

Streams contribution on bathing water quality after rainfall events in Costa do Estoril- a tool to implement an alert system for bathing water quality

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ABSTRACT

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Bathing waters of Costa do Estoril are located near urban and rural areas, crossed by streams discharging into the sea/estuary. In order to evaluate the contribution of these streams on bathing water quality after rainfall events, a monitoring program financed by SANEST, SA was established. The final aim of this work is to be able to provide bathing water quality information from the automatic monitoring of water levels in streams. To achieve this goal, the relationship between water level, flow and contamination must be determined. The monitoring program included sampling of water quality indicators (e.g faecal coliforms) in streams and beaches, water level and discharge measurements in streams and the implementation of models capable of explaining local trends, and ultimately forecast hydrodynamics and water quality. Also, automatic hydrometric stations were installed in Marianas and Sassoeiros streams. These stations automatically measure water level and send real-time alerts to a central workstation when the water level rises above predetermined values. In addition, currents along the beaches were measured using acoustic profilers. These data provide a better comprehension of local hydrodynamics and information to validate models. Results show correlation between water level and flow that allow estimating stream outflow from water level. Numerical predictions were made using MOHID Water Modelling System. Simulations using measured stream discharge show that the model can accurately simulate dispersion and evolution of the streams plume and bathing water quality.

ADDITIONAL INDEX WORDS: *Fecal contamination, alert system, MOHID*

INTRODUCTION

Fecal indicator bacteria (FIB) in coastal waters are largely derived from discharges of untreated sewage or treated sewage effluent that unload directly to the sea or arrive to coastal waters via river systems (WYER et al., 1994). Coastal urbanization and the subsequent replacement of natural vegetation with impervious surfaces increase storm-water runoff and the loading of numerous pollutants into coastal waters (MALLIN et al., 2001). Therefore, streams may significantly contribute to bathing water contamination resulting from rainfall or other short-term pollution events. Several studies show that bathing waters under stream discharge influence reveal higher fecal contamination after rainfall events (WYER, et al., 1994; NEVES & WHITMAN, 2005. Also, increases in human population, number of domestic animals and alterations of the natural landscape lead to increases in the amount of FIB entering nearby waterways. As a consequence, microbial contamination from fecal origins in storm water runoff poses a risk to human health through recreational and bathing contact with surface waters. The New Bathing Waters Directive (2006/07/CE) aims to protect bathers health as well as to preserve, protect and improve environmental quality. In order to achieve this goal, a management plan is required that includes the creation of Bathing

Water Profiles. These profiles (established in accordance with Directive's Annex III) must discern all possible pollution sources, including predictable short-term pollution events or abnormal situations. In contrast, the current bathing water directive (D.L. 236/98) merely takes into consideration water sampling and subsequent FIB quantification, namely Total Coliforms (TC), Faecal Coliforms (FC) and *Escherichia coli* (EC). FIB serve as the regulatory meter by which water quality is measured and standards' must be met (USEPA, 2006). With the actual fecal analysis methods, water quality evaluation, takes at least 18h to obtain analytical results from a laboratory. During this period of time, beach users might have been exposed to harmful pathogens in water. To avoid this, Directive 2006/7/CE enforces the implementation of an alert and prediction system to protect bathers from short-term pollution events.

In compliance with the New Bathing Waters Directive, a monitoring program financed by SANEST, SA and designed by the Technical University of Lisbon (IST) was implemented in Costa do Estoril in order to evaluate streams contribution to bathing water quality. The final aim of this study is to be able to provide bathing water quality information from the automatic monitoring of water level in streams. To achieve this goal, the relation between water level, flow and contamination must be

