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Development of a tool for modelling the fecal contamination in rivers with turbulent flows – Application to the Seine et Marne Rivers (Parisian Region, France)

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Abstract: Bacterial pollution in the water comes in particular from *Escherichia coli* and fecal coliforms, responsible for gastroenteritis and diarrhea, *intestinal streptococci* or *enterococci* (urinary tract infections and peritonitis), *salmonella* which can cause serious gastroenteritis, shigella (dysen-teritis, gastroenteritis), cholera vibrio (cholera). As 23 sites on the Seine and Marne Rivers (Parisian Region) would be identified as the natation competition sites for the Paris-2024 Olympic and Paralympic Games, the water quality at these sites should be seriously monitored. Numerical modelling can be considered as one powerful tool to watch the water quality parameters. However, measurements show that the water quality is not homogeneous in a river cross-section, and one-dimensional (1D) models are not enough to accurately calculate the bacteriological concentration dispersion in the aquatic environments. Therefore, a two-dimensional model has been developed by coupling between the TELEMAC-2D model and its water quality module WAQTEL for simulating bathing water quality in the Seine and Marne Rivers. The model was validated against in situ measurements and was compared against a 1D model. Results show that this model can simulate not only the longitudinal evolution but also the transverse dispersion of bacteriological pollutants. Then, a 3D multi-layer model has been developed around a bathing site using the TELEMAC-3D model. The result of the 3D model is promising and allows us to get a finer representation of the bacteriological concentration in three dimensions..

Keywords: bathing sites; water quality; *Escherichia coli*; numerical modelling.

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1. Introduction

Swimming is a recreational activity during the summer, allowing you to cool off in hot weather. It is also a sport. In urban rivers in cities with millions of inhabitants, the question therefore arises is whether swimming would be possible, or in other words, is the water quality safe for swimming [1]?.

Indeed, there is a high demand for swimming in urban areas with a particular interest in water quality: In Berlin, a study shows that 46% of the bathers questioned are ready to pay to improve the quality of the water in their area's swimming site [2]. Faced with this demand, bathing sites have opened in various European metropolises such as Amsterdam, Rotterdam, Dublin, or Berlin.

In Paris, with the preparation of the Paris-2024 Olympic and Paralympic Games, various bathing sites along the Seine and Marne rivers have been identified and put forward within the framework of an expression of interest [3].

In total, 23 sites have been identified spread over 16 interested cities:

- 6 sites in Seine-Upstream
- 5 sites in Paris
- 7 sites in Seine-Downstream
- 5 sites in Marne

Figure 1 presents the identified bathing sites in the Seine and Marne Rivers.

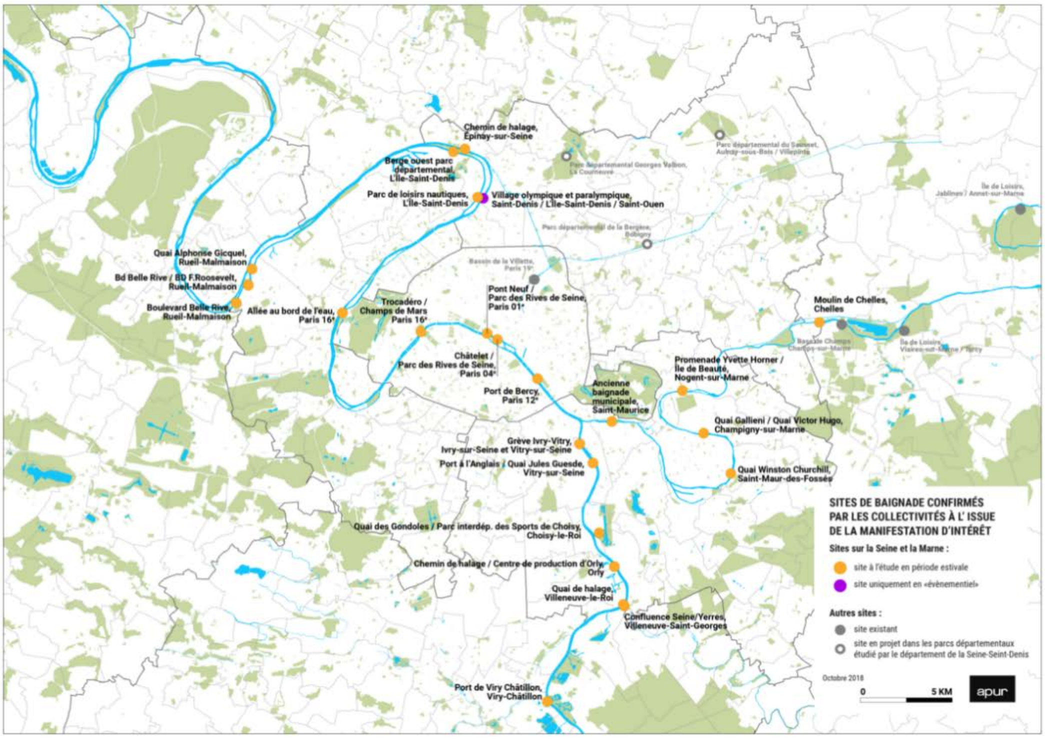


Figure 1. Bathing sites in the Seine and Marne Rivers confirmed by local authorities following the expression of interest (from [3])

Bacterial pollution in the water comes in particular from *Escherichia coli* and fecal coliforms, responsible for gastroenteritis and diarrhea, *intestinal streptococci* or *enterococci* (urinary tract infections and peritonitis), *salmonella* which can cause serious gastroenteritis, shigella (dysenteritis, gastroenteritis), cholera vibrio (cholera).

The European Bathing Water Directive 2006/7/EC highlights the measurement of two microbiological parameters, *Escherichia coli* (EC) and *intestinal enterococci* (IE), as Fecal Indicator Bacteria (FIBs) in the context of monitoring the bathing water [4]. Indeed, EC is the most widely used indicator of Fecal Contamination (FC) and is presented as the best indicator to monitor the sanitary quality of freshwater [5].

When assessing the sources of fecal contamination of rivers, it is usually to distinguish point sources from non-point sources, also called diffuse sources. In an urbanized area as the Seine and the Marne Rivers, the major point source of fecal bacteria consists of Waste Water Treatment Plants (WWTPs) effluents, since most of inhabitants are connected to sewers driving their wastewaters to WWTPs. However, the direct discharge of untreated urban wastewater through Combined Sewer Overflows (CSOs) as well as discharge of some industrial effluents can also contribute to contamination. Rainfall is likely to have a huge impact on the load of fecal bacteria. Due to CSOs and sometimes incomplete treatment in WWTPs in wet weather situations, point sources increase during rain events as well as the non-point sources due to an increased surface runoff.

Once released in rivers, the disappearance of fecal bacteria in aquatic environments results from the combined actions of various biological (protozoan, grazing, lysis) and physico-chemical parameters (nutrients concentration, sunlight intensity and temperature). In addition, fecal bacteria can be removed from the water column through sedimentation. The attachment of fecal bacteria to particles in suspension has important implication for their fate and their mortality after release in river waters [6].

Being aware that modelling is a useful tool to monitor the water quality in rivers, and helps to better understand the sources, fate and transport of the fecal contamination, different numerical models have been developed in the Seine and Marne Rivers to simulate the distribution of FC. First, a module describing the dynamics of fecal bacteria has been developed by Servais in [6]. This module has been coupled on the one hand, to a model of the entire Seine basin up to the estuary mouth (SENEQUE model) [6], and, on the other hand, to a three-dimensional hydrodynamic model of the Seine estuary (SiAM-3D model) [7]. In this FC module, two main processes controlling the fate of FC were considered: mortality and settling. Only one stock of FC was considered in the FC-SENEQUE model, while the FC-SiAM-3D model considers two stocks of FC in the river (free FC and FC attached to suspended sediments). In this model, only attached FC can settle and different mortality rates were considered for free and attached FC.

In 2013, the improved FC module has been coupled to the one-dimensional hydraulic model of PROSE and this model was used to analyze the impact of CSOs in rainy weather [8].

These three models correctly simulate the longitudinal distribution of fecal coliforms in the main rivers of the Seine watershed (SENEQUE and PROSE models) and in the estuary (SiAM-3D). However, none of the studies presented above indicated the high variation of FC concentrations in the transverse direction. Recent measurements carried out in the Seine and Marne rivers in the Parisian Region show that the concentrations of *E .coli* and IE bacteria vary considerably between the river center and the river banks, even in sections, in which there are no external contributions of contaminants [9].

Thus, to establish a precise microbiological state of bathing sites, it is essential to develop a modelling tool, which is able to represent this heterogeneity in the transversal direction.

This paper aims to present a coupled 2D/3D hydrodynamic and microbial water quality model (TELEMAC– WAQTEL model) for studying the fate and transport of *E. coli* in the Seine and Marne Rivers, taking into account the bacterial decay and the settling processes. Three stocks of *E. coli* in rivers were considered: free *E. coli*, *E. coli* attached to suspended sediments and *E. coli* in the deposited sediments. The three stocks are affected by a different mortality rate (first-order kinetics). Attached *E. coli* can settle and deposit in the sediment, while *E. coli* in the deposited sediments can be re-suspended in the water column. The model has been first validated against the measurements in the Seine and Marne Rivers from [9] and then compared with the results of the 1D ProSe model developed within the framework of the PIREN-Seine research program [8]. The simulations will highlight the spatial variability of microbial pollutants not only in the longitudinal but also in the transverse directions in these two rivers. This modeling tool will be used to support monitoring the water quality around bathing sites.

2. *E. coli M*odel selection

2.1. Hydrodynamic modelling

As a first step, the hydrodynamics of rivers must be accurately reproduced, including the processes of advection and dispersion.

To assess the pollutant plumes transported by a river, the fluxes of solute pollutants are generally calculated by multiplying the concentration of matter in all or part of the river by its water discharge passing through the measurement section. This method only allows very rough estimations due to the heterogeneity of the flow in rivers.

However, the heterogeneity of concentrations, downstream of the pollutant plumes, indicates that despite the turbulent nature of their flow, the FIBs do not mix instantly over the entire section of rivers [9]. Other circulations are involved in the redistribution of FIBs within the flow, which depends on the transverse flows of particles.

In the laboratory, these transverse phenomena were demonstrated by Taylor [10] with the classical experiment of a viscous flow in a pipe carrying a solute, showing that the longitudinal transport depends on transverse flows.

In rivers, this phenomenon is amplified by the turbulent nature of the flow, in which the longitudinal velocity profiles depend on the transverse flows with momentum exchanges between the flow and the bed materialized by the stresses that drive the sediments. It is then not possible to calculate the flow of solutes and suspended particles, and therefore of FIBs in a river without accounting for the heterogeneity of the velocity fields and their large fluctuations, characteristic of turbulent flows, within which the trajectories are not stationary.

More recent studies and observations show that turbulence generates mean secondary flows in the plane orthogonal to the main flow not only in meandering rivers but also in straight sections of rivers or channels, in which the flows are not subjected to the action of centrifugal force [11].

More recently, in 2012, secondary flows perpendicular to the direction of the main flow were highlighted by a researcher of the University of Paris Diderot, using ADCP measurements in the Seine at the bridge Simone de Beauvoir in Paris. The stationary vortices extend across the entire channel and rotate at about 0.3% of the streamwise velocity, in accord with prior laboratory observations [12].

