Three-Dimensional Simulation of Bacterial Pollution in Nice Bay for Operational Applications

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THREE-DIMENSIONAL SIMULATION OF BACTERIAL POLLUTION IN NICE BAY FOR OPERATIONAL APPLICATION

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KEY WORDS

Pollution, Modelling, Environmental Fluid Dynamics, Environmental Issues, Environmental Management.

ABSTRACT

Hydrodynamic models of seawater quality are multifactorial. In addition to depending on environmental and meteorological parameters, they are very sensitive to the parameterizastion of bacteriological input data, such as polluant load, flow rate, temperature and nature of the effluent.

In order to simulate the impact of bacteriological pollution on water quality, a knowledge of these data is essential. Nevertheless, their acquisition is complex because the discharges into the natural environment are usually accidental.

In Nice, the general wastewater collector is annually maintained. During this event, the effluents usually collected are discharged into the bay of Nice, via dozen of urban outfalls spread over 4.5km of beach. This paper deals with the numerical modeling of this event. The model used is based on Reynolds-Averaged Navier-Stokes' equations for the calculation of the velocities and water depth (TELEMAC3D). The domain of the model extends from the cape of Nice (East side) to the airport (West side) covering all the beaches.

In addition, a measurement campaign was implemented. Sampling at sea and in network was carried out at strategic positions and at regular intervals in order to know the pollution loads of effluents and sea water. These data have been used to establish the performance of the model to simulate a bacteriological pollution at sea.

Finally, calibration work has been conducted in order to optimize the computing time of simulations. This last point answer to a strong demand from public authorities who are interested in antipicipating the evolution of pollution in order to control its consequences and provide an effective operational responsens.

1. INTRODUCTION

Because of the assimilation capacity of the saline water, the seas and the oceans are commonly used for untreated or partially treated wastewater disposal in many countries (1). Thus the sewage is discharged through marine outfall systems for economical or technical reasons (2, 3).

In the coastal city of Nice in France, the raw effluents are treated by the mean of Haliotis wastewater plan on the East side of the town. But the sewage collecting system consists of combined sewers in which sanitary waste and rainfall water are mixed. So during intensive rain events, the sewer can be overloaded and the overflowing water is discharged through fourteen marine outfalls and three river mouths.

The discharge of this untreated wastewater into the ocean may result in contamination of the marine environment. The presence of fecal bacteria indicator in nearshore waters is usually used to monitor the water quality. This paper will focus on one of the two indicators of the directive 2006/7/CE: Escherichia coli (5). Escherichia coli is a bacteria of the intestinal flora of the human and the animals which is quantified by concentration values in colony forming unit per 100 ml (cfu/100ml). Its presence in the environment indicates the fecal pollution and consequently a risk of human or animal microorganism pathogen (4). Consequently, if the concentration values of this fecal indicator in the bathing water are higher than 1000 cfu/100ml, the health regional authority (ARS) forces to close the bathing site.

In order to improve the decision-making process and to protect public health, the decision-maker needs tools to assist him in monitoring pollution events.

Two scales are commonly used to model a pollutant flowing out of an outfall into a water body: near-field and far-field modeling (6,7). In near field model, the initial mixing of the buoyant effluent jets and the local seawater is calculated by taking into account the geometry of the outfall in addition of the momentum and buancy fluxes. The evolution of flumes in the water body has been more longly discussed in (10, 12, 13) and these local state interactions can be calculated with hydrodynamic models such as Visual Plumes (8, 9, 11).

In far field also referred as dispersion zone, environmental conditions such as the light intensity, the salinity, the water temperature, the diffusion and the advection are the driving forces of the contaminant behavior (14, 15, 16). The initial mixing region no more impacts on the contaminant kinetics.

The time and space scales of the processes induced by near field and far field modelling differ significantly. The goal of this study is to model a long pollution event on a large scale: 31km². So a far field model will be implemented considering the low impact of the initial mixing region.

In order to properly model the far field phenomena, 3D modeling was necessary because the water column is not always well mixed. The temperature and salinity can change rapidly through the water column (17, 18).

This paper aims at presenting the three-dimensional simulations of the chosen microbiological indicator: Escherichia coli. First of all, the field experiments carried out to measure a controlled pollution event are described. Then the models used are introduced. Finally, a discussion of the results of the experiments and simulations is made in the last part of this article.

2. METHOD

In order to maintain annually the wastewater sewage, the municipality is bypassing the discharge of raw effluent through the marine outfalls. These planned events allow to design field campaign coupled with numerical simulations.

2.1 Measurement campaign

On the day of the campaign carried out in 2017, the municipality has limited the raw effluent discharges on three outlets located in the eastern part of the bay of Nice: the Halevy, Païole and Ponchettes outlets at 8, 36 and 12 meters respectively.

The bacteria concentrations were monitored using 7 surface sampling points distributed around the outfalls (Figure 1) and planned at 9 p.m., midnight, 2 a.m. and 6 a.m. It was also decided to take samples of raw effluents, upstream of the outlets, directly into the network and one at the mouth of the Paillon because some outlets discharge directly into this watercourse. For these points, samples were taken at 7 p.m. and 3 a.m. in order to quantify the reduction in the pollutant load due to the domestic use. Which results into 36 samples.