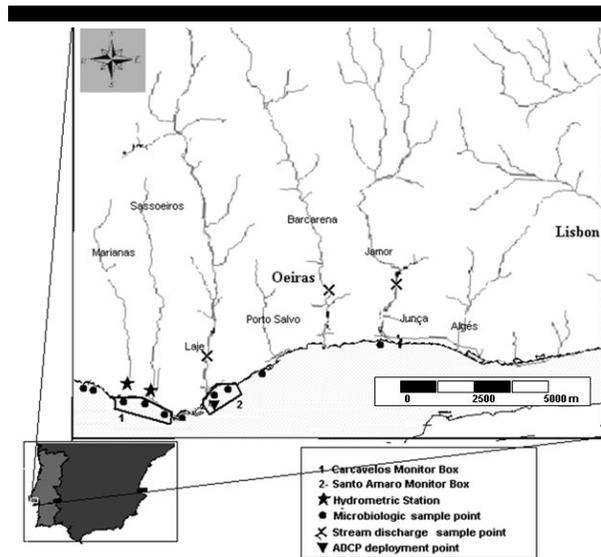


Figure 1. Location of the study site, with streams location, sample points, and monitor boxes representation.

determined. Monitoring work includes determining fecal contamination in streams and coastal waters, understanding stream dynamics (by measuring water level and flow, and ultimately determining rating curves) and the implementation of automatic hydrometric stations in streams. All measurements were performed after rainfall events, when fecal contamination and streams flow are expected to be higher. To complement the monitoring program, currents along bathing waters were measured using acoustic profilers. Monitoring results were used as inputs to the numerical model Mohid, to explain trends, forecast bathing water hydrodynamics and quality.

METHODOLOGY

Study site

Over 30 km long, Estoril coast extends from Oeiras (near Tagus estuary mouth) to Cascais, without a declared boundary between estuarine and oceanic waters. Along the shore line, several beaches are intercalated with streams. Some of the catchment areas of these streams start at Sintra ridge of mountains (600 m high), which is a major local geological feature individualizing this region's drainage area (NEVES et al., 2002). The study area (Figure 1) comprised by this monitoring program is located between Algés (38°41'58.92''N 9°13'45.36''W) and Parede (38°41'14.56''N 9°21'20.99''W) and includes 5 bathing waters (Caxias, Santo Amaro, Torre, Carcavelos and Parede) and 8 streams (Algés, Junça, Jamor, Barcarena, Porto Salvo, Laje, Sassoeiros and Marianas). Although all study sites were monitored, this paper focuses on the results from Santo Amaro and Carcavelos bathing waters. These two beaches were selected because they are the biggest sandy beaches in the area, and the most searched by bathers and surfers, who frequent it all year round. Santo Amaro, on the Municipality of Oeiras, is located 15 kms west of Lisbon (capital city of Portugal), and limited on the west side by Laje stream. Carcavelos bathing water, on the Municipality of Cascais, is limited on the west by Marianas stream, and Sassoeiros stream outflows right in the middle of the beach. Usually, during summer season dams are placed by SANEST, SA near the end of Sassoeiros and Marianas streams,

stopping water from discharging in the beach and therefore assuring bathing water quality, but rainfall events and streams flow increase may cause dams to be passed over compromising bathing water quality

Sampling methodology

Sampling took place between 2007 and 2008 in 10 field campaigns performed after rainfall events. All monitoring work was performed during ebb-tide (when sea water level is lower than stream level), since at this time streams are expected to be discharging to coastal waters. Water samples were collected in streams (near the mouth but in places without salt water influence) and along shore (beaches). In Carcavelos, 3 sampling points were considered: Carcavelos West, Middle and East and in Santo Amaro 2: Santo Amaro West and East (Figure 1). Samples were kept cool and dark during transport to the analysing laboratory. FC and EC levels were determined by membrane filtration, following the standard methods reported in D.L. 236/98.