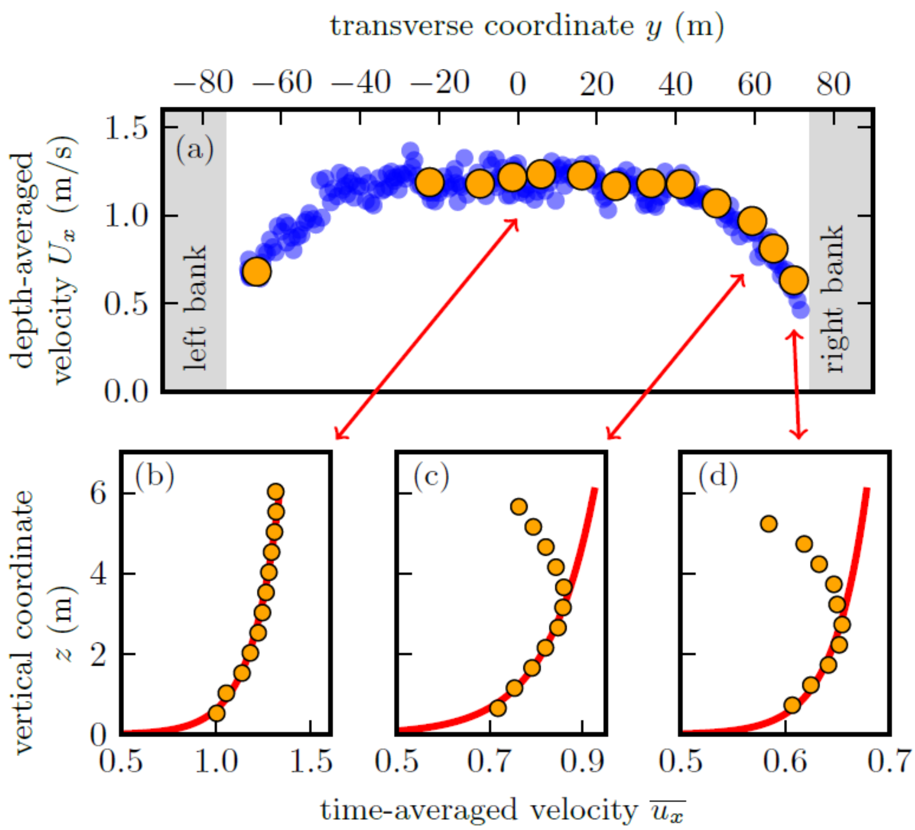


Figure 2. Streamwise velocity measurements (ms^{-1}) in the Seine river during winter high flow (a) Depth-averaged velocity Ux from moving measurements (blue) and from static measurements (yellow); (b), (c) and (d) Time-averaged depth profiles with fitted logarithmic profiles (red curve) (from [12])

In conclusion, multiplying the averaged discharge with the concentration of the FIBs within a plume, cannot correctly represent the heterogeneity of the velocity field in rivers nor the dynamics of fecal contamination in a bathing site. We need a modelling tool to generate spatially and temporally continuous concentrations and to better understand the transport of fecal contamination.

2.2. Physical representation of FIB dynamics

In addition, we are interested in models that provide a reliable physical representation of the evolution of the concentrations of EC and IE markers in the liquid mass.

These contaminations are transported in the form of microorganisms of varying sizes. The finest particles (free FIB) are held in suspension by the turbulence of the flow and occupy the entire water column. They are transported by advection. The attached FIB to suspended sediment are carried and dispersed in the water mass as a tracer, but also subject to the laws of sedimentary physics: they settle in calm waters and produce areas of polluted sediment (attached FIB to bed sediment) and can be re-suspended by a strong flow.

These three families of FIB behave differently with respect to sedimentation and are affected by a different mortality rate. In general, bacteriological pollution of fecal origin at a bathing site disappears after 24 to 72 hours in the presence of sun. In contrast, it can last a few days in dark conditions [13].

This disappearance results from the combined action of various physicochemical and biological parameters, which interact with each other [14]. The predominant factors that influence mortality including temperature, salinity, sunlight, and pH, will be one-by-one discussed in more detail below.

In inland rivers, the salinity is almost zero and therefore has no effect on coliform mortality.

The effect of temperature on the decay of bacterial populations should be evaluated in the dark to eliminate the effect of solar radiation. If salinity and pH are kept constant, then the effect of temperature can be represented by the Arrhenius expression [15]:

$$\boldsymbol{k_d(t) = k_{d20}\vartheta_M{}^{T-20}}, \quad (1)$$

Where T (°C) is the temperature of the water; k_{d20} is the rate of degradation of microorganisms observed at 20 °C in fresh water, and ϑ_M is a parameter which controls the sensitivity of k_d to variations in T.

The graphs in Figure 3 from [15] illustrate the effect of temperature on bacterial mortality based on the research conducted at different time by four different research laboratories. Data in these graphs were collected from aquatic environments with salinity below 3‰ and pH between 6 and 8 to neutralize the effects of excessive salinity and acidity / alkalinity in the studied aquatic environments. Two environments were tested: an environment rich in nutrients and another poor in nutrients. In the graphs, the black curve is optimum fit curve. Thus, the parameters of this curve are presented in Table 1.

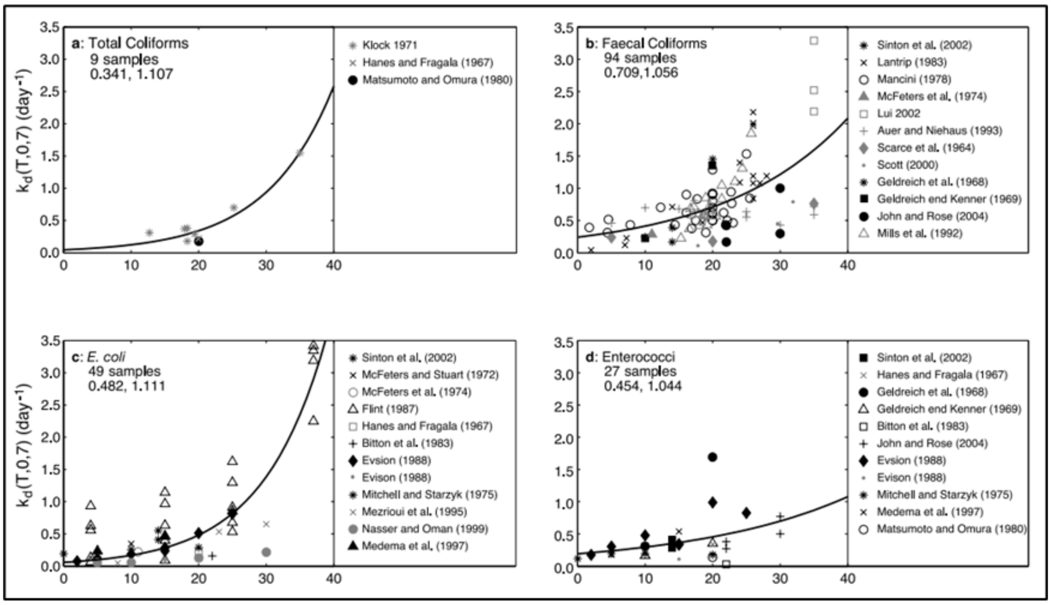


Figure 3. Variation of natural mortality (''dark death'') rates *kd (T, S, pH)* as a function of temperature for 4 different organism groups. Only investigations from waters with salinity <3% (S < 3%)and pH values between 6–8 were included. Data points collected from studies in a relatively nutrient rich medium are shown in gray and points collected from studies conducted within a nutrient poor medium are colored black. The solid line indicates the optimum fit to the data for equation (1) based on a least square regression with all data and model parameters k_{d20} and ϑ_M are included (from [15]).

Table 1. Parameters of the optimum fit curve.

Parameter	Symbol	*E. coli*	*Enterococci*
Mortality rate in fresh water	$k_{d20}(d^{-1})$	0.48	0.45
Mortality temperature multiplier in fresh water	$\vartheta_M(-)$	1.11	1.04

The data shows high variation in the mortality rate as a function of temperature. A similarity can be observed between coliforms, with temperature multipliers, ϑ_M, of 1.04 – 1.11. However, E. coli shows a higher sensitivity to temperature than enterococci.

The effect of *pH* on survival of coliforms has been studied in fresh and saline water. Although there is some doubt about the optimum *pH* (i.e., the *pH* at which the decay rate is least), most authors found mortality rates significantly increase outside of the "neutral" range (Figure 4).

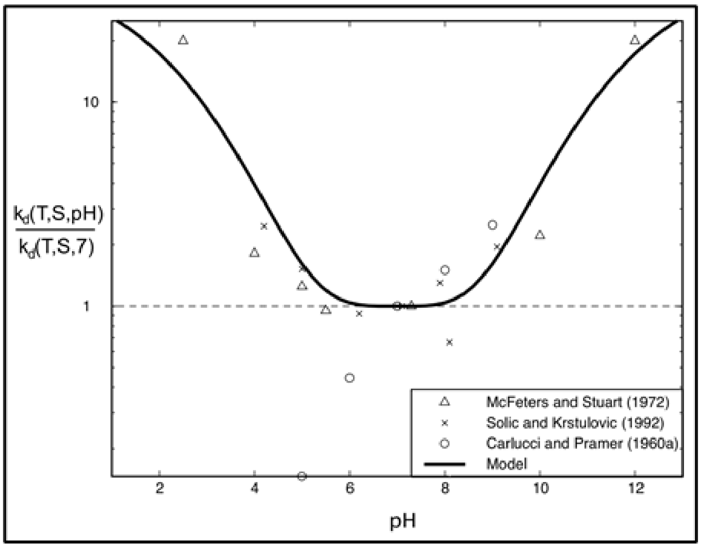


Figure 4. Mortality of coliforms $k_d(T, S, pH)$ as a function of *pH* where T is temperature, S is salinity (from [15])

Sunlight exposure is an important inactivation mechanism for all forms of pathogens and microbial indicators in both fresh and saline waters. Evison [16] observed that the effect of light is extremely important, the lethal effect of light increasing with increasing intensity, as would be expected. However, the inactivation mechanism due to solar radiation is only dominant in waters of high clarity. Consideration must also be given to the attenuation of radiation with depth and the attenuation of radiation by the suspended load.

In conclusion, temperature is usually the predominant factor in the degradation of *E. coli* in rivers such as the Seine and the Marne.

Thus, to establish a precise microbiological state of bathing sites, and to quantify the risks caused by microbial pollutants, it is needed, on the one hand, to consider the important factors determining the mortality rates of the contamination indicators, and on the other hand, to model the longitudinal and transverse dispersions of contaminant pollutants in the natural environment with precision.

Many studies have shown that concentrations of fecal contaminants in waters can be described using coupled 2D or 3D hydrodynamic and water quality models [17], [18], [19].

In this study, the TELEMAC-MASCARET system has been selected [20] as this tool not only provides high spatio-temporal resolution information about water depths, velocities but also that its source code can be modified thanks to the open-source code. The modelling environment can also be launched on parallel processing which significantly reduces computational time.

The open-source TELEMAC-MASCARET system is a set of modelling tools allowing the treatment of every aspect of natural free-surface hydraulics: 1D, 2D or 3D currents (MASCARET, TELEMAC-2D, TELEMAC-3D), sedimentology (SISYPHE, GAIA), water quality (WAQTEL), wave (TOMAWAC), underground flows (ESTEL-2D, ESTEL-3D). It was first developed by the National Hydraulics and Environment Laboratory (LNHE), of the Research and Development Division of EDF (EDF R&D).

Its 2D hydrodynamics module, TELEMAC-2D, solves the so-called shallow water equations, also known as the Saint-Venant ones, using the finite-element or finite-volume method and an unstructured mesh of triangular elements [21].

Its 3D hydrodynamics module, TELEMAC-3D, uses the same horizontally unstructured mesh as TELEMAC-2D, but solves the Navier-Stokes equations, whether in hydrostatic or non-hydrostatic pressure distribution allowing shorter waves than those in a shallow water context [22].

The WAQTEL (Water Quality TELemac) [23] module is the water quality module that was developed by LNHE for the TELEMAC-MASCARET system.

For the present study, a general 2D model has been proposed by the direct coupling of TELEMAC-2D and WAQTEL. For each step of calculation time, the coupling is done in the following way:

- TELEMAC-2D calculates the difference in level of the free-surface level, the velocity field;
- WAQTEL calculates the transport of suspended sediments, the bedload, and the transport of bacteria.

Then, a 3D sub-model has been developed to model a smaller domain around bathing sites. This is suitable in the case where we observe the presence of significant transverse and vertical convective phenomena linked to recirculation currents due to the morphologic and bathymetric changes. It is worth noting that 3D models are more time-consuming than 2D models.

In the water quality module WAQTEL, the sub-module MICROPOL was selected. This module is dedicated to model the evolution of micro-pollutants in rivers. It introduces 5 tracers:

- Suspended sediment (SS)
- Bed sediment (SF)
- Free micro-pollutants (C)
- Micro-pollutants absorbed by SS (C_s)
- Micro-pollutants absorbed by SF (C_f)

The evolution of suspended solids (SS) and bottom sediments involved in this module is represented by the classical deposition and re-suspension laws for cohesive sediment of Krones and Partheniades.

$$SED = \begin{Bmatrix} wSS\left(1 - \frac{\tau_b}{\tau_s}\right) if\ \tau_b < \tau_s \\ 0 \qquad\qquad if\ \tau_b \geq \tau_s \end{Bmatrix}, \quad (2)$$

$$RS = \begin{Bmatrix} e\left(\frac{\tau_b}{\tau_r} - 1\right) if\ \tau_b > \tau_r \\ 0 \qquad\qquad if\ \tau_b \leq \tau_r \end{Bmatrix} \quad (3)$$

,

Where SED is the deposition flux

RS is the erosion flux

τ_b is the bottom shear stress

τ_s is the critical shear stress for sedimentation

τ_r is the critical shear stress for re-suspension

e is the Partheniades constant

wSS is the settling velocity

The model representing the evolution of micro-pollutants assumes that the transfer of micro-pollutants between the dissolved and particulate phases correspond to either adsorption or ionic exchanges modeled by a reversible reaction of 1st kinetic order. Without any data to calibrate these functions, for the sake of simplicity, we considered that these two fractions evolved independently, without any interaction between them. And the ratio of free bacteria to total bacteria was estimated based on measurements.