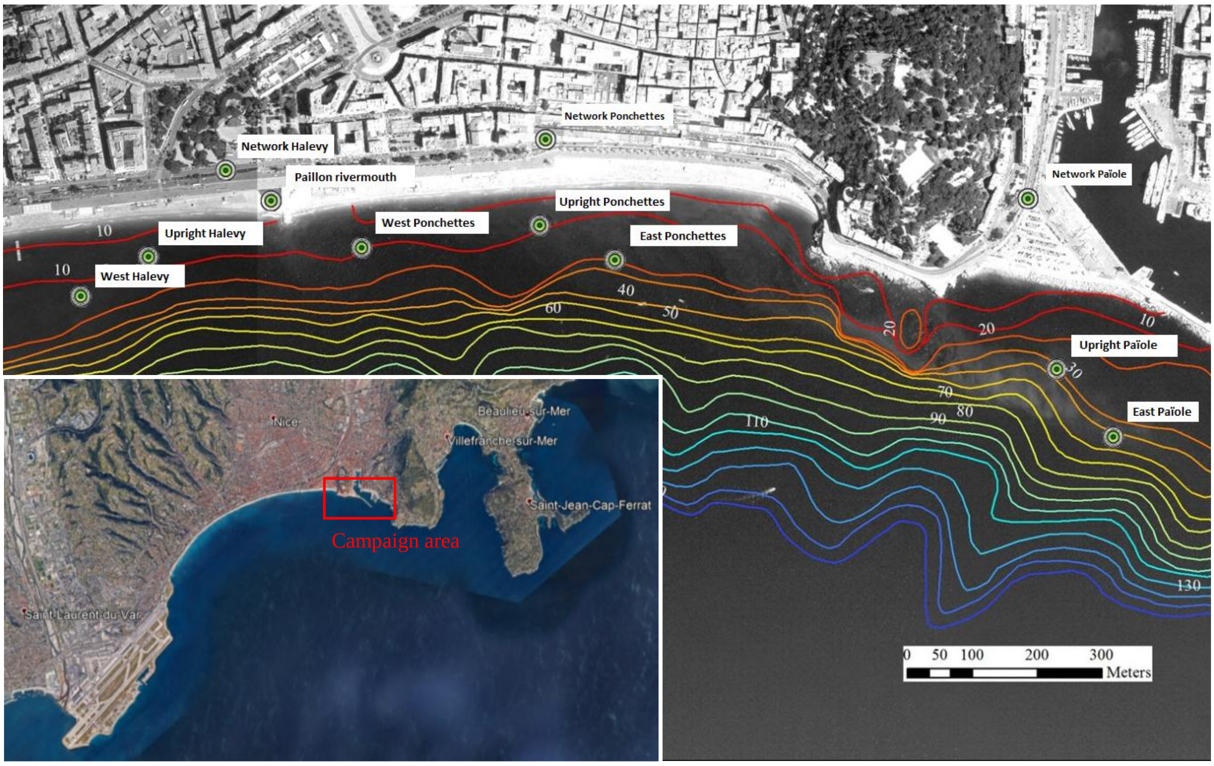

Figure 1: Position of 11 sampling points in the bay of Nice.

All samples were analyzed in the laboratory using an analytical method based on determining the Most Probable Number of bacteria (MPN) present in the sample. The latter involves inoculating numerous dilutions of the sample into tubes of enrichment broth, then subculturing the tubes onto selective agar. Thus the sample is diluted and then inoculated into a series of wells of a microplate which contains the dehydrated culture medium. The microplates are examined under UV (366nm) after 36 hours of incubation at 44°C. The presence of Escherichia Coli is revealed by detection of its enzyme: β-D-glucuronidase. Finally, the results are then reported in a table which directly gives the Most Probable Number as well as a 95% confidence interval.

Tables of test results are based on statistical calculations to determine the probability of bacteria being present in a diluted sample [21]. Statistical laws also make it possible to estimate a probable number of bacteria according to their presence or absence in the diluted samples. Protocols for determining MPN in a sample are based on the work of Mc Grady as well as Halvorson and Ziegler [21],[22].

2.2 Hydraulic model

The results of these laboratory analyses provide data to simulate the event using numerical hydrodynamic models. On the one hand, samplings in networks and in the Paillon were used as input data, on the other hand, the accuracy of the model was established with the results of the sea samples.

The calculation code is Telemac3D, developed by EDF. It is mainly based on the non-conservative form of the Navier-Stokes equations [19]. TELEMAC-3D solves the Reynolds-Averaged Navier-Stokes equations [25] with the incompressible form of the mass conservation and the non-conservative momentum equations. These equations are then discretized by a finite element method.