Stream dynamics

When possible, streams flow and water level were also determined. Water level was measured with a scale and flow measurements were performed using a StreamPro ADCP (from Sontek). Flow measurements require a regular section and a minimum water level, so discharge measurements were not always possible. Moreover, the final branches of Algés, Junça and Porto Salvo are piped and therefore, inaccessible, making it impossible to determine water level and flow. Nevertheless, flow and water level were determined in most campaigns performed in Jamor, Barcarena, Laje, Sassoeiros and Marianas. As a surplus value, two automatic hydrometric stations were installed in Marianas and Sassoeiros in order to improve stream water level monitoring. These stations register water level on an hourly basis (or more frequently, if necessary) and once a day send stored data to a computer workstation through GSM connection. Alarms were set to be sent when water level rises above predefined values. Thus, when water level rises above 0.3m in Marianas and 0.6m in Sassoeiros (round about the dams high), an alarm is immediately sent to the central workstation PC.

Coastal hydrodynamics

Coastal hydrodynamics was studied using an Acoustic Doppler Current Profiler (Sontek ADCP Workhorse Sentinel). Horizontal profiles using bottom tracking were performed along shore, and moored systems were mounted in all studied areas in order to study currents direction and intensity in the entire water column, considering layers of 0.5 m. ADCP data serve to better understand local hydrodynamics and to validate Mohid simulations.

Modelling

As mentioned, numerical simulations were performed using Mohid (www.mohid.com). Mohid is a fully non-linear, three-dimensional, baroclinic model developed by IST that is under continuous development (MIRANDA et al., 2000; MARTINS et al., 2001). Mohid has been used successfully in several numerical studies along the Tagus estuary in the last past years (see PORTELA, 1996; PINA, 2001; LEITÃO, 2003; FERNANDES, 2005; SARAIVA et al., 2007; MATEUS et al., 2008) as well as in other estuaries and water bodies (e.g. VAZ et al., 2007; MALHADAS 2008), and has proved its ability to simulate physical and biogeochemical processes in the water column. A complete description of the model can be found in MARTINS et al. (2001) but some of the main features are presented here. Two transport

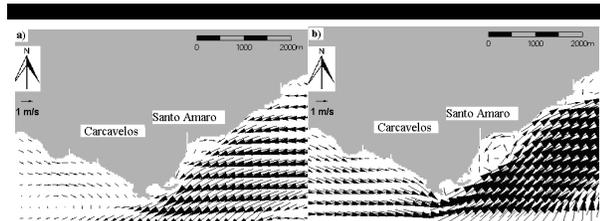


Figure 2. Results of velocity modulus, and direction simulated by Mohid for 21 April, during ebb tide a), and flood tide b).

models are coupled in Mohid, the Eulerian and Lagrangian formulations. Main advantage of the Eulerian approach is that the same equations and numerical methods are used both for the hydrodynamic model and for the transport of water constituents. However, with this approach, it is difficult to label water masses and relate their positions in any instant of time with their release points. That task is easily accomplished in Lagrangian models because particles can carry information about their origin (BRAUNSCHWEIG, 2003; GARCIA, et al., 2005; SARAIVA et al., 2007). As an example, it allows studying the dispersion of river plumes in coastal waters. Also important for this work, Mohid enables simulation results to be analyzed in limited areas (Monitor Boxes) which allows studying bathing waters separately. Output results for each box include total water volume and fecal contamination in the box, water volume and fecal contamination from each stream for each time step.

In order to study the impact of stream discharges on bathing waters, stream discharge simulations were performed using microbial concentrations and flow values measured during field work (except for Junça, Algés and Porto Salvo streams where flow was estimated from historical data). Two different simulation scenarios are presented in this paper: scenario 1-considering the contribution of ALL streams (typical scenario after a rainfall event) and; scenario 2- WITHOUT the contribution of Marianas and Sassoeiros (typical summer scenario, when dams prevent these streams from reaching the bathing waters).