The model also includes an exponential decay law of micro-pollutant concentrations in each compartment of the modeled ecosystem, through a constant L.

$$C_t = C_0\ e^{-Lt}, \quad (4)$$

Where:

C_0: concentration of micro-pollutants at time 0

C_t: concentration of micro-pollutants at time t,

L: is the mortality rate

By default, this mortality rate is constant in WAQTEL. Within this work, the mortality law was modified to consider the effect of temperature following the equation (1).

The internal sources of each of these tracers correspond to the phenomena of deposition/re-suspension and exponential decay. Taking these phenomena into account leads to the following equations of the evolution of micro-pollutants F in each of the three compartments, water, suspended particulate matter (SS) and bottom sediments (SF).

Dissolution phase:

$$F(C) = -L.C, \tag{5}$$

Adsorption by SS phase:

$$F(C_{SS}) = -L.C_{SS}, \tag{6}$$

Adsorption by bottom sediments (tracer neither advected nor diffused):

$$\frac{\partial C_{ff}}{\partial t} = \frac{SED}{SS}.C_{SS} - \frac{RS}{SF}C_{ff} - L.C_{ff}, \tag{7}$$

where $C_{ss} = SS.C_S$ and $C_{ff} = SF.C_f$

Given the similarity between micro-pollutants and fecal bacteria, it was decided to use this module to model the evolution of FIB.

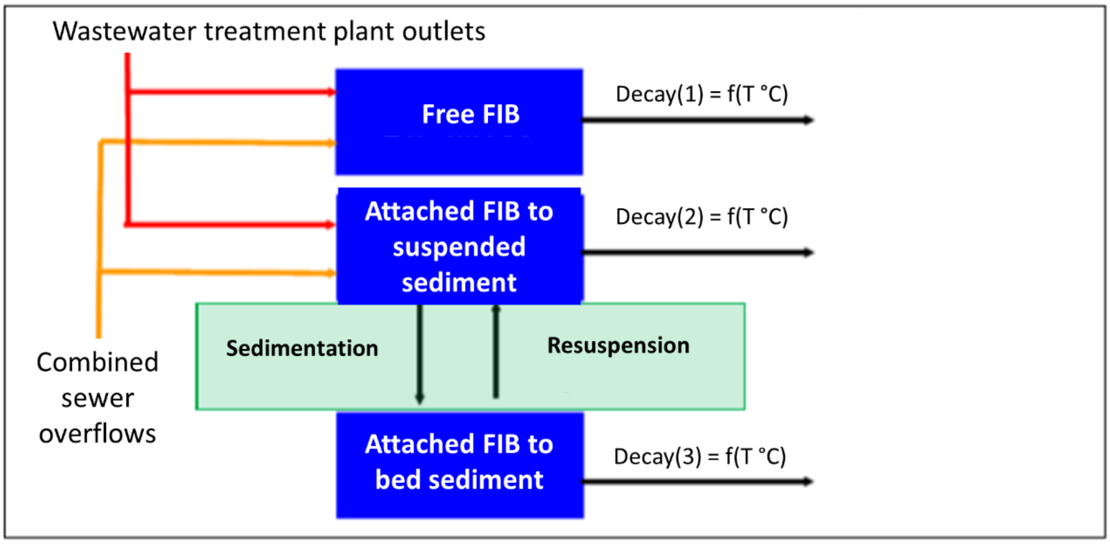


Figure 5. Scheme for modelling bacteriological concentration dispersion in WAQTEL module

3. Model application

3.1. Study area

The Seine is a navigable river along two thirds of its course. The Marne is also classified as navigable and channeled over 183 km from Epernay to its confluence with the Seine.

The Seine and the Marne share the same hydrographic regime with a maximum discharge in January and a minimum in August.

Upstream reservoirs on the Seine and main tributaries (Marne, Aube, Yonne) contribute to a minimal flow of 70 to 100 $m^3 s^{-1}$ in the Seine and of 56 $m^3 s^{-1}$ in the Marne during summer.

The Marne River presents a complex geomorphology with pronounced meandering and islands of different shapes and sizes which the turbulent flow plays an important role while the Seine River is consisted of straight sections with less turbulent flow.

The 16 million of inhabitants of Île de France represent 28% of the total population of France. Paris and its suburbs constitute the major anthropogenic pressure within the basin [24]. An important sewer network brings wastewater to seven treatment plants along the course of the two rivers. Urban runoff or combined sewer overflow during rain-fall events are the predominant sources of microbial contamination during low flow periods [25].

According to the Water Directive, the water quality monitoring is required during at least four successive bathing seasons, and the data set to estimate water quality must include more than 16 samples (four samples per season).

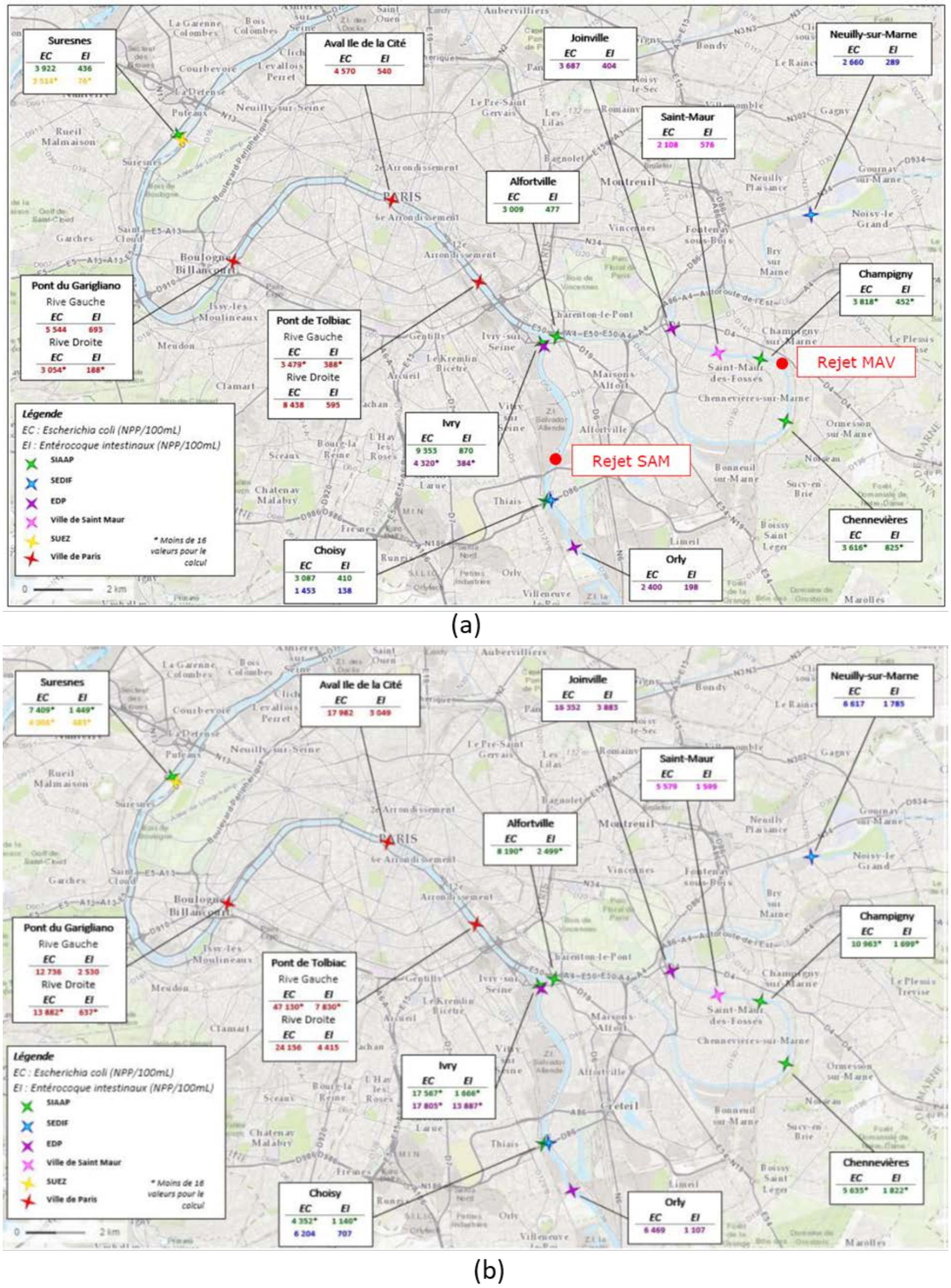


Figure 6. Percentile 90th of *E. coli* (EC) and *intestinal enterococci* (IE or EI in French) along the Seine and the Marne for 2011-2014 : (a) dry weather; (b) rainy weather (in [26] , (p 42, 43))

Analysis of the bacteriological data from different measurement sites in the Seine and the Marne Rivers in between 2011 and 2014 allow us to highlight the spatial evolution of bacteria. They are presented in Figure 6 and summarized as below:

- The water quality along the Seine and the Marne for the period of 2011-2014 did not yet respect the EU Bathing Water Directive, especially during rainy periods (> 900 CFU/100 mL).
- In the Seine River, between Choisy-le-Roi et Ivry-sur-Seine there is a clear increase in the 90th percentile of *E. coli* due to the impact of the wastewater treatment plant Seine-

Valenton (SEV or SAM in the past) and the Fresnes-Choisy combined sewer discharge. Between Ivry and the Tolbiac Bridge, it is difficult to establish an evolutionary trend: the confluence with the Marne leads to variable concentrations which depend on hydrological conditions. The data tend to show that the 90th percentile values would decrease in dry weather but increase in rainy weather.

- In the Marne River, between Neuilly-sur-Marne and Joinville-le-Pont, there is an increase in the 90th percentiles due to the arrival in a more urbanized area. Between Joinville-le-Pont and Saint-Maur-des-Fossés, the 90th percentiles tend to decrease. However, between Saint-Maur-des-Fossés and Champigny-sur-Marne, the concentrations tend to increase. Between Chennevières and Alfortville, we observe a slight improvement in bacteriological quality, in connection with the distance to the wastewater treatment plant Marne Aval (MAV) outlet.

3.2. Data collection and analysis in dry weather

A measurement campaign was carried out on the Seine and the Marne Rivers upstream of Paris in August 2017 with the aim of producing a map of the sanitary water quality in dry weather by Mouchel et al. [9].

The Seine upstream campaign was organized on August 3rd (from PK[1] 163 to PK 149) and 4th (from PK 148 to PK 132) 2017 from Corbeil to the Seine-Marne confluence.

The Marne campaign was carried out on August 21st and 22nd, 2017 in which the sampling was organized from Gournay-sur-Marne to the Seine-Marne confluence.

One section was sampled every kilometer substantially. It is important to highlight that three points were sampled in each section: on the right bank, on the left bank and at the center of the section. Samples on each bank were collected 10 meters from the bank. All samples were collected 10 cm below the water surface.

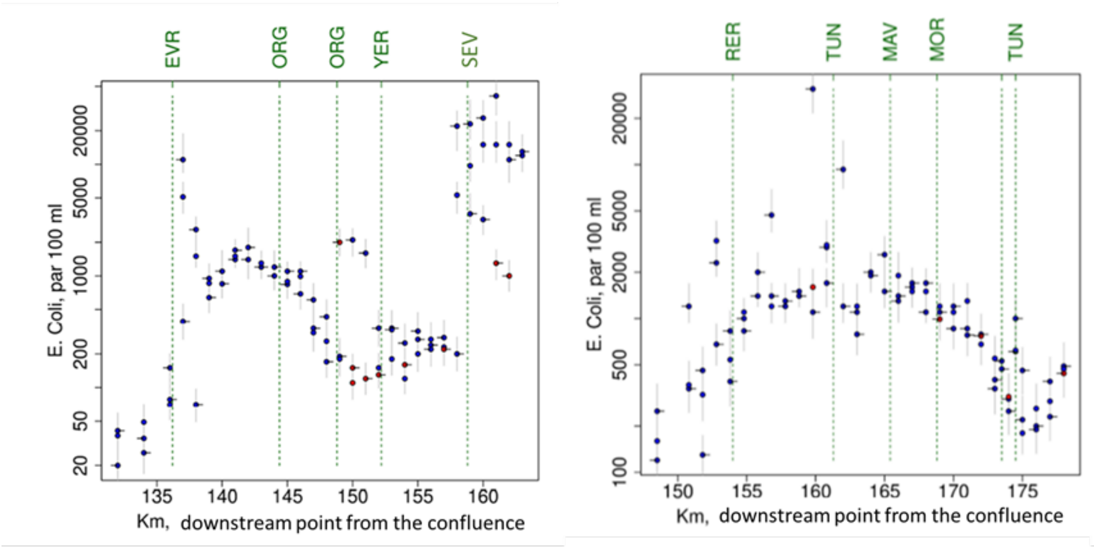
From the collected samples, analyzes were performed to determine the ratio of free bacteria to total bacteria. This ratio is 51% for *E. coli* and 49% for IE with respective standard deviations of 11% and 28%.