Equation 1:

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0$$

$$\frac{\partial U}{\partial t} + \vec{U} \vec{grad}(U) = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}(\nu_H \frac{\partial U}{\partial x}) + \frac{\partial}{\partial y}(\nu_H \frac{\partial U}{\partial y}) + \frac{\partial}{\partial z}(\nu_V \frac{\partial U}{\partial z}) + F_x$$

$$\frac{\partial V}{\partial t} + \vec{U} \vec{grad}(V) = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}(\nu_H \frac{\partial V}{\partial x}) + \frac{\partial}{\partial y}(\nu_H \frac{\partial V}{\partial y}) + \frac{\partial}{\partial z}(\nu_V \frac{\partial V}{\partial z}) + F_y$$

$$\frac{\partial W}{\partial t} + \vec{U} \vec{grad}(W) = -g - \frac{1}{\rho_0}\frac{\partial p}{\partial z} + \frac{\partial}{\partial x}(\nu_H \frac{\partial W}{\partial x}) + \frac{\partial}{\partial y}(\nu_H \frac{\partial W}{\partial y}) + \frac{\partial}{\partial z}(\nu_V \frac{\partial W}{\partial z}) + F_z$$

where U, V and W are the components of the velocity vector U in the x, y and z directions respectively; p is the pressure at the depth z; ρ0 is the reference density value; νH and νV are the horizontal and vertical eddy viscosity respectively; g is the acceleration of gravity and Fx, Fy, Fz are the external forces components such as Coriolis force, centrifugal force or the wind forcing, in the x, y and z directions respectively.

In addition, Telemac3D can model the transport of tracers. In our model, three different tracers are used: Temperature and salinity are active tracers, and the concentration of E.Coli, which is a passive tracer. Tracers are said to be active if it impacts the hydrodynamics of the flow, otherwise they are passive. Their evolution over time depends on three different physical factors:

- Advection, the transport of the tracer by the flow.
- Diffusion of the tracer resulting from movements induced by differences in concentrations.
- Sources and catchments.

For more details on bacteriological tracer and its mortality in Telemac3D refer to the article R. Dumasdelage & O. Delestre 2019 [20].

The calculation grid (Figure 2) includes all the beaches of Nice from Lympia port (the easternmost) to the Lanterne beach (the westernmost) as well as the coastline of the airport of Nice. This grid is made up of 31 vertical planes and each plane has nearly 60,000 triangular elements for 30,000 nodes.

The resolution is finer around the outlets as well as the rivers in order to represent more accurately the topography and the local velocity field while ensuring the stability of the model. In the following, this last point will be studied at greater length because it greatly impacts the calculation time as well as the quality of the results.

