FAECAL POLLUTION MODELLING AS A MANAGEMENT TOOL IN COASTAL AREAS: A CASE STUDY IN ESTORIL, PORTUGAL

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CHAPTER SYNOPSIS

Background
Over the last decade a considerable investment has been made in the major bathing area of the Estoril coast (Portugal) to mitigate feacal pollution and to achieve compliance with the mandatory standards of the EC Bathing Water Directive. This chapter reports a study made in 2004 combining hydrodynamic, numerical drogues dispersion and *Escherichia coli* (E. coli) decay modelling techniques. Validated with field data this work aimed at identifying a potential source of pollution of the bathing water of Torre beach, where high counts of faecal indicators have occasionally been reported.

Results
Results show that hydrodynamic processes govern the distribution of contaminants in the receiving area and that its abundance is also strongly influenced by light. The modelling approach was able to provide evidences of the impact of a punctual source of contamination on the surrounding bathing areas.

Conclusions
The study reported here has lead to the eradication of the pollution source and subsequent improvement of local water quality, leading to the classification of St. Amaro Beach (Oeiras Bay) as a bathing area.

1 SEWAGE DISPOSAL IN COASTAL AREAS

The discharge of untreated or partially treated sewage effluents into coastal areas has been a common practice in many developing countries for some decades now. In European countries, especially those facing inner sea or limited water supplies, the pollution of water systems is a steadily growing challenge because it poses a threat to human health and has major socio-economic impacts. Concern about the effects on the quality of such water bodies have, therefore, become a major issue is coastal management.

The ability to quantitatively relate waste loads with temporal and spatial changes in the receiving water body is a requirement for reliable decisions to achieve specific water quality objectives. And these relationships are quite sensitive to natural environment conditions. As for the persistence of faecal indicator bacteria, studies have revealed a number of environmental parameters, especially solar radiation, salinity, and temperature, that cause their declining [1–4].

The use of numerical models to assess pollution effects caused by sewage discharge has become widespread [5–10]. The residence time of faecal contaminating agents is very low when compared to other pollutants, usually ranging from less than an hour to some dozens of it, and occasionally up to some days [1]. The short life span of these organisms outside their hosts imposes limitations to their spread in the water, even under intense hydrodynamic regime. Nevertheless, their potential to compromise water quality standards in bathing areas must be assess, with numerical models playing a significant role in this process.

This chapter reports on a case study that goes back to 2003, where the application of such a model was required. The study was prompted to evaluate the hypothesis of a brook (Ribeira da Lage) being a possible cause of water contamination in one particular beach (Torre beach, Fig. 1), characterized by an irregular water quality record in routine analysis.

Achieving this goal has required the integration of experimental work (to test the adequateness of feacal decay models), field work (several campaigns and monitoring programs) and modelling studies. The experimental work lead to the choice of an algorithm for E. coli decay in the water available in the literature. This algorithm, in turn, was programmed into MOHID allowing coupling of hydrodynamic models with a dynamic T90 decay model for E. coli.