RESULTS AND DISCUSSION

Study site hydrodynamics

Figure 2 shows hydrodynamic results (current velocity and direction) for Carcavelos and Santo Amaro simulated by Mohid for 21st April 2008. Figure 2a refers to an ebb-tide situation and figure 2b to a flood-tide situation. As can be observed, during the ebb-tide circulation occurs mainly from east to west but due to

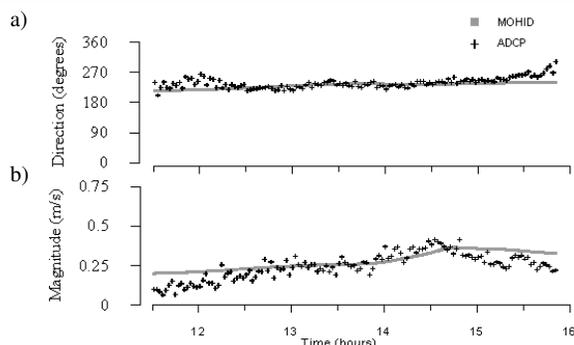


Figure 3. ADCP measurements and Mohid results, in Santo Amaro bathing water: a) direction; b) magnitude.

Table 1. Monitoring results, from 21st April campaign, geometric mean, minimum and maximum results from 2007/2008 monitoring plan, in Carcavelos and Santo Amaro bathing waters and streams.

	Sampling point	Indicator ufc/100ml	2007/2008 Monitoring Plan			
			April 21st	GM	Min	Max
Bathing Waters	Santo Amaro East	FC	3.5E+2	6.5E+2	8.0E+1	2.9E+3
	Santo Amaro West	FC	3.9E+2	1.1E+3	3.5E+2	2.9E+3
	Carcavelos East	FC	3.6E+1	1.2E+2	5.0E+0	5.5E+3
	Carcavelos Middle	FC	3.8E+2	2.7E+2	6.0E+0	6.1E+3
	Carcavelos West	FC	1.0E+2	9.7E+2	2.1E+1	4.2E+5
Streams	Alges	FC	4.5E+6	1.8E+6	5.5E+4	8.7E+6
	Junça	FC	9.6E+5	1.1E+6	4.0E+4	7.0E+6
	Jamor	FC	2.7E+4	1.1E+5	4.5E+3	5.1E+6
	Barcarena	FC	3.2E+4	3.8E+4	1.2E+4	7.0E+4
	Porto Salvo	FC	7.5E+6	3.3E+6	3.5E+5	1.4E+7
	Laje	FC	2.7E+4	7.7E+6	1.7E+4	1.3E+7
	Sassoeiros	FC	9.0E+4	1.7E+5	1.9E+4	6.1E+6
	Marianas	FC	5.5E+5	6.3E+5	9.0E+4	1.1E+7

coast design and velocity differences, a recirculation pattern is formed in Carcavelos and Santo Amaro. During flood-tide, currents are mainly from west to east along the shoreline in Carcavelos, with higher velocities in Santo Amaro forming a vortex. A detailed description of Tagus estuary circulation patterns can be found in FERNANDES, (2005). Mohid results were compared with ADCP field measurements performed in 17th March 2008 (Figure 3). As can be seen in figure 3 a), the current measured with ADCP has the same direction of that estimated by the model. Magnitude values (Figure 3 b) also show that model results follow the same tendency as the ADCP measurements.

Microbial water quality

Legislation in force (D.L. n.º 236/98) reports maximum acceptable values and maximum recommendable values of FC for bathing waters of 2000 ufc/100ml and 100 ufc/100ml, respectively. Table 1 shows the monitoring results for Carcavelos and Santo Amaro. Maximum (Max), minimum (Min) and geometric mean (GM) FC values are presented together with the results from 21 April 2008 campaign. Observation of maximum values shows that all sampling points present, at least once, "bad" water quality result. Mean values show that these bathing waters have "recommendable" quality ($100 < FC \leq 2000$ ufc/100ml), however Carcavelos East "good" quality ($FC < 100$ ufc/100ml).