The bacteria mortality constants were estimated and given by Mouchel et al. [9] in Table 2. It is reminded that the obtained constants are based on strong assumptions, and examination of the curves confirms that the assumption of exponential decay is far from a perfect representation of reality.

Table 2. Estimated mortality constants in the Seine and Marne rivers (Source: [9])

Sector	PK	Constant (h^{-1})	Standard deviation	Temperature (°C)	n
Marne	166-178	0.072	0.007	20.3-21.3	44
Marne	166-173	0.074	0.009	20.3-21.3	24
Seine upstream	141-148	0.108	0.013	22.3-23.0	24
Seine upstream	141-157	0.063	0.008	22.3-23.0	51
Seine Parisian	164-173	0.036	0.007	21.6-22.2	63
Seine Parisian	175-187	0.020	0.012	21.6-22.2	33

[1] PK is a kilometric unit used by the Navigation Service of the Seine and the Marne Rivers



(**a**) (**b**)

Figure 7. The measured longitudinal evolution of *E. coli* on the Seine (a) (EVR: discharges from the Evry and Corbeil wastewater treatment plants; ORG: confluence of the Orge ; YER: confluence of the Yerres; SEV: outlet of the Seine-Valenton wastewater treatment plant) and Marne (b) rivers (RER: RER bridge, between Bry-sur-Marne and Noisy-le-Grand; TUN: entrance/arrival of the Saint Maur tunnel; MAV: outlet the Marne-Aval plant; MOR: confluence of the Morbras.) The small lines indicate the samples taken from the left bank (line to the left), right bank (line to the right) or in the center (no line). (from [9])

Longitudinal evolutions of measured *E. coli* along the Seine and the Marne are given in the Figure 7.

The measured longitudinal evolution of EC on the Seine

Compared to the measurement between 2011-2014, the water quality at the upstream limit was excellent. The sharp increase in concentrations on the left bank and at the center probably corresponds to discharges from the wastewater treatment plants of Corbeil and Evry.

Subsequently, the concentrations decreased by almost an order of magnitude, which testifies to a process of disappearance of FIB.

Another very strong increase appeared at PK 158. It was also positioned on the left bank and one kilometer upstream of the outlet of the SEV treatment plant (located on the right bank). The discharge point, which would explain the impacts, was therefore located on the left bank, between PK 157 and 158. After Mouchel et al. [6], the Fresnes-Choisy combined sewer was a plausible candidate. The Val-de-Marne department confirmed the occurrence of an exceptional release during the period when the measurement campaign was carried out. The average daily discharge rate on August 3rd was estimated at 0.25 $m^3 s^{-1}$.

The measured longitudinal evolution of EC on the Marne

In general, the bacteriological quality deteriorated regularly in the most upstream part of the sector (from Gournay-sur-Marne to the entrance of the Saint-Maur tunnel). These concentrations continued to increase reaching a maximum of the order of 2000 CFU/100 mL for EC at the entrance of the loop of Saint Maur. In this sector, we note several values clearly above the evolution trend, all located on the left bank in the cities of Bry-sur-Marne, Champigny and Joinville-le-Pont.

From PK 165, the concentrations began to decrease. At PK 170, the EC concentration was around 1000 UFC/100mL. Morbras did not appear to be a major contributor to fecal contamination in dry weather either. The EC concentration observed at PK 175 (Saint Maur tunnel) was around 200 CFU/100 mL.

After the outlet of the Saint Maur tunnel (PK 175), an increase in EC levels was observed at the confluence with the Seine without explanation.

The discharge of the Marne during the study period of August 21st and 22nd was 28 to 29 $m^3 s^{-1}$.

These data were used to validate the present models in dry weather.

3.3. Computational domain

Two 2D models have been separately developed, one on the Seine River and another on the Marne River.

On the Marne, the model extends from the bridge of Champigny to the confluence with the Seine. The model includes two liquid boundaries. The upstream limit is located about 100m upstream the outflow of the MAV wastewater treatment plant. The downstream limit of the model is located right before the confluence of Seine-Marne.

The modeled domain presents a complex geomorphology with islands of different shapes and sizes. The mesh generator Bluekenue [27] makes it possible to define the mesh according to given criteria (stress lines, size map, etc.) so that the calculations are optimized in computation time, but also in terms of precision. The mesh has 132546 nodes and 254701 elements with an averaged mesh size of 3-5 m.

On the Seine River, the model extends from the Ablon-sur-Seine dam to the confluence with the Marne River. Different from the Marne, this section of the Seine River is quite straight without islands. The mesh has 86839 nodes and 177702 elements with an averaged mesh size of 5 m.

The model domains are presented on Figure 8 below.

Most of the bathymetric data were provided by VNF[3], EPTB-SGL[4]. In the Marne, the bathymetric date from Champigny to Saint-Maur-des-Fossé were measured by PROLOG-INGENIERIE in 2019. The bathymetry ranges in between 21.49 mNGF[5] and 39.35 mNGF in the Marne and in between 21.75 mNGF and 36.42 mNGF in the Seine.

In addition, two local 3D models have been developed around a bathing site on the Seine and the Marne Rivers. On the Marne, the Saint-Maur bathing site was selected. This site is located in a complex environment that includes several islands, a navigation channel and a secondary channel. On the Seine, the Vitry-sur-Seine bathing site was selected.

The TELEMAC-3D models use the same horizontally unstructured mesh as that of TELEMAC-2D but in a smaller domain. Vertically, the TELEMAC-3D mesh was developed according to a series of horizontal layers located between the bed and the surface. For these models, we have opted for 10 vertical layers with a homogeneous distribution of layer thicknesses. Usually, bacteriological measurements are taken at a depth of about 10-50 cm from the water surface. Considering the average water depth in this area varies between 3 and 7 m, 10 layers would be sufficient to compare with the measurements if available.

[3] VNF : Navigable Waterways of France, responsible for the management of the majority of France ‘s inland waterways network and the associated facilities

[4] EPTB-SGL : EPTB Seine Grands Lacs : Public Territorial Institute of the Seine basin, responsible for the management of the navigation dams and lakes upstream the region of Paris

[5] NGF : Niveau général de la France is the official levelling network in mainland France, with the zero level detemined by the tide gauge at Marseille

(**a**) (**b**)

Figure 8. 2D computational domain on the Seine River (a) and Marne river (b). The red rectangular presents the computational domain of 3D models

These models were validated against the measured data from [9] in dry weather and compared against the results of the 1D bacteriological ProSe model [83] in rainy weather.

3.4. Physical and numerical parameters

3.4.1 Time step

TELEMAC-2D offers unconditionally stable semi-implicit solution methods. However, it is recommended to adopt a time step such that the Courant number is not larger than 3 in general. Hence, the selected time step was equal to 1 s. The same time step has been also used for the 3D models.

3.4.2 Turbulence model

For 2D models, the k-epsilon turbulence model was selected. For 3D models, it is not recommended to use the k-epsilon turbulence model in the case of stratification simulations because it can give bad results [21]. Experiences show that the k-omega vertical model is more suitable than the two Nakagawa and k-epsilon models in modelling EC concentration releases. This will be presented in detail in the §3.7.5.

3.4.3 Bed roughness

Friction coefficients were calibrated by comparison with water levels measurement. A constant Strickler friction coefficient of 40 $m^{1/3}s^{-1}$ was selected for both the Seine and Marne models after calibration.

3.4.4 Advection & diffusion parameters for tracers

For solving the advection step for tracers, the recommended scheme when there are tidal flats (scheme NERD) was selected. It is reminded that the stability of this scheme is conditioned by a Courant number lower than 1. This condition is satisfied with the selected time step of 1 s.

Similarly, the recommended method for solving tracer diffusion (the conjugate gradient method) was also selected. In TELEMAC, the tracer's diffusion coefficient should be specified because it has a very important impact on tracer diffusion in time. In version v8p1r1, this parameter is the same for all tracers. In this study, the diffusion coefficient of FIB was calibrated using the data of Mouchel et al. [9]. The calibrated value is equal to 0.01 $m^2\ s^{-1}$.

3.4.5 Sediment parameters

The erosion and sedimentation parameters depend on the physico-chemical characteristics of the sediments. Because these properties are poorly known, these parameters were kept as default values in the models, except the settling velocity. The settling velocity found within the framework of the PIREN-Seine project which is equal to 6.6 cm/h was selected [8].

3.4.6 Bacteria parameters

As mentioned in the §2.2, a sensitivity analysis was performed on the Marne model to select the best ratio between free *E. coli* to total *E. coli*. Different simulations were performed with different ratios between 25%, 50%, 70% and 100%. The model gave the best result with the ratio of 50% of free *E. coli*. Hence, this value was applied for all the models in this study. As discussed in the previous section, the water temperature is one of predominant factors to influence natural mortality. However, during summer, the observed water temperature in the Seine and the Marne varies little around 20 °C, and its effect can therefore be neglected.

The mortality constant was then calibrated using the measurement from Mouchel's campaign. Two different values were tested: the one estimated by Mouchel et al. in [6] (0.063 and 0.072 h^{-1} for the Marne and the Seine River, respectively) and the one found within the framework of the PIREN-Seine project (0.045 h^{-1} for free EC in [8]). The latter value was then selected after the calibration step.

3.5. Validation of hydrodynamic model

Firstly, the hydrodynamic model was validated against available gauges data on the Marne. The same period of the campaign in [9] (from August 21st until 22nd 2017) was selected as the validation period.

The calculated water level at the Créteil station was compared against the measured data extracted from https://www.hydro.eaufrance.fr/. The position of this station is given in Figure 9. Figure 9 shows good agreement between the measured and calculated values.. It is necessary to re-mention that the Seine and Marne are navigable rivers with many dams along the rivers. In summer with low discharges, the water level between two dams is normally maintained at retention level.

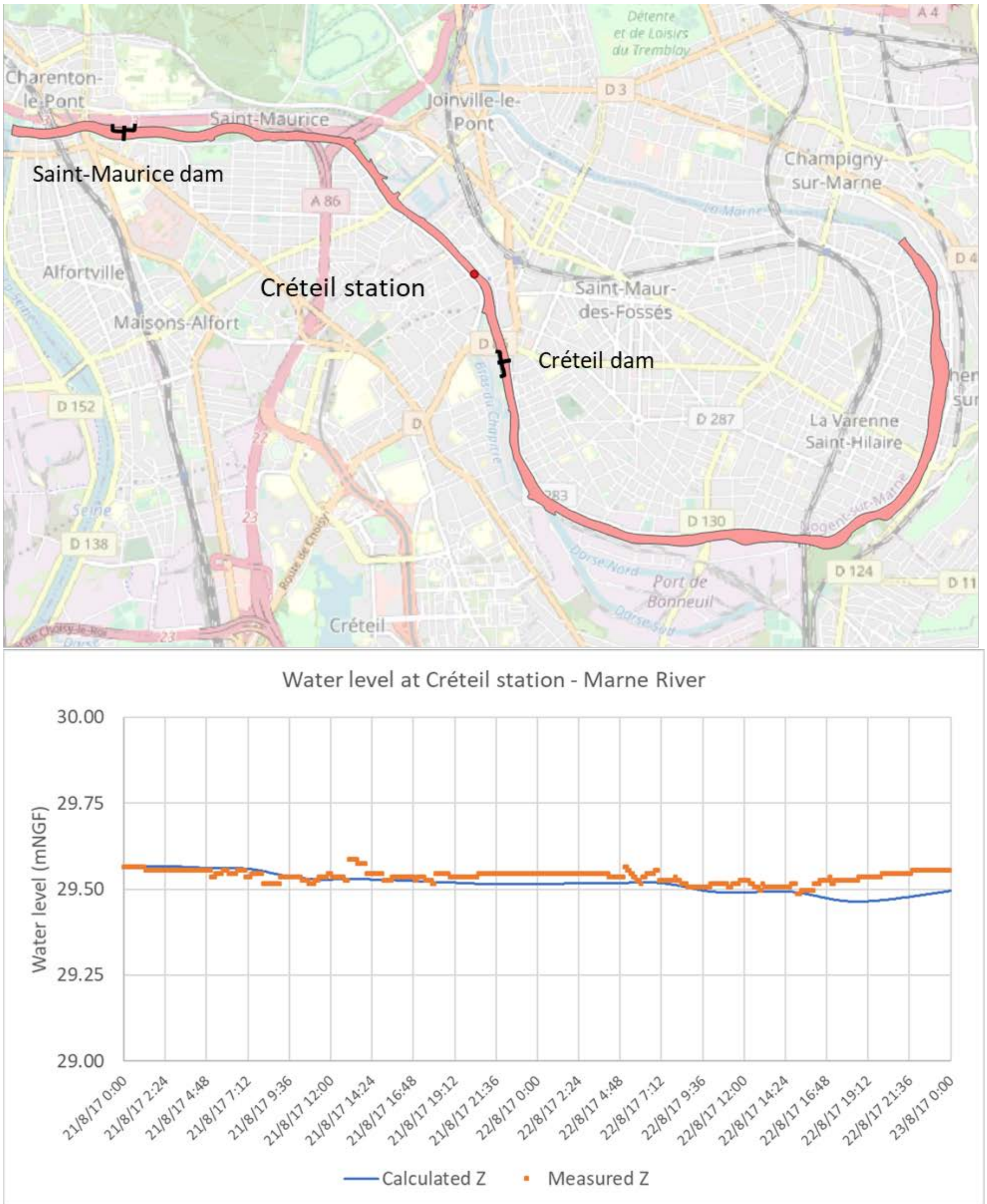


Figure 9. Comparison between measured and calculated water level at Créteil station (red dot) on the Marne River

Furthermore, a comparison was made between the calculated and estimated average velocity along the longitudinal profile of the Seine and Marne during the same period as the campaign in [9]. The average velocity calculated by the TELEMAC-2D model is illustrated in Figure 10. Figure 10 shows that the velocity is of the order of 0.15 m s^{-1} on the upstream Seine between PK 151 and PK 163, which agrees well with the values estimated during the measurement campaign in 2017.