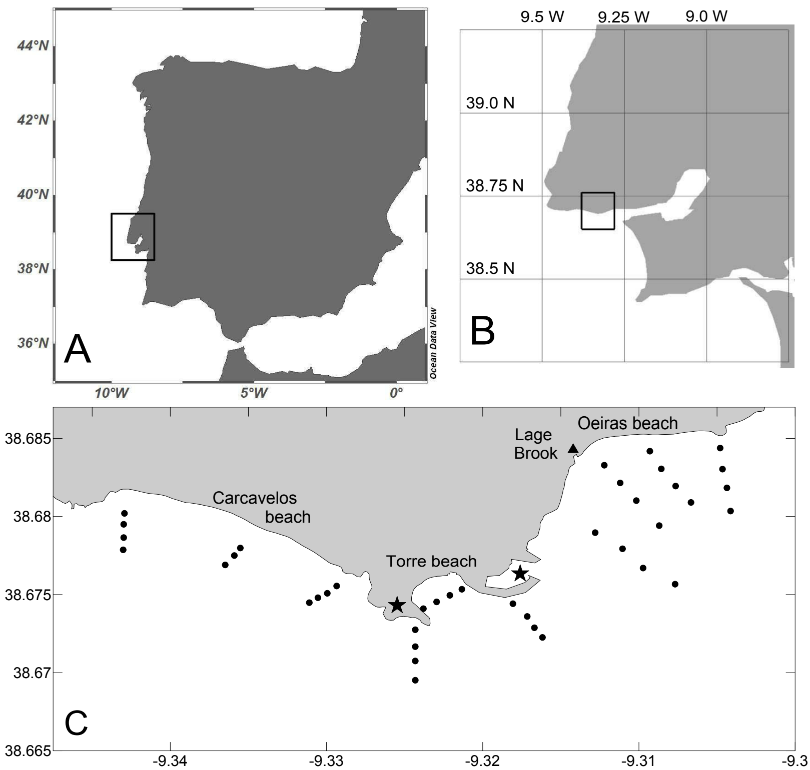

Figure 1. *Location of the study area and stations (dots) monitored during the campaigns undertaken in May (2004). The system is located near the Tagus estuary, one of the biggest estuaries in Iberia (A), on the western side of the estuary mouth (B). Estoril cost extends for another 20 km northwest ward. Two structures set the limit to the Torre beach (C), namely, an old fort on the left and a marina on the right side (marked with stars).*

2 THE STUDY AREA

The study site is located in the Estoril coast near Tagus estuary in Lisbon, Portugal (Fig. 1). Since this is a popular vacation site during summer months, improvements in water quality have been a major concern in order to minimize public health risks. The goal has been to ensure that contamination levels achieve compliance with Directive (76/160/EEC) Imperative standards for bathing water quality in all the beaches along the Estoril coast. The Estoril coast has suffered significant intervention since mid-1990, mostly related to the identification and eradication of point sources. By the time this study was made there were no treated effluents of wastewater treatment plants in the area or any other identified source of feacal pollution.

The Estoril coast line has a complex morphology, characterized by several piers, bays, rocky and sandy beaches. Water circulation patterns are largely determined by the coast orientation and its irregular pattern, where sandy bays are interrupted by rocky geological structures. The Torre beach (Fig. 1) is located near the mouth of Tagus River, in an area where flow velocities usually reach higher values. The hydrodynamic regime is very complex with tidal meandering currents and eddies in the near coastal section. Previous field studies using current meters and Acoustic Doppler Current Profiler equipment revealed that off the coast of Carcavelos beach (west of Torre beach) starts an eddy formation in mid ebb that grows to the size of almost all Estoril coast in low tide. To the east of Torre beach, in Oeiras beach, several eddies form both during ebb and flood. A schematic representation with the general circulation pattern of the studied area is shown in Figure 2.

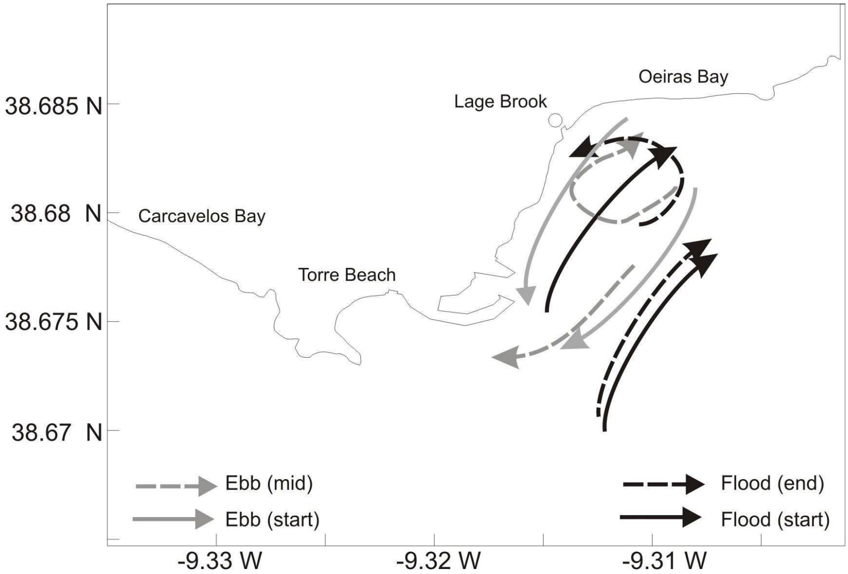

Figure 2. *Major circulation patterns in the study area. Arrows are used to illustrate the general circulation pattern and do not quantify the intensity of currents. Dashed arrows show the direction of eddies formed during ebb and flood start.*