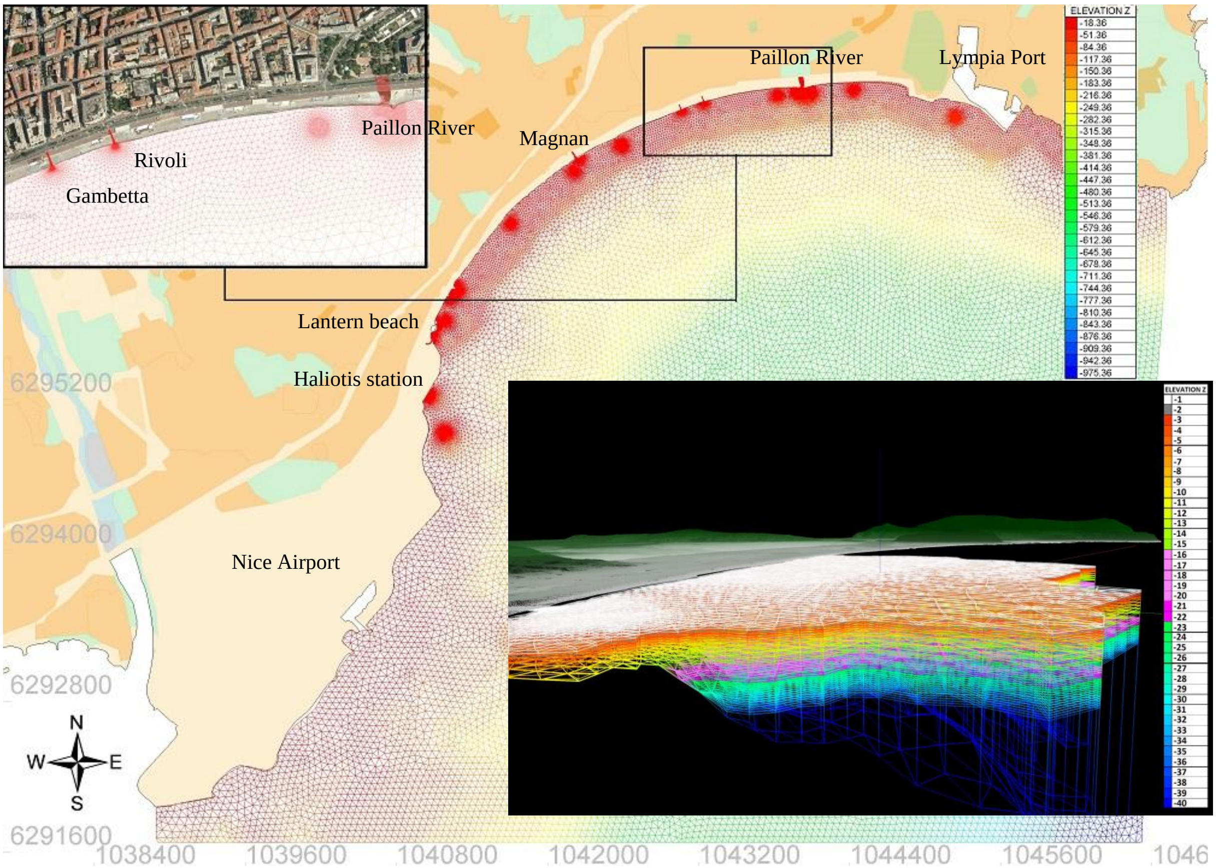

Figure 2: Calculation grid of the bay of Nice model with a view of the vertical planes.

The physical parameters taken into account are: wind, Coriolis force, temperature, salinity and swell. The wave driving forces are calculated using the TOMAWAC (Telemac based Operational Model Addressing Wave Action Computation) calculation code.

This phase averaged model calculates the sea state by solving the balance equation of the action density directional spectral at each point of the horizontal computational grid (23,24). Finally, the wave driving forces computing in Tomawac are transmitted to Telemac3d which calculate the nearshore current.

3. RESULTS AND DISCUSSION

3.1 Field Measurement campaign

The measurements carried out in the field as well as the laboratory analyses highlight different points.

First of all, the results of the analyses are consistent. The bacteriological load is very high in the network, much lower at the outfalls and low once away from the outfalls; respectively of the order of several millions, several tens of thousands and several thousands of CFU per 100 mL (Figure 3). These observations illustrate the vertical diffusion of the bacteriological tracer through the water column. Moreover, there is a horizontal dispersion of the pollutant load in the sea water depending on the distance from the outfall. This dispersion is caused by the diffusion and advection phenomena driven by the current and the concentrations field.

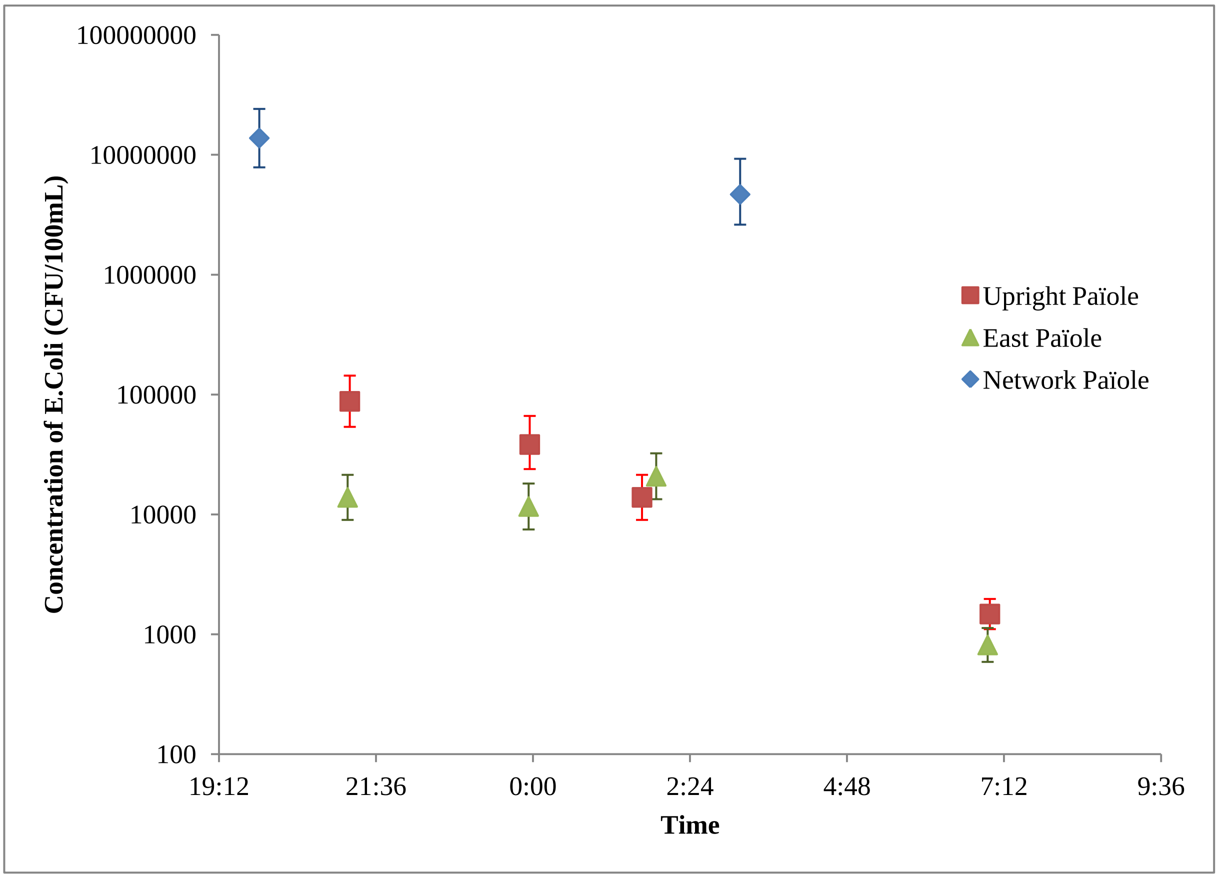

Figure 3: Evolution of concentration of E.Coli around Païole emissary.