On the Marne, a similar result was also obtained. The average velocity calculated by TELEMAC-2D model varies between 0.1 and 0.14 whereas the value estimated by Mouchel et al. in [9] is 0.124 m s^{-1}.

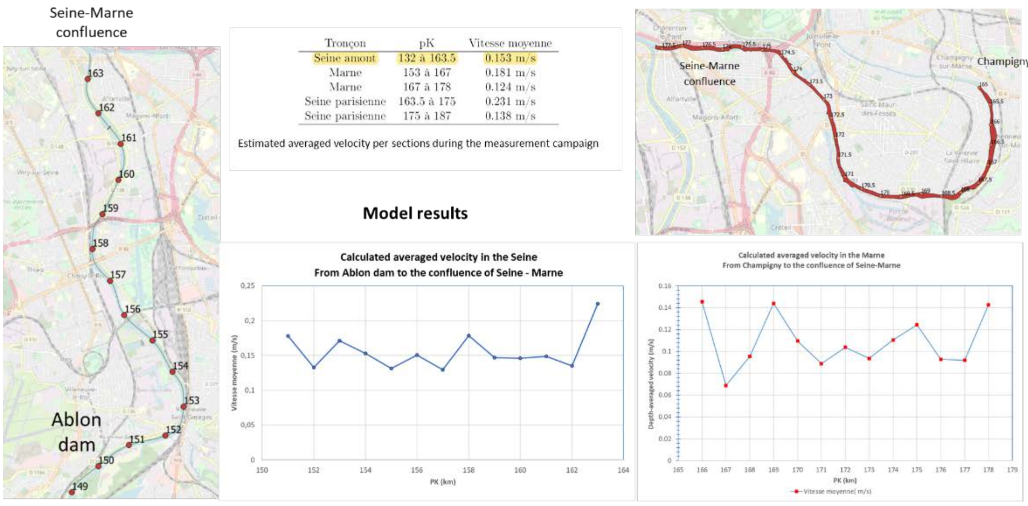


Figure 10. Modelled depth-averaged velocity by TELEMAC-2D in the Seine and the Marne

3.6. Model validation in dry weather

3.6.1 Initial and boundary conditions

For dry weather simulation, a constant flow discharge and E. coli concentration were imposed at the upstream boundary of the Seine model (83 $m^3 s^{-1}$; 200 CFU/100 mL) and the Marne model (28 $m^3 s^{-1}$; 1500 CFU/100 mL). At the downstream boundary, a constant water level (28.1 m NGF) was imposed, while the temperature and bacteriological values were let free.

The EC concentration was set to 200 CFU/100 mL at the initial condition.

3.6.2 Wastewater sources

Only one wastewater source of the MAV treatment plant was considered in the water quality model of the Marne.

According to the authors of the measurement campaign, the EC concentration released from the MAV plant in dry weather ranges from 30,000 to 100,000 CFU/100 mL with a constant flow rate of 0.33 $m^3 s^{-1}$.

According to the data of SIAAP [26], the discharge of the MAV plant was equal to 0.29 $m^3 s^{-1}$ on the August 21st 2017. The EC concentration at the outlet of the MAV plant was estimated equal to 4.4E+04 CFU/100 mL , which agrees with the observation of the measurement team [9].

Table 3. Data of wastewater treatment plants from SIAAP

Date	River	Treatment plant	Discharge ($m^3 s^{-1}$)	NH4 (mg L^{-1})
03/08/2017	Seine	SEV (SAM)	3.80	0.15
21/08/2017	Marne	MAV	0.29	0.27

On the Seine river, the discharge released from the SEV plant was equal to 3.8 $m^3 s^{-1}$ on the August 3rd 2017, and the EC concentration was estimated equal to 1.5E+04 CFU/100 mL [26].

Beside the SEV plant, two important pollutant sources have been added to the Seine model.

The first one is the Fresnes-Choisy collector. The Fresnes-Choisy collector is a storm water collector receiving many overflows from combined collectors located upstream, it also serves periodically as an outlet for the Bièvre. Therefore, when wastewater is present in this collector, it is diluted, even much diluted, except in very exceptional cases of pollution. The Val-de-Marne department confirmed the occurrence of an exceptional release during the period when the measurement campaign was carried out.

The average daily discharge of Fresnes-Choisy collector on August 3rd was equal to 0.25 $m^3 s^{-1}$. No measured data on EC concentration was available.

According to our knowledge, this outlet is a "river" type discharge, with a distinction between the concentrations in dry weather and in rainy weather:

- The dry weather concentrations are around 6.5E+04 CFU/100 mL based on the data from the summer 2016 measurement campaign.
- The rainy weather concentrations were calculated from the correlation between FIB and N-NH4 and are equal to 1.25E+06 CFU/100 mL.

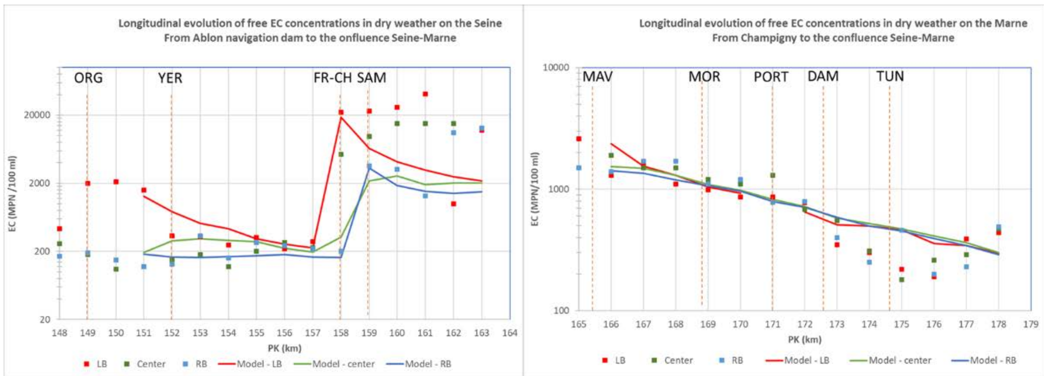
These two concentrations were tested in the model to find the best agreement between the measurement and the models results.

The second source of pollution is the Orge River, which is located right upstream the Ablon dam. A discharge of about 1.4 $m^3 s^{-1}$ was measured. However, no EC concentration measurement was available.

In this simulation, an EC concentration of 2.0E+04 CFU/100 mL was assumed. Note that the upstream limit of the TELEMAC-2D model is downstream of the Ablon dam, we decided to inject the flow and EC concentration of the Orge immediately downstream of the Ablon dam on the left bank (PK 151).

3.6.3 2D model results

Figure 11 presents the numerical results against the measured longitudinal evolution of EC concentration on the Seine (left) and Marne River (right).



(**a**) (**b**)

Figure 11. Comparison between measured & modelled longitudinal evolution of free EC concentration in dry weather on the Seine (a) and Marne rivers (b)

On these graphs, the red line presents the calculated free *E. coli* concentrations on the left bank, the blue line on the right bank, and the green line at the center of the river whereas the points represent the measurement.

Firstly, the result of the Seine model shows that the calculated EC concentrations on the left bank at PK 151 is close to 2000 CFU/100 mL, which agrees well with the measurement. The model also shows that the influence of this pollution source seems quite weak on the transverse profile. This is also observed in the measurement, from which the concentrations at the center and on the right bank did not increase downstream of this source.

At PK 158, the model simulated well the increase in EC concentrations on the left bank due to the Fresnes-Choisy collector. It is noted that a high concentration of EC from the Fresnes-Choisy collector was applied to the model. This is consistent with the observation of Mouchel's team and the confirmation of the department of Val-de-Marne on the intensity of this pollution source during the campaign.

The increase in concentration due to the SEV plant is also well calculated in the model. Nevertheless, downstream of the SEV outlet, the modelled EC concentrations by TELEMAC-2D are generally lower than those measured. It is noted that between PK 159 and PK 163, several permanent releases can be identified on both sides of the Seine. They were not considered in the model due to the lack of information on concentrations and discharges at these collectors. These sources could contribute to an increase in EC concentrations in the river as well as the homogeneity of the transverse concentrations.

Secondly, on the Marne River, in general, the EC concentrations decrease regularly from the Champigny bridge to the confluence with the Seine, especially at the center of the river and on the right bank.

On the left bank, an increase is observed immediately downstream of the MAV plant's outlet. Although the location of this increase is not identical with the measurement (PK 166 in the model instead of PK 165 in the measurement), we believe that the model result represents better the reality because the MAV plant's outlet is located downstream of PK 165. There could be an error in the measured longitudinal profile since the longitudinal evolution of measured conductivity in [9] shows an increase in conductivity at PK 166 instead of PK 165.

The impact of this source is quite weak in the longitudinal profile, over a limited distance of approximately 1 km downstream of the source. These results are consistent with the measurements.

Nonetheless, the model is not able to represent the variations in EC concentration from PK 173. Here, the measurement shows an abrupt decrease in EC values from about 800 CFU/100 mL to 400 CFU/100 mL without any explanation from the measurement team. Similarly, the increase in EC concentrations from PK 175 observed in the measurement is difficult to explain, according to the authors, and many factors could be mentioned, for example the outlet of the Saint-Maur tunnel with the navigation of ships.

In conclusion, although the measured E Coli concentrations are quite scattered over this section of the Marne River, the TELEMAC-2D model shows its ability to correctly model the decrease in longitudinal EC concentrations.

In overall, the obtained results with the TELEMAC-2D model are reasonable compared to the measurements. It is important to underline that the TELEMAC-2D model can represent the transverse variation of the EC concentrations. This is a strong point of the TELEMAC-2D model compared to the one-dimensional model.

3.7. Model validation in rainy weather

3.7.1 *E. coli* modelling by ProSe model in rainy weather

For the validation of the model in rainy weather, without a complete dataset, it was decided to model an existing scenario of the ProSe model and then compare with its results.

The ProSe model is a one-dimensional model with the bacteriological module, which has been used for the development of the master plan for sanitation by the SIAAP [8].

The REF-SC4B scenario focuses on the upgrading of the sewage network, resulting in the elimination of permanent overflows in dry weather. The other improvement included in this scenario is the disinfection of the MAV and SEV wastewater treatment plants by decreasing the concentration of FIBs by 3 log units at the station outlets [25].

It is worth noting that Prose is a 1D model that can only give the averaged value of the water quality of the river at its center. In other words, it cannot represent the concentration variation in the vertical and transverse profiles which is essential in monitoring the water quality of bathing sites.

3.7.2 Simulation period & boundary conditions

In order to compare with the ProSe model, a simulation was carried out with TELEMAC-2D for a period of 6 days from 06/04/2011 to 06/10/2011 and also at a graphical output time step of 15 minutes. This period is sufficient because it covers the pollution peaks on the rivers.

For the Seine River, the upstream limit of the TELEMAC-2D is identical to that of the ProSe model. The flow hydrograph as well as the bacteriological concentration of 160

CFU/100 mL at the upstream limit of the ProSe model were retained for the TELEMAC-2D.

Nevertheless, for the Marne, since the computational domain of the TELEMAC-2D model is smaller than the ProSe one, the hydrograph as well as pollutograph calculated by the ProSe model at the bacteriological control point of Champigny were injected at the upstream boundary of the model.