The Lage brook, located at the west end of Oeiras beach (marked as a triangle in Fig. 1), was a known source of faecal contamination based on earlier water quality analysis. It drains from a relatively large watershed, where clandestine domestic sewage discharge were known to occur, but the flow regime during spring and summer is low ($\sim$0.04 $m^3 s^{-1}$). The dynamic dispersion of its plume is mostly controlled by the eddy rotation. Torre beach is a small bay between two man-made structures: a marina pier and the surrounding walls of a fort (marked as stars in Fig. 1). The local circulation in this small area consists, basically, of a continuous recirculation, with significant tidal differences. These were induced by a small eddy resulting from the interaction of currents along the coast and the water mass located inside the small bay. The recirculation pattern inside the bay tends to prevent outside water to reach the beach, thus lessening the water renovation in it.

EXPERIMENTAL AND FIELD WORK

2.1 Experimental faecal decay test

A review of the literature available at the time was performed to evaluate faecal decay algorithms derived in situ and laboratory studies of mortality rates of E. coli. Among the models that were found we have selected two based on their adequacy to the nature of our study. For simplicity the algorithms are referred to by the name of their authors, namely Canteras et al [11] and Chapra [12]. Both models considered the decay of E. coli as a function of water temperature, salinity and light radiation.

Laboratory experiments were realized to evaluate the response of both algorithms, according to the methodology proposed by other authors in similar studies [13,14]. Starting with known concentrations of E. coli and salinity, several water samples were exposed to different levels of light radiation and temperature. The results obtained in the laboratory essays were then compared with each algorithm prediction to determine which reproduced the observations more accurately. The outcome of these experiments led to the choice of the Canteras et al algorithm for our study.

2.2 Water sampling strategy

The monitoring program to assess the water quality in Torre beach had the duration of 10 weeks (13 May to 15 July 2003), with sampling being carried out in the morning twice a week, usually between 7-9 a.m. Samples were transported and stored at 4^o C. Water analyses were performed in less than 24h after sampling with E. coli enumeration made by the membrane filtration method following the recommendations of the American Public Health Association (APHA) [15].

To identify possible faecal contamination sources in the surrounding area, a parallel sampling program was established. Four sampling campaigns were made (8, 14, 21 and 28 May 2003) to determine the contamination field for the area. For simplicity, campaigns are numbered from C1 to C4, and this terminology will be used henceforth. These campaigns considered 32 sampling stations between Carcavelos and Oeiras beach (dots in Fig. 1). Samples were taken by boat twice a day, one in early morning and the other in the beginning of the afternoon, so that both tidal periods could be considered. The sampling period was never greater than 30 minutes in both morning and afternoon campaign. The same procedure described earlier for storage and enumeration faecal bacteria was followed.

3 MODELLING APPROACH

3.1 Hydrodynamic model

The MOHID hydrodynamic model was used to achieve an accurate characterization of the flow regime of the study area. MOHID is a 3D finite volumes model [16] using an Arakawa-C grid [17] to perform the computations. A discrete form of the governing equations is applied macroscopically to the cell control volume. The grid is defined explicitly and the equations are solved using the same procedures, irrespectively of the cell geometry.

The hydrodynamic governing equations are the momentum and the continuity equations. The hydrodynamic model solves the primitive equations in Cartesian coordinates for incompressible flows. The momentum and mass evolution equations are portrayed in Eq. 1 and 2, respectively, where u_i is the velocity vector components in the Cartesian x_i directions, η is the free surface elevation, υ is the turbulent viscosity and p_{atm} is the atmospheric pressure. p is the density and p' its anomaly, ρ_0 is the reference density, g is the acceleration of gravity, t is the time, h is the depth, Ω is the Earth velocity of rotation and ε is the alternate tensor.

