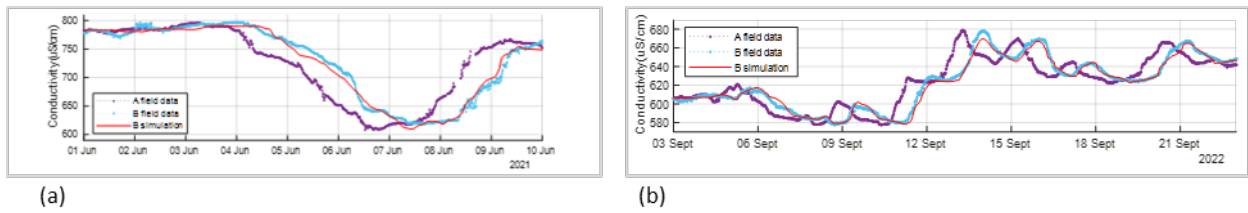


Figure 3. Measured conductivity at point A (upstream, purple) and measured (blue) and simulated (red) conductivity at point B (downstream), in June 2021 (a) and September 2022 (b).

The time lag between local peaks and valleys from upstream to downstream was used to estimate the mean transfer time. In September 2022, the transfer time estimated from field data ranged from 13h to 20h20min and the mean velocity ranged 1.5 to 2.3 cm/s. The transfer time from simulated results ranged from 15h10min to 21h40min and the mean velocity from 1.4 to 2.0 cm/s (Figure 4).

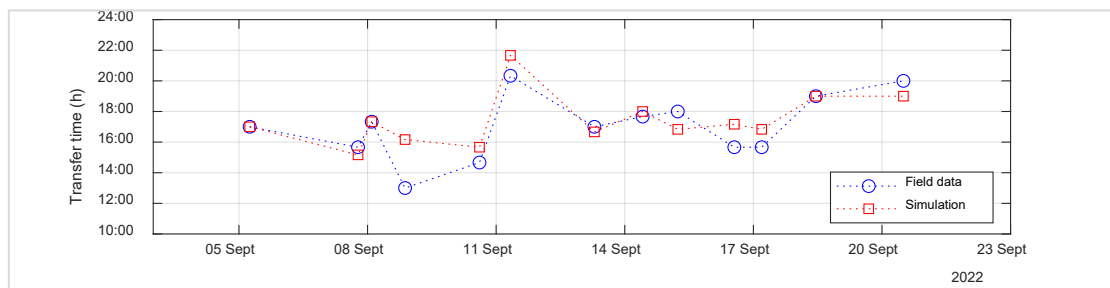


Figure 4. Transfer time estimated from field data and simulated results in September 2022

Finally, the transfer of a bacterial contamination consecutive to a rainfall episode, in September 2021, was simulated. At point A, punctual values of peak T were linearly interpolated and used as upstream input. Simulated peak T values at point C were converted to *E. coli* concentrations according to Eq.1 and compared with field data. All the field data were within the 95% confidence interval of the simulation results.

According to the simulation results at the bathing area, *E. coli* threshold for bathing (900 MPN/100mL) was overpassed between 16th Sep. at 1PM in the bottom and at 6PM in the surface, and 21st Sep. at 9.30 AM (Figure 5). Thus, the bathing area would had been closed from September 16th afternoon to 21st at 10AM.

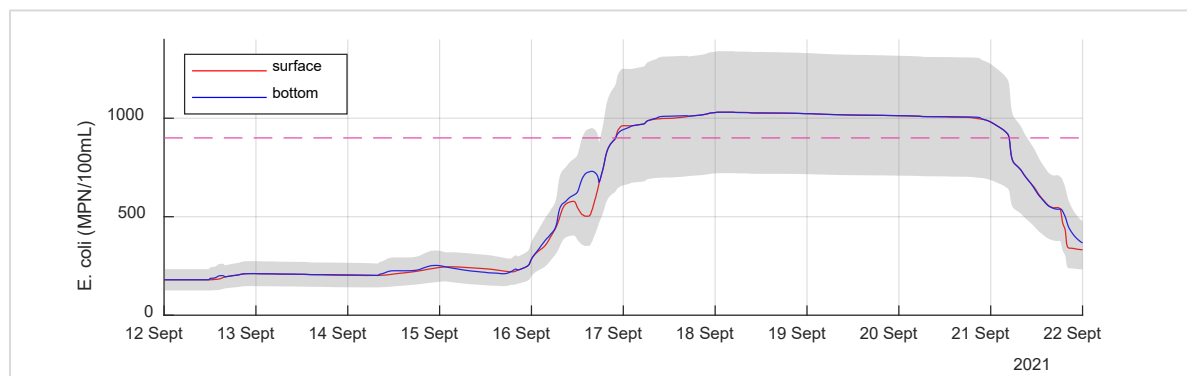


Figure 5. *E. coli* concentrations from simulated peak T at point B (dash line: *E. coli* threshold for bathing activity).

4 CONCLUSION

The thermal stratification was well simulated. The conductivity evolution from point A to point B was also well simulated. The transfer time estimation with field data and with simulation results was very close, indicating a good estimation of the mean flow velocity. The transfer of bacterial contamination was correctly simulated. The

simulation provided the duration of the overpass of the regulatory threshold for bathing activities, at the bathing area. These results show the capability of Telemac 3D hydrodynamic model to simulate the impact of hydro-meteorological conditions on the fate of contaminants. Combined with a continuous monitoring station, it could be implemented as an early warning system for decision making and sanitary risk attenuation.

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