3.7.3 Wastewater sources

In this simulation, seventeen polluted sources were added in the Marne model, including the MAV treatment plant outlet. For the Seine model, fifteen polluted sources were added in the model including the SEV outlet.

The values of the mortality constants used in the model are those used in the ProSe model and measured by the PIREN-Seine team on samples collected from the Seine. A value in the lower range of those measured by PIREN-Seine is used for *E. coli* (0.040 and 0.012 h^{-1} for free EC and EC attached to suspended and deposited sediments respectively).

Other physical parameters were kept identical to the model in dry weather.

3.7.4 2D model results

Figure 12 compares the pollutographs calculated by ProSe and TELEMAC-2D at two different control points in the Seine and the Marne models.

Two points on the Marne model are Chennevières and Charentonneau.

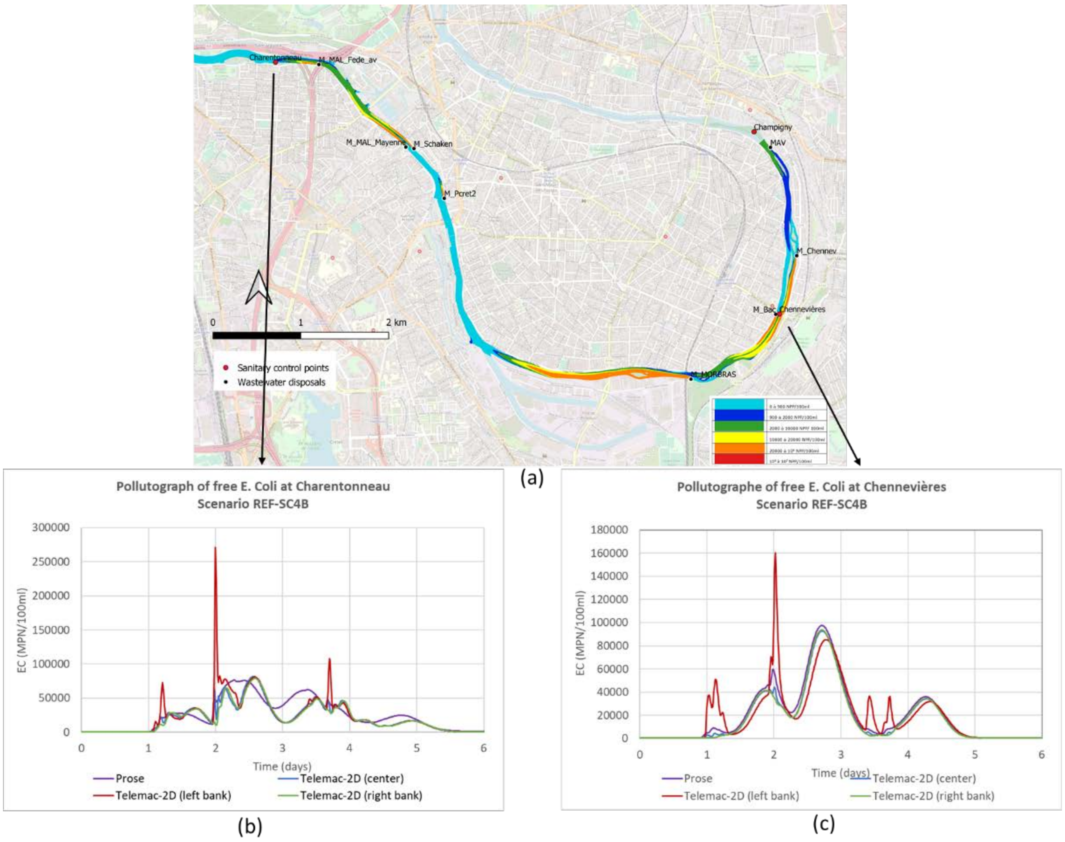


Figure 12. Modelled EC concentration diffusion by TELEMAC-2D for the Marne River (a) and comparison of the calculated pollutographs by ProSe and by TELEMAC-2D at Charentonneau (b) et at Chennevières (c)

At Chennevières, the EC concentration calculated by TELEMAC-2D at the center of the Marne is almost identical to that calculated by the ProSe model. Nevertheless, the TELEMAC-2D results on the left bank are much higher. Indeed, after 2 days, the concentration on the left bank calculated by TELEMAC-2D reached the peak of 1.6E+05 CFU/100 mL, while the result of ProSe was 6.0E+04 CFU/100 mL (almost 3 times lower). This is due to the fact that most of the important sources are located on the left bank, and a 1D model like ProSe is not able to correctly represent the high variability of concentrations over the width of river.

At Charentonneau, the result of the pollutograph calculated by TELEMAC-2D at the center of the river is not completely identical to that of ProSe. However, the same peak was obtained after 2.5 days (around 8.0E+04 CFU/100 mL) on the results of the two models. Similar to Chennevières, the concentration of EC on the left bank is much higher than at the center and on the right bank (2.7E+05 CFU/100 mL).

It should be emphasized that almost all-important pollutant sources are located on the left bank. As a result, the *E. coli* concentrations downstream of these sources were significantly increased over a long distance. However, the diffusion of bacteria remains limited transversely downstream of wastewater disposals. This phenomenon is particularly visible downstream of the Morbras release – the biggest pollution source in the model. The representation of this cross-section variation is very useful in monitoring the water quality at bathing sites.

On the Seine River, the calculated pollutographs by ProSe and by TELEMAC-2D at two control points: Choisy-le-Roi and Port-à-l'Anglais were also compared. The results are presented on Figure 13 below.

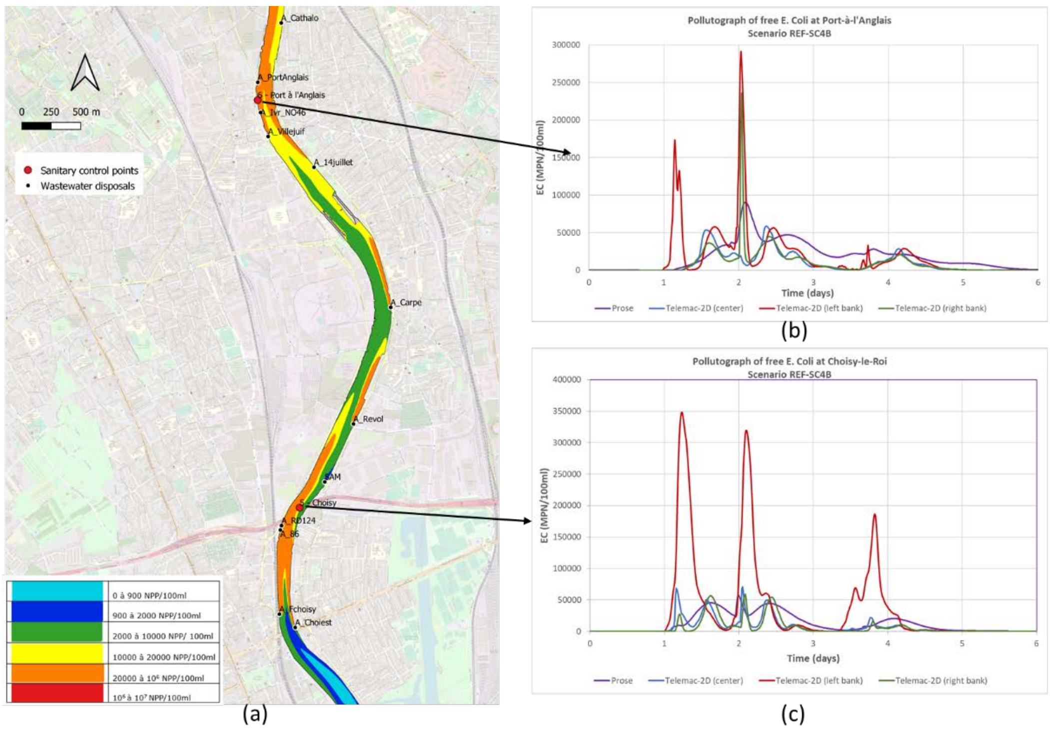


Figure 13. Modelled EC concentration diffusion by TELEMAC-2D on Seine River (a) and comparison of calculated pollutographs by ProSe and TELEMAC-2D at Port-à-l'Anglais (b) et Choisy-le-Roi (c)

At Choisy-le-Roi, the EC concentration calculated by TELEMAC-2D at the center of the Seine is not identical to that of Prose as observed on the Marne. The shape of the pollutograph calculated by TELEMAC-2D is sharper than that calculated by ProSe. However, the peak concentration is similar (around 6.0E+04 to 7.0E+04 CFU/100 mL after 2 days).

Nevertheless, the concentration calculated by TELEMAC-2D on the left bank is much higher with a peak of 3.5E+05 CFU/100 mL (about 6 times higher) due to the Fresnes-Choisy collector.

The Port à l'Anglais point is located on the left bank. The result calculated by TELEMAC-2D shows higher concentrations on both banks than at the center of the river, with the peaks of 3.0E+05 and 2.4E+05 CFU/100 mL on the left and the right bank respectively after 2 days. This is due to different disposal points along the two banks of this section.

At the center of the river, the concentration peak came 0.5 day later, with a value of 4 to 5 times lower (6.0E+04CFU/100 mL). The ProSe model gave the averaged result on the cross section, in which the peak reached 9.0E+04 CFU/100 mL after 2 days (i.e., 3 times lower than the value calculated by TELEMAC-2D on the left bank).

Compared to the 1D ProSe model, the TELEMAC-2D model shows similar results of EC concentrations at the center of the river. However, it is observed from the TELEMAC-2D results that, under the impact of disposal points along the river banks, the EC concentration at the center of the Seine and Marne rivers can be much lower than near the banks. Since the river bathing sites are normally located near banks, accounting for this cross-sectional variation is very important to establish a precise microbiological state of bathing sites.

The calculated longitudinal EC concentration profile by TELEMAC-2D were also compared against the measured one in rainy weather. It is reminded that for this simulation, the EC concentrations from the SEV and MAV plant outlets were reduced by 3 log.

(**a**) (**b**)

Figure 14. Modelled longitudinal profile of free *E. coli* concentration by TELEMAC-2D in rainy weather on the Seine River (a) and Marne River (b).

On the Seine, between the Ablon dam (PK 150) and PK 154, the *E. coli* concentrations are stable. The water quality is quite good with concentration values below 900 CFU/100 mL. From PK 154, the EC concentration start to increase. Between Choisy-le-Roi (PK 156) and Ivry-sur-Seine (PK 162), the impact of the SEV plant is not visible knowing that this concentration was reduced by 3 log in this scenario. Nevertheless, there is still a clear increase in concentration, especially on the left bank, due to the Fresnes-Choisy discharge, which is located in between PK 157 and PK 158 and other outflows located downstream of the SEV plant's outlet. This is consistent with the evolution trend discussed in §3.1 as well as the longitudinal profile measured in [9].

On the Marne, according to the bacteriological measurements between 2011 and 2014, there is a slight improvement in the bacteriological quality between Chennevières and the confluence with the Seine. This trend is also observed on the results of the TELEMAC-2D model.

In conclusion, the results obtained from the TELEMAC-2D model in rainy weather indicate that the model correctly simulates the longitudinal evolution trends of bacteriological pollutants. Moreover, it also allows us to model the transverse variation induced by pollution sources located on both riverbanks.

3.7.5 3D model results

Although the results of the TELEMAC-2D models are quite promising, it may not be sufficient in certain places where knowledge of the dispersion of pollutant plumes in the vertical dimension is required. Moreover, the TELEMAC-2D model does not allow us to specify the exact position of the sewer overflows in the water column because the results of TELEMAC-2D are depth-averaged.

It was therefore decided to develop a TELEMAC-3D micro-model around a bathing site. As mentioned in the previous section, on the Marne, the Saint-Maur bathing site was selected because this site is located in a complex environment that includes several islands, a navigation channel and a secondary channel. In a similar way to the Marne, a 3D micro-model was developed on the Seine around the Vitry-sur-Seine bathing site.

It is worth noting that the boundary conditions of the TELEMAC-3D models were extracted from the results of the TELEMAC-2D models using the nesting technique. This technique allows us to impose the external forcing on the 3D upper boundary (hydrographs, bacteriological concentrations) which vary not only in time but also in space. The TELEMAC-3D code has been modified to account for this variation in EC concentration in the transverse direction.

Figure 15 presents the diffusion of EC concentration from the upstream boundary of the TELEMAC-3D Saint-Maur model. It can be observed that without any disposal point, the EC concentration is higher at the center of the river than near the banks and is higher at the bottom than near the water surface.