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial p_{atm}}{\partial x_i} - g\frac{\rho(\eta)}{\rho_0}\frac{\partial \eta}{\partial x_i}$$
$$-\frac{g}{\rho_0}\int_{x_3}^{\eta}\frac{\partial p'}{\partial x_i}dx_3 + \frac{\partial}{\partial x_j}\left(\upsilon\frac{\partial u_i}{\partial x_j}\right) - 2\varepsilon_{ijk}\Omega_j u_k \tag{1}$$

$$\frac{\partial \eta}{\partial t} = -\frac{\partial}{\partial x_1}\int_{-h}^{\eta} u_1 dx_3 - \frac{\partial}{\partial x_2}\int_{-h}^{\eta} u_2 dx_3 \tag{2}$$

3.2 Application to the study site

Simulation conditions were selected to represent the surroundings of Torre beach. The main forcing mechanisms for the circulation considered in the model were tide and Tagus river outflow. To minimize the open boundary constraints in the local current patterns, a three nested model system was implemented: first covering a part of the Portuguese west coast (37°N – 41°N), second encompassing all the Tagus estuary area (38.1°N – 39.9°N), and finally the third that covered the immediate zone of the study area. The adopted methodology for the model nesting followed the methodology proposed by other authors [18].

The first domain is characterized by a regular square grid with 223×168 computation points, each cell covering an approximated area of 4 km^2. The second nested domain, forced by the boundary conditions imposed by the first domain, has 162×162 computation points and a minimum resolution of 300 m. Third nested domain has 100×200 computation points, having a minimum resolution of 20 m, and was forced by boundary conditions with detailed spatial and temporal variability. FES95.2 global tidal solution [19] was imposed at the open boundary of the first domain. It was assumed an intense vertical mixing implying a homogeneous water column in all three domains, and so only two spatial horizontal dimensions (2D) were considered.

3.3 Numerical drogues

The use of tracers in the study of sewage dispersion has been widespread in experimental scenarios but not so much in numerical ones. Bacterial and fluorescent tracers (e.g., rhodamine) can be used as indicators for the distribution of particles originated in brooks and rivers or entering any receiving water body [20]. Following the same rationale, a lagrangian model was used to simulate the dispersion of wastewater in the coastal area.

Tracers are transported by currents calculated by hydrodynamic model. Besides its spatial position, each tracer is characterized by volume and E. coli concentration, a commonly used indicator for which guidelines and mandatory standards have been specified in the EC Directive. In emission, each tracer has the same microbiological and physical characteristics of the Lage brook. Both volume and concentration vary in time, but in response to different parameters; volume is affected by turbulent mixing while microbiological indicators depend on environmental such as radiation, temperature and salinity.

A continuous discharge was set for the brook during the simulation period. Based on numerous water samples collected in the effluent (Lage brook) over some past years, the initial concentration (moment of discharge) of E. coli for each tracer was set as 10^5 MPN/100ml, a typical concentration found in local water samples. Tracers were released with an interval of 150 s, being the number of tracers a function of the initial box volume (given by grid area and batimetry) divided by the initial volume defined for the tracers (300 m^3). Brook flow was set to a constant value (0.04 m^3 s^{-1}), measured with a flow meter in previous monitoring campaigns, and was considered explicitly in the hydrodynamic model. The initial tidal condition chosen for the simulations start, i.e. drogues emission start, was the end of high tide (at 19.00h on 12 May). A complete tidal cycle is achieved before early morning, the time of day when faecal counts are usually higher.

3.4 E. coli decay model

As stated before, we have adopted the Canteras et al algorithm [11] to account for the mortality rates of E. coli. The simultaneous combination of all factors is accounted as:

$$k = 2.533 \times 1.04^{(T-20)} \times 1.012^{S} + 0.113 i_z \quad (3)$$

where S and T are the surrounding water salinity and temperature (°C), respectively, and i_z the radiation (watt m^{-2}) at depth$z$ (m). Radiation levels in the water ambient are estimated by the hydrodynamic model where the light extinction is a function of light absorption by water and suspended sediments concentration. The radiation is known for each vertical layer (depth integrated).