Secondly, the decrease during the night of the bacteriological load observed in the samples is coherent with the use of the network. Around 8 pm, there is a high level of domestic use while at 2 am the activity is much lower (Figure 4). The same observation can be made for the evolution of the bacteriological load of the network samples, except for one sector.

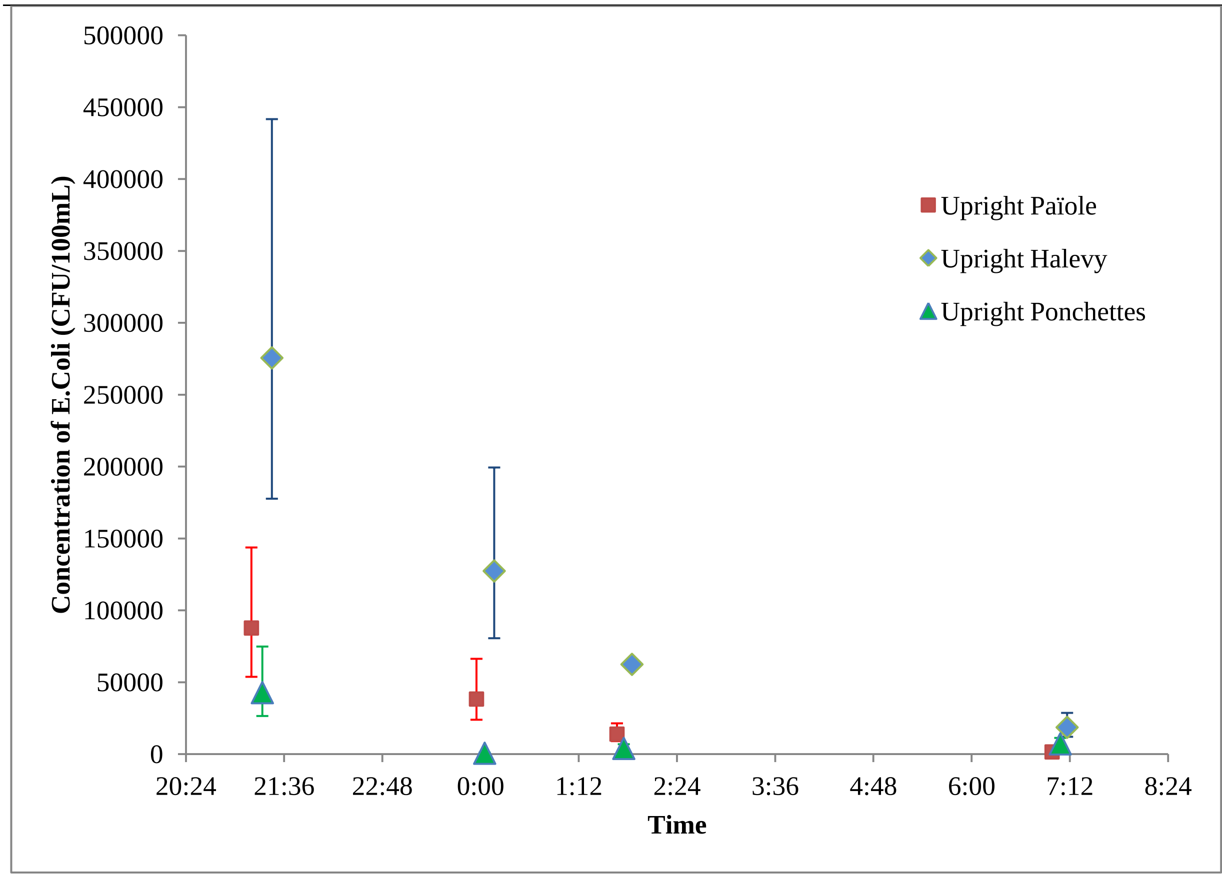

Figure 4: Evolution of E.Coli upright of the outlets, the vertical error bars represent the 95% confidence interval of the MPN method.

Indeed, in the Halevy area, the evolution of the bacteriological load in the network is different from the evolution observed at the sea outlet. There are three main causes for this observation. The first is doubts about the position of the network sample. In fact, the flow observed during network withdrawals was low compared to our expectations. The second is linked to the confidence interval of the bacteriological analyzes for high concentration of E.Coli, which is very wide and which therefore does not allow certain trends in the evolution of the bacteriological load to be transcribed. This confidence interval comes from the statistical approach of the MPN method. The last is the uncertainty about the position of the sample at sea because the equipment allowing us to locate us was a GPS application on a tablet (Google Maps), with an accuracy of around ten meters.