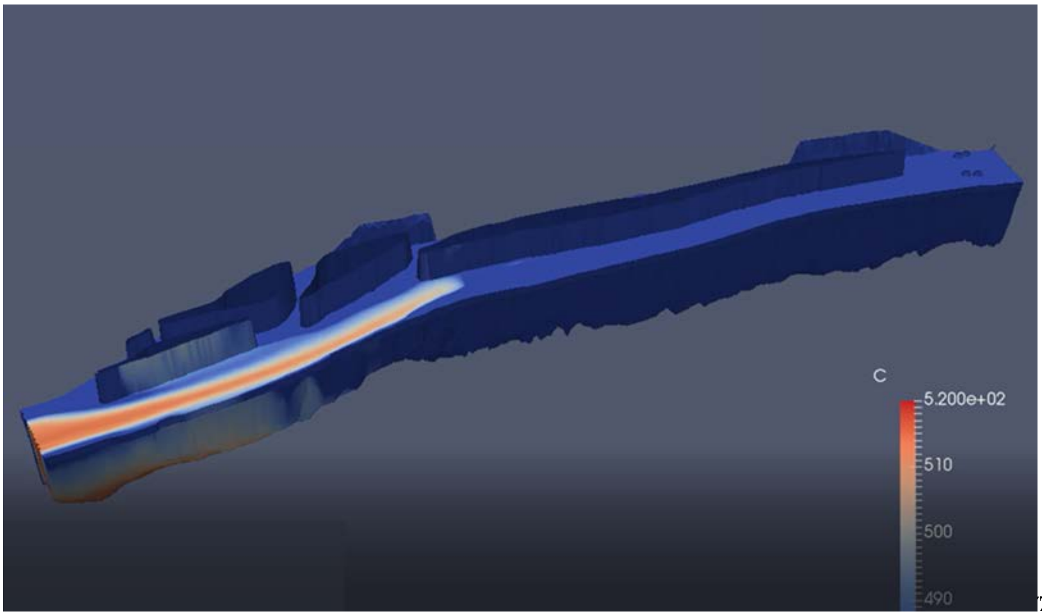


Figure 15. Variation in EC concentrations at the upstream boundary of the TELEMAC-3D model

In 3D models, experiences show that the turbulence model plays an important role in modelling tracer concentrations. It is not recommended to use the k-epsilon turbulence model in the case of stratification simulations [23]. A comparison of different turbulence models in the vertical (mixing length Nakagawa, k-epsilon and k-omega) was carried out in the Saint-Maur bathing site model. In these simulations, only one pollution source was considered: the Chennevières outlet. Figure 16 shows the superiority of the k-omega model compared to the mixing length and k-epsilon models in modelling *E. coli* concentration diffusion. Those two models gave a field of concentrations of pollutant which are too mixed not only on the vertical but also in the horizontal direction, while the k-omega model gave a clear stratification on both directions. The use of the k-omega model allows undoubtedly a better description of the stratification.

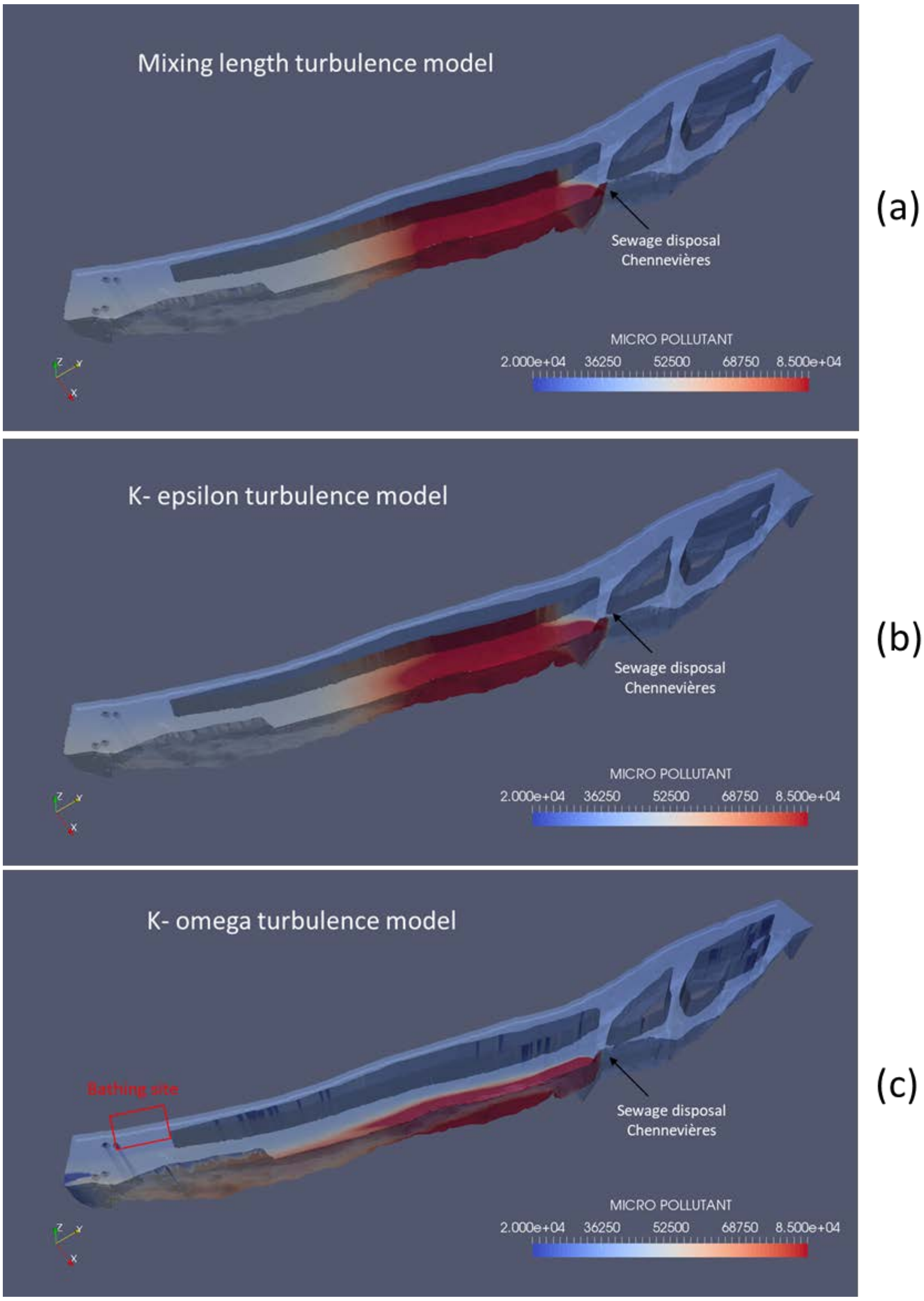


Figure 16. Impact of vertical turbulence models in modelling the concentration diffusion in TELEMAC-3D : (a) mixing length model; (b) k-epsilon model; (c) k-omega model

The Saint-Maur bathing site has been proposed on the right bank of the Marne and is shown on Figure 17. It can be observed that the high concentration of EC induced by the Chennevières outflow remains in the main channel on the left bank due to the presence of the Casenave island while the bathing site is located on the other bank. Visually, the effect of this source seems negligible on this bathing site. In case of using a one-dimensional model, the impact of this island could be neglected and the calculated EC concentration at this bathing site could be over-estimated.

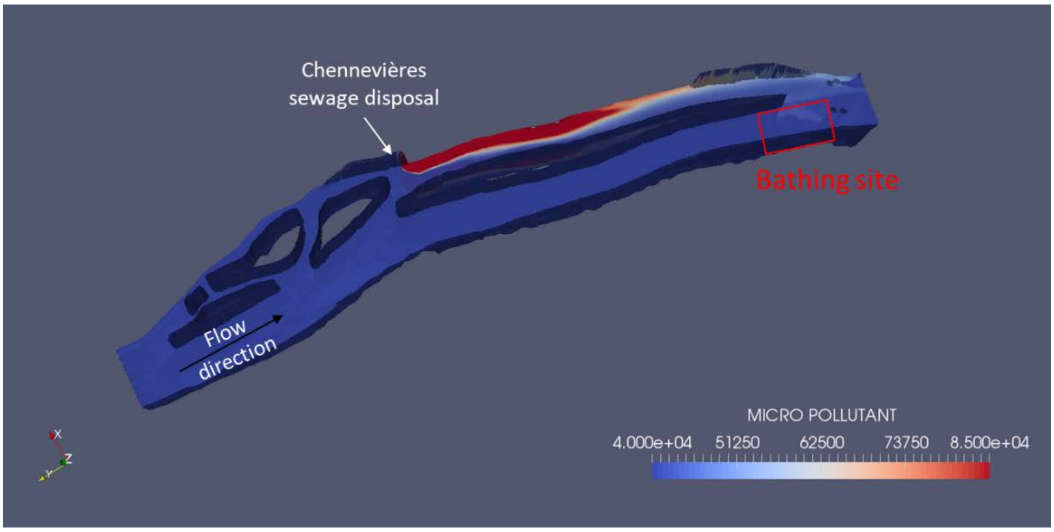


Figure 17. Modelled diffusion of EC concentration rejected from the Chennevières outlet using TELEMAC-3D

The below graphs present the results of TELEMAC-3D model upstream of the Vitry-sur-Seine bathing site in the Seine river. Firstly, the longitudinal and transverse evolutions of *E. coli* concentrations modelled by TELEMAC-3D agree well with the 2D results as shown in Figure 18.

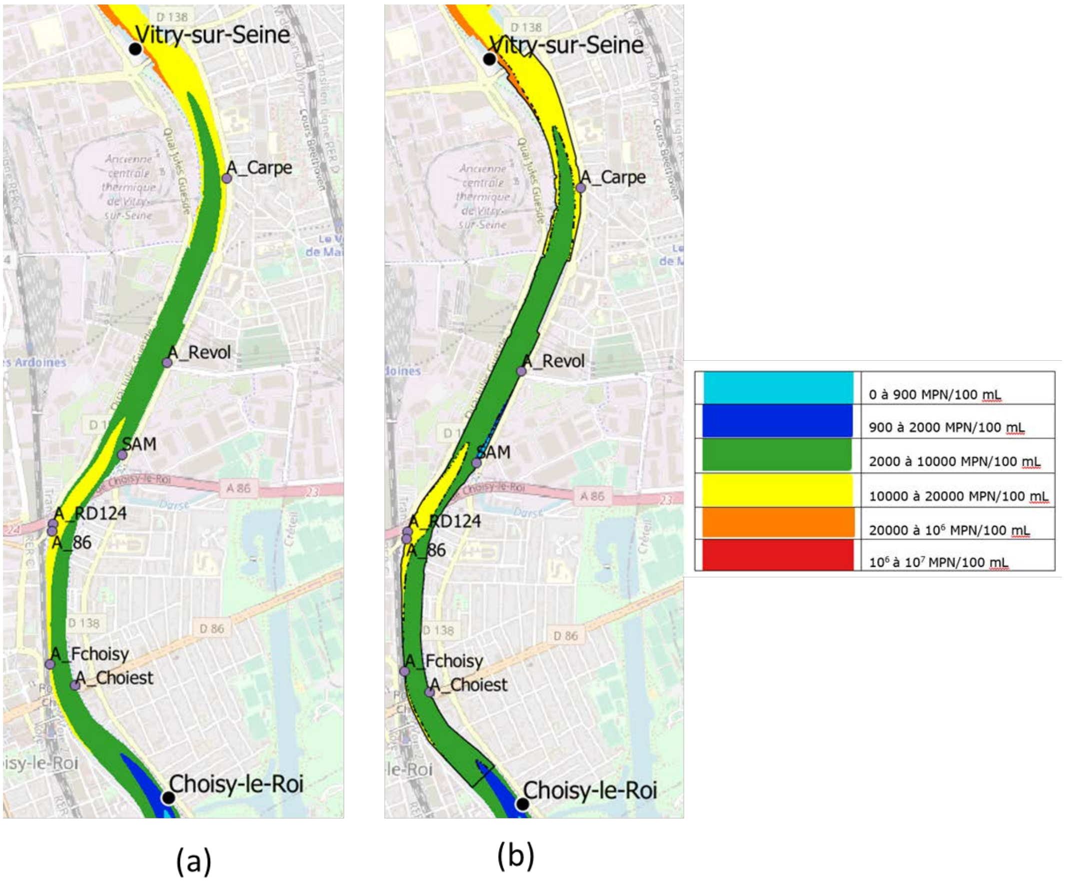


Figure 18. Comparison between the result of TELEMAC-2D model (a) and the averaged result over the vertical of TELEMAC-3D model (b) on the Seine

Secondly, it is observed from the 3D models results on Figure 19 that depending on the discharge of the pollution sources, the bacteriological concentrations rejected can be homogeneous or not in the vertical profile. For example, with an important source like Fresnes-Choisy, the concentrations are well-mixed near the source, but they become higher at the bottom than the water surface once they are diffused far from the source point.

On the transverse profile, the TELEMAC-3D result is similar to TELEMAC-2D one with higher concentrations near the left bank while the concentrations at the center and on the other bank are much lower.