Bacterial decay is usually expressed as T_{90}, the time in which 90% of population is no longer detectable, meaning 1 log reduction in number of pathogens. Assuming a first-order loss, the 90% mortality time is obtained by:

$$T_{90} = 2.303/k \tag{4}$$

4 RESULTS

4.1 Field data

An identification of any possible source of contamination inside or in the vicinity of the Torre bay was performed before any interpretation of the field data. Despite all the efforts to eradicate faecal pollution sources in the past, two potential sources were recognized and investigated: the fort on the right side of the beach, and the marina on the left. Being an old construction and an actual residence, the fort was selected as the starting point to look up for any possible hidden discharge. After a thorough search along the fort walls, both above and below the water levels, it was possible to conclude that no such source was present.

Faecal pollution originated in coastal marinas have been a somewhat neglected example of contamination sources [21], but it was assumed as a potential threat for the water quality in Torre beach. After a detailed examination, the marina ended up by being excluded as a possible source of contamination because it only harbored small recreation and fishing boats. Water sampling for analysis was performed to verify this observation. The presence of other potential point and non-point sources was also excluded after a thoroughly inspection of the site.

Fecal distribution fields obtained from all campaign samples suggests the Lage brook (east from Torre beach) to be the source of contamination. In a total of 6 campaigns out of 8, E. coli counts above 100 MPN/100ml were observed (Table 1). Whenever contamination was found in the results, higher concentrations were always related with the brook (Fig. 3, panels A and B). No other source could be identified in the final analysis.

Usually, concentration decreased with increasing distance from the Lage brook. Except for the last campaign (C4), higher counts of fecal contamination occurred in the start of ebb, possibly caused by an increase in the Lage output as a consequence of tidal shift. Although the afternoon period of campaign C2 was characterized by the higher contamination values (5400 MPN/100ml), they were confined to the surroundings of the brook. The same pattern was observed with campaign C3, where despite low values observed in morning and afternoon periods, the higher counts of E. coli (peaking 400 MPN/100ml) where observed in the morning period in the middle of Oeiras bay.

All campaigns, despite different weather and tidal conditions, showed similar results. For this reason, only the results of campaign C1 will be discussed. The morning sampling period began during the starting period of ebb. From the results it is possible to identify a plume with its origin in the Lage brook, and spreading westward. This plume appears to have an influence on the waters inside Torre bay, with the higher observed value of E. coli around 700

Table 1. *Samples where faecal contamination was detected. Measurements were made inside Torre beach in early morning, during May and July (2003).*

Date	Time	E. coli	Tide(m)			Sampling	
		MPN/100ml	Amplitude	max	min	Level (m)	Phase
13 May	7.30	350	2.49 (average)	3.27	0.78	1.02	flood (start)
27 May	8.25	420	1.8 (average)	2.95	1.15	1.63	flood
28 May	8.10	170	1.96 (average)	3.04	1.08	1.26	flood (start)
18 Jun	8.10	900	1.8 (average)	2.91	1.11	2.02	mid-ebb
24 Jun	7.35	2000	1.31 (neap)	2.68	1.37	1.89	mid-flood
25 Jun	7.53	400	1.49 (neap)	2.78	1.29	1.72	flood (start)
01 Jul	7.55	300	1.98 (spring)	2.97	0.99	1.27	ebb (end)
08 Jul	8.05	120	1.67 (neap)	2.86	1.19	2.71	flood (end)
09 Jul	8.05	280	1.78 (neap)	2.93	1.15	2.31	mid-flood

MPN/100ml. Considerably high contamination values are also observed in the east side of Oeiras bay (around 1400 MPN/100ml). Assuming the Lage brook as the only source of contamination, this occurrence can be explained either by the cyclonic vortex (counter clockwise) developed during the previous flood period, or by the remains of the brook plume transported eastward during flood.