Another point is Paillon situation. During the sampling campaign, the river was closed by a permeable bead of pebbles. The bacteriological load was as high there as in the network, but it was difficult to quantify the amount of water that flowed into the sea.

In addition to the input bacteriological data discussed below, the outflow rates were recorded using automatic flow-meters.

Regarding the weather conditions on the day of sampling, the wind was very weak (2 m/s) and of North-West incidence, the swell was also very weak (height < 0.5 m) and from the North West. According to analyses around the Ponchettes emissary, which had sample points both East and West, the concentration of bacteria was important eastside and very low Westside. These results show a link between wind and wave directions and the propagation of bacteria.

Finally, to better characterize the temperature and salinity of the water column, the data used come from the EOL buoy. This buoy is located in the bay of Villefranche-sur-Mer. It measured temperature and salinity every meter from the surface to a depth of 50m.

3.2 Results of the model

First of all, the simulation covered a period from 7:00 p.m. to 8:00 a.m. The results of the model compared to those of the analysis are presented in Figure 5.

The curves in red represent the number of E.Coli CFU per 100 mL calculated by the model. The results were retrieved from the nodes of the calculation grid closest to the GPS coordinates of the samples (Figure 6). The curves in blue correspond to the number of bacteria calculated on a node close to that of the red curves.

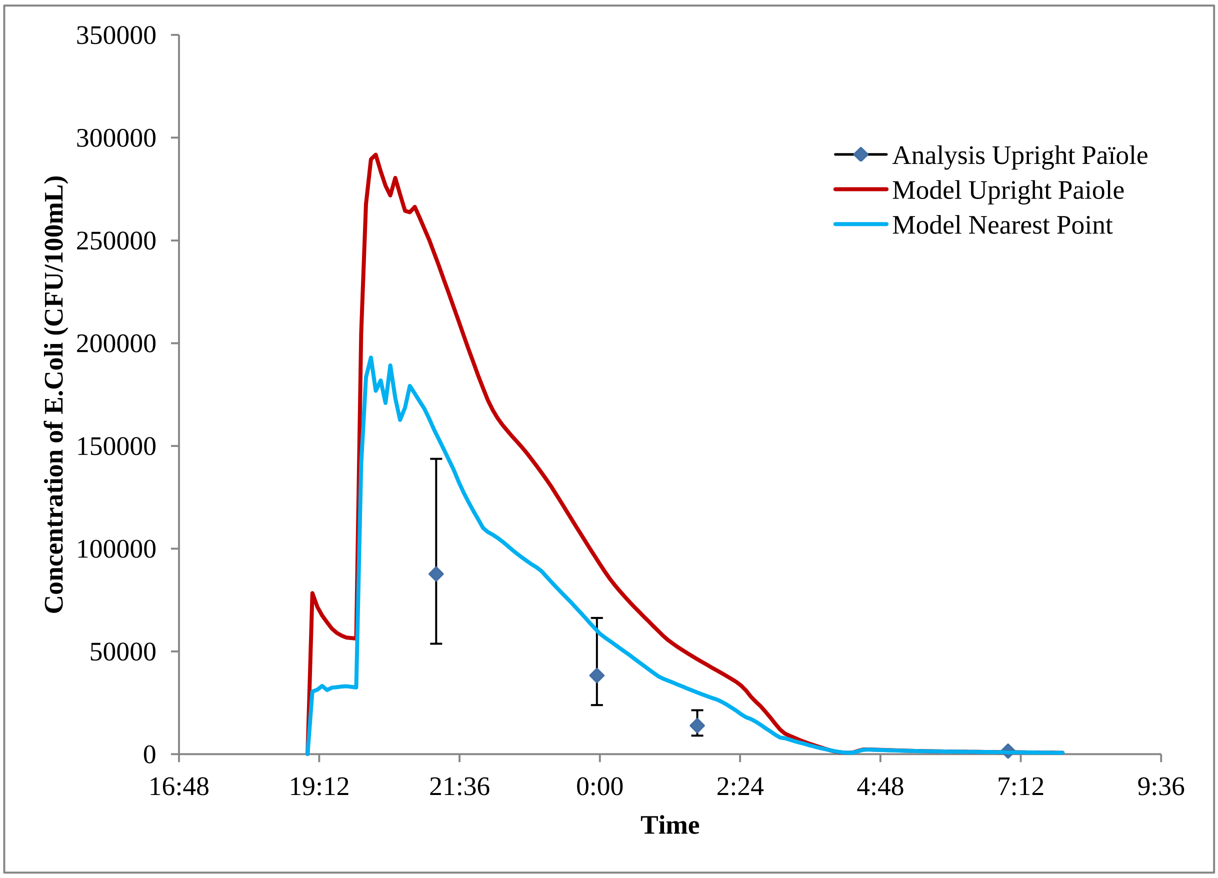

Figure 5: Results upright of Païole's outlet; in black the results of the analysis; and results of the model upright the outlet and of the nearest point of the sample position in red and blue respectively.