It is worth noting that for the monitoring of water quality at bathing sites, people are interested in the quality of the surface water. Compared to the TELEMAC-2D model, the 3D model gave a detailed results on the vertical. This could be necessary in case where the presence of considerable transverse and vertical convective phenomena is observed.

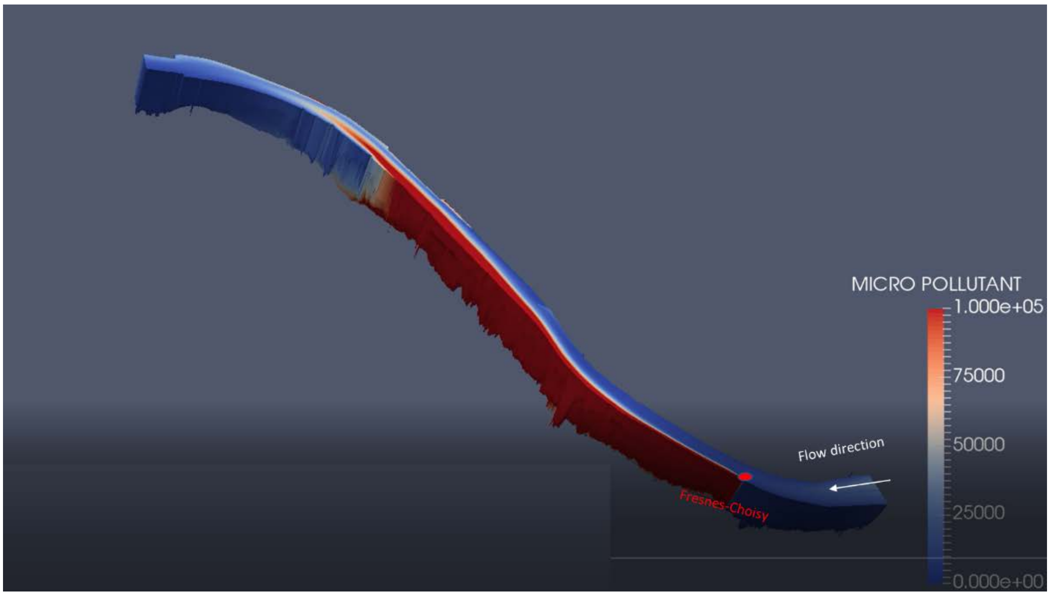


Figure 19. The modelled diffusion of EC concentration along the vertical by TELEMAC-3D model on the Seine river

4. Discussion

As bacterial pollution in the water can cause serious public health problems, the local government has paid a great attention on monitoring water quality at bathing sites in the Seine and Marne Rivers.

According to the regulations for bathing in fresh water (European Directive 2006/7 of 15 February 2006), the monitoring of bathing water quality is based on the concentrations of two bacteria of fecal origin: *Escherichia coli* and *intestinal enterococci*.

Although there has been an improvement in the water quality in the Seine and the Marne Rivers since the end of the 1980s, recent microbiological analyses show that episodes of high concentrations in fecal indicators are still present, especially during rainy periods. This contamination makes the Seine and Marne Rivers difficult to bath without wastewater management.

Being aware that numerical modelling is one power tool for short-term forecasting of the dispersion and evolution of pollutants of bacteriological plumes, the main objective of this paper is therefore to develop a numerical model for the prediction of water quality in bathing sites. This model considers three types of FIB: free FIB, FIB attached to suspended sediments, and FIB in the deposited sediments. This model also takes into account the mortality of the FIB and the settling – resuspension processes. Most important, this modelling tool is able to model the spatial variability of the microbial pollutants not only in the longitudinal but also in the transverse direction.

A 2D model on the Seine and another one on the Marne River, with a length of approximately 15 km, representative both from the hydrodynamic conditions and the impact of pollution sources were developed. The models were validated against the in-situ measurement in dry weather from Mouchel et al. [9], and then compared with the results of the 1D ProSe model in rainy weather [8,24].

The results show that the 2D model can represent the dispersion and the evolution of bacteriological pollutants longitudinally and transversely.

The model can be then considered as a powerful tool for managing the pollution sources in rivers. It can help us to identify the sources of pollution that may have strong impact on the quality of bathing waters, and in the case if a pollution risk is identified, to evaluate the proposed management measures, which would be implemented to ensure the health protection of population, as well as to plan the actions for eliminating these sources of pollution.

Nevertheless, TELEMAC-2D may not be sufficient in some places where the knowledge of the dispersion of pollutant plumes on the vertical is required. In this case, it is recommended to combine it with a 3D micro-model. TELEMAC-3D is able to model bathing sites and its surroundings in a finer way when significant transverse and/or vertical convective phenomena is observed.

Within this research, no data is available to validate the developed 3D models. A measurement campaign in terms of 3D velocity and bacteriology will be necessary. This campaign will aim at highlighting the 3D potential variations in bacteriological flow in bathing sites.

Moreover, although the effect of water temperature was included in the modelling of the decay rate of *E. coli* concentration, it could not be validated due to the lack of data. Besides, since sunlight is also an important factor affecting the survival of bacterial, it would be interesting to include the effect of sunlight in the modelling and validate it against measurements.

6. Patents

Author Contributions: Conceptualization, Lan-Anh Van; Data curation, Aïcha Jairy; Formal analysis, Kim-Dan Nguyen and François Le Marrec; Methodology, Lan-Anh Van and Kim-Dan Nguyen; Resources, Aïcha Jairy; Supervision, Kim-Dan Nguyen and François Le Marrec; Visualization, Lan-Anh Van; Writing – original draft, Lan-Anh Van; Writing – review & editing, Kim-Dan Nguyen, François Le Marrec and Aïcha Jairy.

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Data Availability Statement:

Part of the data presented in this research are not publicly available and was provided by the SIAAP.

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Conflicts of Interest:

The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

References

1. Kistemann, Thomas, Alexandra Schmidt, and Hans-Curt Flemming. "Post-Industrial River Water Quality—Fit for Bathing Again?" International Journal of Hygiene and Environmental Health 219, no. 7, Part B (2016): 629–42. https://doi.org/10.1016/j.ijheh.2016.07.007.
2. Meyerhoff, Jürgen, Alexandra Dehnhardt, and Volkmar Hartje. "Take Your Swimsuit along: The Value of Improving Urban Bathing Sites in the Metropolitan Area of Berlin." Journal of Environmental Planning and Management 53, no. 1 (January 1, 2010): 107–24. https://doi.org/10.1080/09640560903399863.
3. https://www.apur.org/fr/nos-travaux/sites-baignade-seine-marne-heritage-jo-paris-2024-presentation-sites-issus-manifestation-interet
4. European Union (EU). "Directive 2006/7/EC of the European Parliament and of the Council of 15 February 2006 Concerning the Management of Bathing Water Quality and Repealing Directive 76/160/EEC.," n.d.
5. Edberg, S.C., E.W. Rice, R.J. Karlin, and M.J. Allen. "Escherichia coli: The Best Biological Drinking Water Indicator for Public Health Protection." Journal of Applied Microbiology 88, no. S1 (December 2000): 106S-116S. https://doi.org/10.1111/j.1365-2672.2000.tb05338.x.
6. Servais, Pierre, Tamara Garcia-Armisen, Isabelle George, and Gilles Billen. "Fecal Bacteria in the Rivers of the Seine Drainage Network (France): Sources, Fate and Modelling." The Science of the Total Environment 375 (May 1, 2007): 152–67. https://doi.org/10.1016/j.scitotenv.2006.12.010.
7. Garcia-Armisen, Tamara, B Thouvenin, and Pierre Servais. "Modelling Faecal Coliforms Dynamics in the Seine Estuary, France." Water Science and Technology : A Journal of the International Association on Water Pollution Research 54 (February 1, 2006): 177–84. https://doi.org/10.2166/wst.2006.466.
8. Poulin, M., Pierre S., J-M Mouchel, C. Therial, L. Lesage, Rocher, A. Goncalves, S. Masnada, F. Lucas, and Nicolas Flipo. "Modélisation de La Contamination Fécale En Seine : Impact Des Rejets de Temps de Pluie. Programme PIREN-Seine Rapport Modélisation de La Contamination Fécale Par Temps de Pluie." Programme PIREN-Seine, 2013.
9. Mouchel, J-M, I. Colina-Moreno, and N. Kasmi. "Evaluation des teneurs en bactéries indicatrices fécales en Seine dans l'agglomération parisienne par temps sec." PIREN-Seine. Paris, France, 2018.
10. Taylor, G.I. "The Dispersion of Matter in Turbulent Flow through a Pipe." In Proceedings of the Royal Society of London, 223:446–68. A, 1954
11. Gibson, A. "On the Depression of the Filament of Maximum Velocity in a Stream Flowing through an Open Channel." In Proceedings of the Royal Society of London, 82:149–59. A, 1909.
12. Chauvet, H., O. Devauchelle, F. Metivier, E. Lajeunesse, and A. Limare. "Recirculation Cells in a Wide Channel." Physics of Fluids 26, no. 1 (January 1, 2014): 016604. https://doi.org/10.1063/1.4862442.
13. El-Sharkawi, Fahmy, L. El-Attar, A. Abdel Gawad, and S. Molazem. "Some Environmental Factors Affecting Survival of Fecal Pathogens and Indicator Organisms in Seawater." Water Science and Technology 21, no. 1 (January 1, 1989): 115–20. https://doi.org/10.2166/wst.1989.0013.
14. Georges, I., and P. Servais. "Sources et Dynamique Des Coliformes Dans Le Bassin de La Seine." Programme PIREN-Seine, 2002.
15. Hipsey, Matthew R., Jason P. Antenucci, and Justin D. Brookes. "A Generic, Process-Based Model of Microbial Pollution in Aquatic Systems." Water Resources Research 44, no. 7 (July 1, 2008). https://doi.org/10.1029/2007WR006395
16. Evison, L. M. "Comparative Studies on the Survival of Indicator Organisms and Pathogens in Fresh and Sea Water." Water Science and Technology 20, no. 11–12 (November 1, 1988): 309–15. https://doi.org/10.2166/wst.1988.0300.
17. Ouattara, Nouho Koffi, Anouk de Brauwere, Gilles Billen, and Pierre Servais. "Modelling Faecal Contamination in the Scheldt Drainage Network." Journal of Marine Systems 128 (December 1, 2013): 77–88. https://doi.org/10.1016/j.jmarsys.2012.05.004.
18. Sokolava, E., T. Pettersson, and O. Bergstedt. "Hydrodynamic Modelling and Forecasting of Microbial Water Quality in a Drinking Water Source." Journal of Water Supply: Research and Technology - Aqua 63, no. 3 (2014): 189–99.
19. Viegas, Claudia, Ramiro Neves, Rodrigo Fernandes, and Marcos Mateus. "Modelling Tools to Support an Early Alert System for Bathing Water Quality." Environmental Engineering and Management Journal 11 (May 1, 2012): 907–18.
20. Hervouet, Jean-Michel. (2007). "Hydrodynamics of Free Surface Flows: Modelling With the Finite Element Method", 1–4. John Wiley & Sons, Ltd, 2007. https://doi.org/10.1002/9780470319628.
21. "TELEMAC-2D User Manual - Version V8p2." EDF R&D, December 1, 2020.
22. "TELEMAC-3D User Manual - Version V8p2." EDF R&D, December 1, 2020.
23. "WAQTEL Technical Manual - Version V8p2." EDF R&D, December 1, 2020.
24. Even, Stéphanie, Michel Poulin, Josette Garnier, Gilles Billen, Pierre Servais, André Chesterikoff, and Michel Coste. "'River Ecosystem Modeling: Application of the PROSE Model to the Seine River (France).'" Hydrobiologia 373 (juin 1998): 27–45. https://doi.org/10.1023/A:1017045522336.
25. Mouchel, Jean-Marie, Françoise S. Lucas, Laurent Moulin, Sébastien Wurtzer, Agathe Euzen, Jean-Paul Haghe, Vincent Rocher, Sam Azimi, and Pierre Servais. "Bathing Activities and Microbiological River Water Quality in the Paris Area: A Long-Term Perspective." In The Seine River Basin, edited by Nicolas Flipo, Pierre Labadie, and Laurence Lestel, 323–53. Cham: Springer International Publishing, 2021. https://doi.org/10.1007/698_2019_397.

26. PROLOG INGENIERIE, and Hydratec. “Mise à jour du SDA du SIAAP pour l’atteinte de l’objectif baignabilité en Seine et en Marne.” SIAAP, 2017 2016.
27. Blue Kenue™: software tool for hydraulic modellers. Available online : *https://nrc.canada.ca/fr/recherche-developpement/produits-services/logiciels-applications/blue-kenuetm-logiciel-modelisateurs-hydrauliques* (accessed on 23rd February 2022*)*