The contaminated plume can be traced as far as the east side of Carcavelos beach, where values reaching 390 MPN/100ml are observed. Another clear illustration of this far-reaching impact of the discharge at Lage brook is observed in the morning campaign C4 (Fig. 3, panel C). Values as high as 600 MPN/100ml were found in the east side of Carcavelos bay. The extension and persistence of high values of contamination on the surrounding areas of Lage brook found in the morning periods can be explained as a consequence of low mortality rates of coliforms during night periods [1,22–24]. However, the lack of meteorological data for each campaign and sampling day does not allow to set a clear relation between atmospheric conditions (especially radiation levels) and E. coli counts. The results also imply the occurrence of discharge from the Lage brook during flood, given the lack of retention capacity in its final section. This hypothesis is validated by the numerical simulations presented below.

In the afternoon period of campaign C1 (Fig. 3, panel B), started during the beginning of flood, contamination values were low (309 MPN/100ml being the higher observed value) when compared to the morning period. Nevertheless, it is possible to identify a plume pointing east, associated with the Lage outflow. The plume direction follows the typical flow pattern (velocity field) under flood tidal period. Lower values in the afternoon can be explained by the conjugation of low brook discharge during flood and high mortality rates during daylight.

Results clearly show that the westward expansion of the Lage plume in Oeiras bay (eventually reaching Carcavelos bay) meets its favorable conditions under ebb regimes and with low solar radiation. Similar observation have been made in NW England beaches [25], leading them to suggest that whenever possible, all sampling of EU designated bathing waters should be carried out in the early morning period.

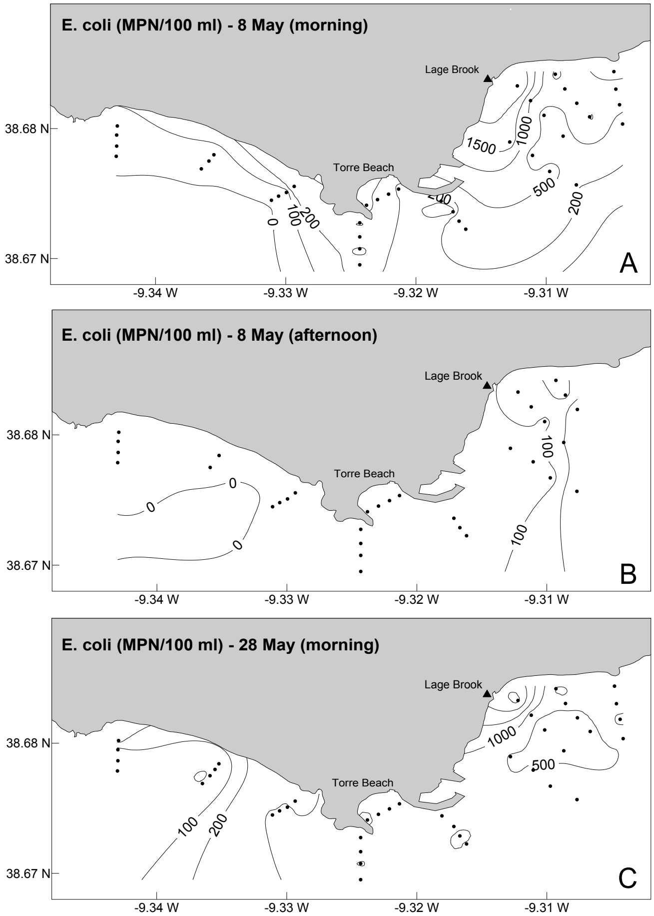

Figure 3. *Horizontal E. coli distribution (MPN/100ml) for Campaigns C1 and C4: A) in the starting period of ebb with samples taken in the morning; (B) in the starting period of flood with samples taken in the afternoon; (C) in the starting period of flood (samples taken in the morning).*

4.2 Model results

A proper representation of the hydrodynamic regime of the study area is imperative. Results for the second level hydrodynamic model that gives the boundary condition for the finer resolution model of the Torre beach area were previously validated. Model results for velocity fields seen in Figure 4 agree with the typical circulation pattern of the study area. While the dispersion pattern of particles is a consequence of the velocity-field determined by the hydrodynamic model, the extension and persistence of particles trapped near the coast is a function of T_{90} values. The ability to model both these processes is particularly relevant in settings like Torre beach, because of the high residence time inside the bay imposed by the hydrodynamic regime.