The spatial variability of the model results is very important at a depth of 1m, the sampling depth. Indeed, the accuracy of the position of the samples at sea is of the order of ten meters while the resolution of the calculation grid varies between 3 meters, which correspond to an "outfall" zone. Thus, assessing the accuracy of the model is deeply affected by the position of the boat while samples were collected. Figure 6 shows this variability, around the outlets, the concentration of bacteria can be divided by 10 within 3 meters of the position of the outlet.

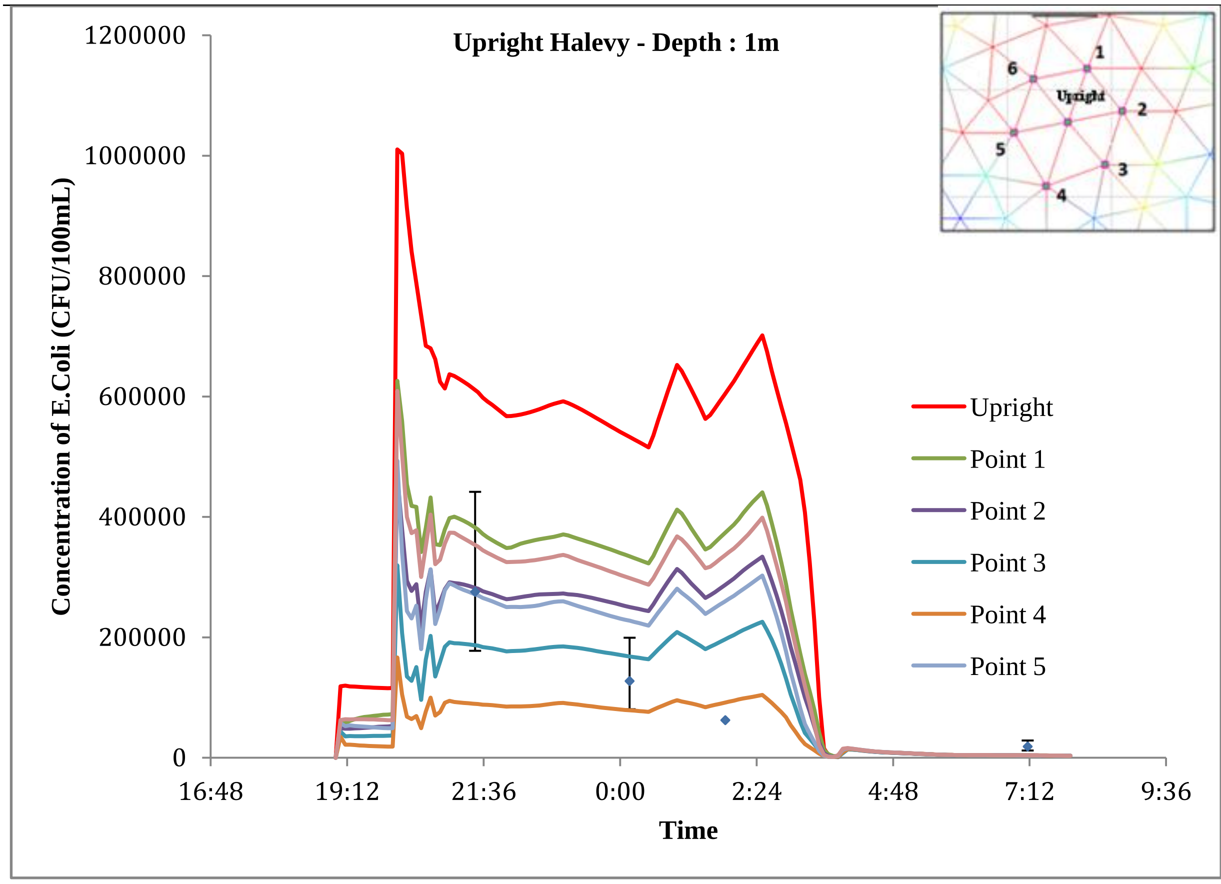

Figure 6: Vertical variability upright Halevy outlet at 1 m depth.

Based on the results, the model manages to follow the evolution of the bacteriological load at the upright of the emissaries, in particular the Païole one which is the deepest. Also, the sudden increase and decrease in surface area is consistent with the start and end of the discharge from the outlets.