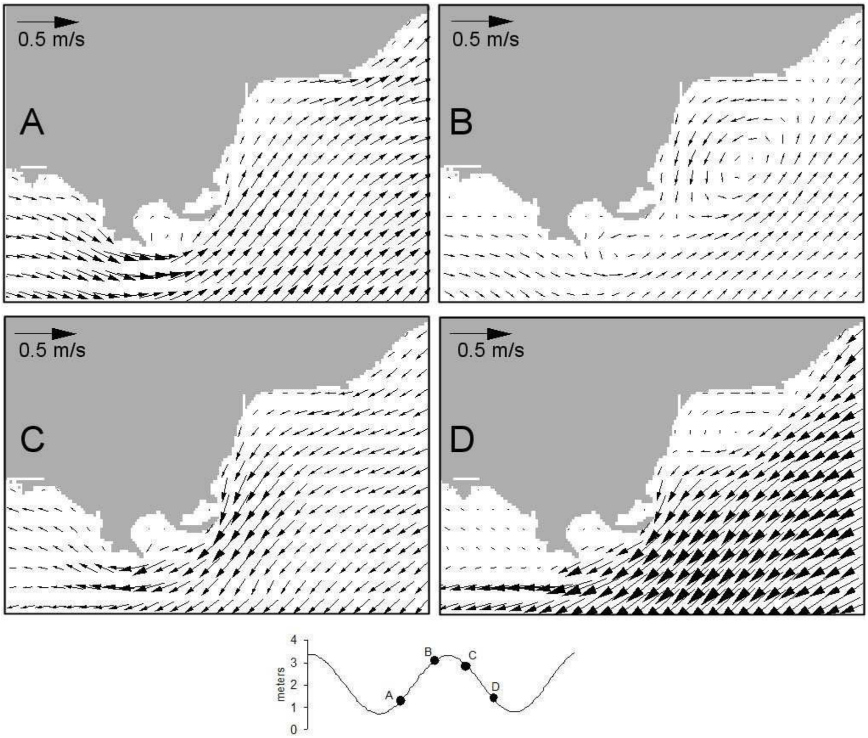

Figure 4. *Model results for the velocity field at four tidal instants indicated in the lower panel (sea surface height). Tidal conditions at each moment are: (a) flood start, (b) flood end, (c) ebb start, (d) mid-ebb.*

Figure 5 shows four instances of the simulation of the evolution of tracers with faecal concentrations. Five hours after the beginning of the simulation (at 0.00 a.m.) the plume has been carried along the coast by the ebb current, reaching the entrance of the marina. Under the absence of radiation influence on the mortality rate ($T_{90} > 15$ h), the observed 1 log unit decrease in E. coli concentration is explained on the basis of dilution and contribute of salinity and temperature. By 4 a.m., tracers reached Carcavelos bay with a concentration range of two log units ($10^3 - 10^4$ MPN/100ml). It is also possible to see some particles trapped inside Torre bay where higher concentrations are observed (10^5 MPN/100ml). Since a constant dilution rate is assumed, the differences seen so far are explained on the basis of the time passed since emission, with higher concentrations denoting a more recent emission.

Four hours later, (8 a.m.), with $T_{90} < 3$ h due to light radiation, only a few particles are noticed off Carcavelos bay and inside Torre bay. Simulated concentration (around 10^3) and results from samples made inside Torre bay are in the same range for this time of day (Table 2). Higher values seen near Lage brook represent recently emitted tracers transported by currents induced by tidal shift. Finally, at 12 a.m. contamination can only be observed in the surrounding area of the Lage brook. According to the simulation, no contamination occurs inside Torre bay from 9.30 a.m. onwards.