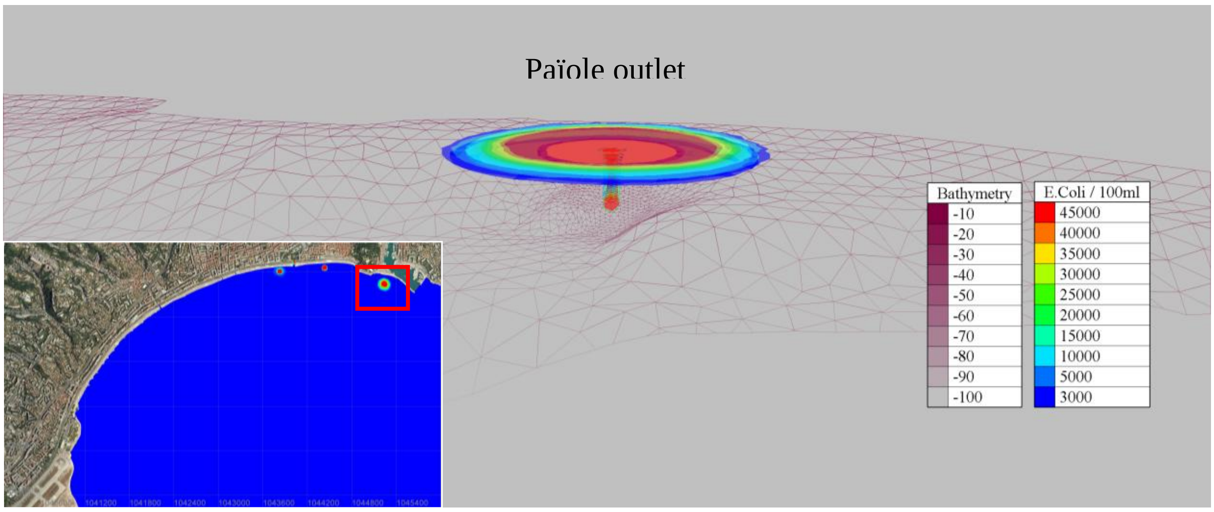

Figure 7: Concentration of E.Coli after 1 hour of discharge at Païole outlet. The horizontal dispersion in the first 5 layers after the vertical transport of the pollutant.

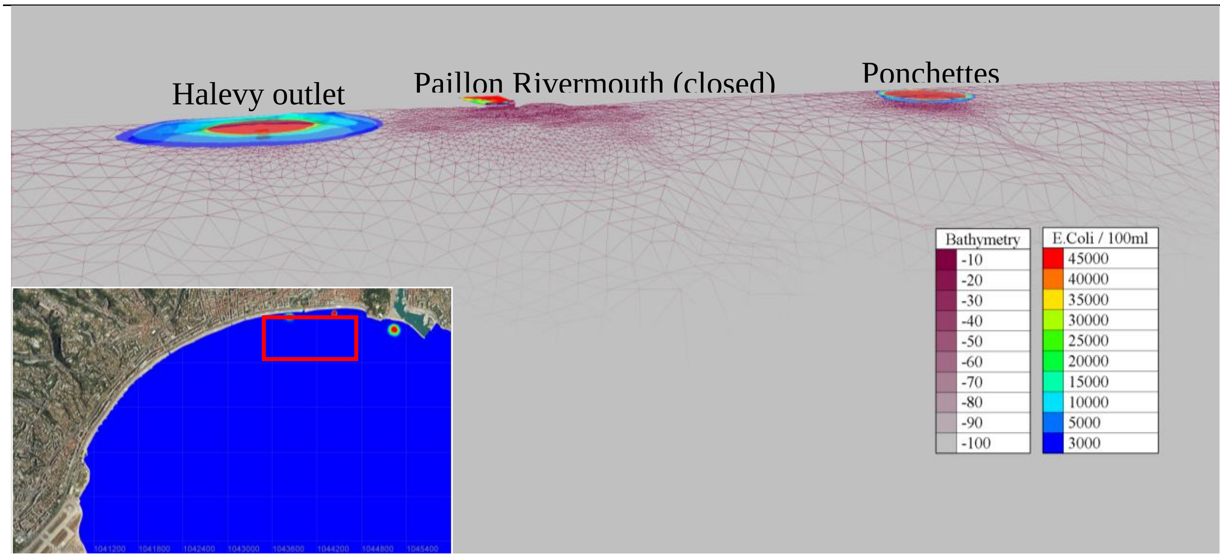

Figure 8: Concentration of E.Coli after 1 hour of discharge at Halevy and Ponchettes outlets.

Telemac3D can launch a simulation with parallel processors thanks to the domain decomposition. The infrastructure of the NCA metropolis does not allow the calculation time to be reduced under 23 hours for 13 hours of simulation.

In that case, running a simulation on 8 processors implies that Telemac3D will split the 3D mesh into 8 parts equal in number of points and simultaneously perform calculations on them. A specific effort was made to create computational grid exposed on Figure 2 in order to reduce the number of elements while keeping the simulation stable. Thanks to that the calculation time was nearly halved. With a suitable machine, the computation time can be considerably reduced.

4. CONCLUSION

Microplate analyses are the laboratory process applied by the public health agency to monitor the bathing water quality. This method is very time consuming and have high uncertainties. Samples must first be taken at sea or on the beach, then analyzed and finally, 40 hours later, results are obtained with a high degree of uncertainty. This delay pushes to extend the closures as a precautionary measure.

The model presented is therefore very interesting; despite the high computation time it remains inferior to the laboratory analysis. Moreover, even if the spatial accuracy of the results is to be reviewed, the objective is to be able to correctly predict the end of the pollution event. On this point, the model is satisfactory and meets the expectations of public authorities.

Nevertheless the model still needs to be tested on more events to be functional and the accuracy must be improved. A validation of the hydrodynamic parameters of the model, especially the velocity fields, will also be necessary.

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