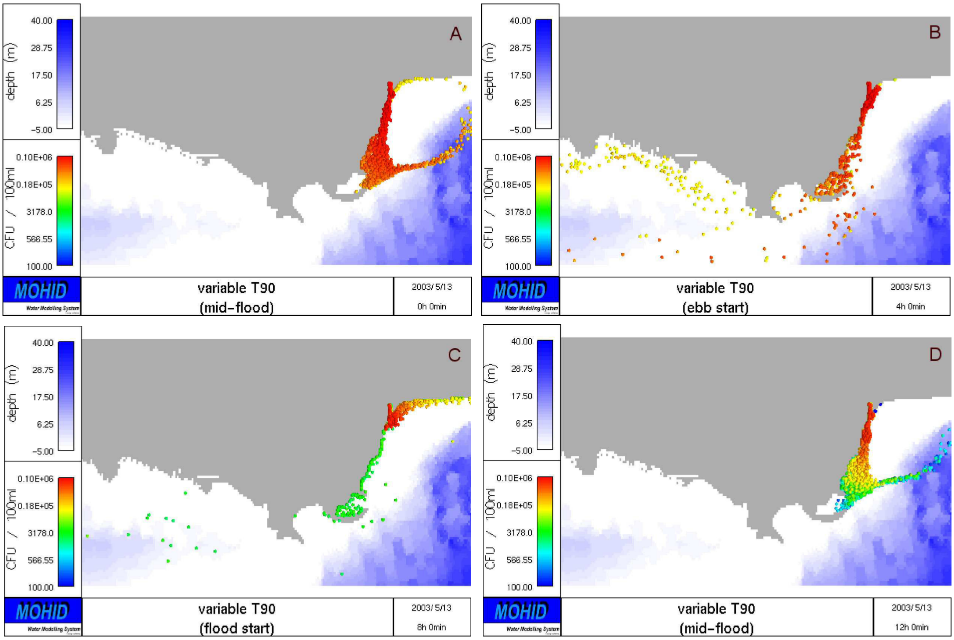

Figure 5. *Simulated dispersion of numerical drogues in the study area with the color code showing* E. coli *concentration in particles. Tidal conditions at each instant are: (a) mid-flood, (b) ebb start, (c) flood start, (d) mid-flood. The exact simulated time is mentioned in the figures.*

5 MAIN CONCLUSION FROM THIS STUDY

The study described in this chapter reports on a development made to equip the MOHID model with E. coli decay algorithms. This improvement made the model more versatile in the study of microbiological water quality, more specifically in the simulation of the dispersion and decay of faecal contamination in the receiving water bodies. With this upgrade in the code the model was able to simulate scenarios that previously modelling efforts failed to reproduce. Field data for contamination in the study area show that higher E. coli counts were:

- Found around the Lage brook area of influence;
- Associated with ebb starting period when brook discharge increases;
- Recorded mainly during the morning period, independent of the tidal regime. These observations suggested that the contamination might be locally induced by the Lage brook and that the role of solar radiation is a determinant in E. coli decay.

Model results have satisfactorily reproduced the observed patterns, validating the advanced hypothesis of Lage brook as the origin of contamination in the area. In addition, the model results provided a possible explanation for the observed patterns. It has been stressed that monitoring programs must take into account the diurnal variation of fecal indicators and should be able to explain it [26]. Hence, the modelling methodology used in this study was considered as useful as a management tool for other sites with similar pollution problems.

Table 2. *Summary of the results obtained in the May (2003) campaigns. Maximum and minimum values (range) measured in the samples.*

Campaign	Day		Tide	E. coli (MPN/100ml)
C1	8	morning	ebb (start)	14 – 2900
		afternoon	flood (start)	<1 – 309
C2	14	morning	flood (start)	<1 – 4300
		afternoon	ebb (start)	<1 – 5400
C3	21	morning	ebb (start)	<1 – 400
		afternoon	flood (start)	<1 – 80
C4	28	morning	flood (start)	2 – 2700
		afternoon	ebb (start)	<1 – 40

The present study comprising field data with model applications helped to solve a complex fecal pollution problem in one of the most attended bathing areas in Portugal. As an outcome of this study the discharge at Lage brook was eradicated. An overall improvement of the water quality of the studied area was achieved, leading to the classification of St. Amaro Beach (located in the Oeiras Bay) as a bathing area.

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