As for streams, obtained values were compared with the classification of INAG (National Water Institute) for water courses of multiple uses. This classification considers waters with FC concentrations above 20000 ucf/100ml to be "heavily polluted". Both maximum and mean FC values measured during this monitoring plan are above this value. These results are attributed to illegal sewage discharges that can be found along the water courses, and also to discharges that are not visible, on the piped streams, especially near the sea (SANEST, 2008).

Stream dynamics

Figure 4 shows stage-discharge relations calculated from assembled flow and water level data, for Marianas, Laje and Sassoeiros streams. Good correlations were obtained for these streams (0.9387, 0.7882 and 0.7149, respectively) which allowed determining rating curves for Marianas ($y = 2.0466 x^{2.2191}$), Sassoeiros ($y = 2.6135 x^{3.0092}$) and Laje ($y = 172.08 x^{3.0092}$), being y the discharge and x the water level. Results so far do not make possible to calculate this relation for the other streams, consequently future work will include successive steamflow measurements at different stream stages to determine (and maintain, since rating curves are not static and sometimes must be recalculated) stage-flow relations. The determination of rating

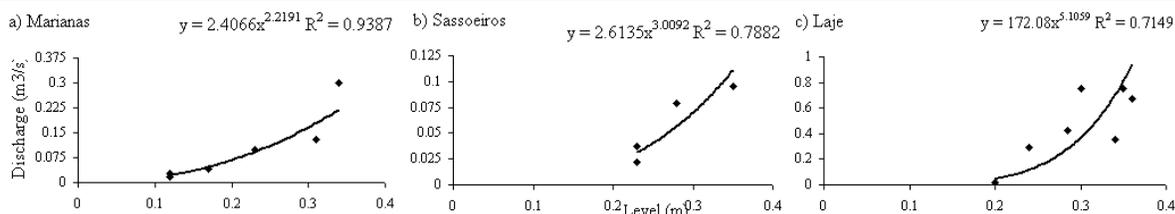


Figure 4. Stage-discharge relations, obtained through the monitoring results, of discharge and stage in Laje, Sasseoios and Marianas

curves is crucial since the final aim of this project is to be able to provide bathing water quality information from the automatic monitoring of stream stages. In order to do so, the relation between fecal contamination and flow must be determined, along with the relation between rainfall and fecal and water level, since the fecal indicator organism concentrations are increased by high discharge after rainfall (WIER et al., 1994).

Modelling

Figure 5 represents fecal contamination results from field campaign (with circles), tide level, and Mohid simulation results for 21st April 2008. Mohid simulation results include: mean fecal contamination (ufc/100ml), and individual stream contribution to fecal contamination (%) in each monitor box. Figures 5a (Carcavelos) and 5b (Santo Amaro) refer to simulation scenario 1 (that considers all streams discharge) and Figures 5c (Carcavelos) and 5d (Santo Amaro) refer to scenario 2 (without Marianas and Sasseoios streams contribution).

As can be seen in figures 5a and 5b, in both bathing waters, fecal contamination decreases along the day, just increasing after 6 pm, which can be explained by the solar radiation effect that increases bacteria decay (CANTERAS et al., 1995). Also, it can be observed that field measurements (circles) are in accordance with model simulated results (grey squares).

Model results represent mean fecal contamination in each monitor box. This average value is the ratio between FC and water mass in the monitor box which means the model considers a homogeneous contamination in the entire water column. Despite this limitation, the model can accurately simulate streams plume dispersion.

Individual stream contribution (%) was calculated dividing each stream fecal contamination by total stream contamination (sum of all 8 streams). To simplify the graph, only Sasseoios, Marianas and Laje streams were represented. In Carcavelos monitor box (figure 5a), Sasseoios stream seems to represent the highest contribution to fecal contamination, followed by Marianas stream. Laje stream discharge apparently does not affect this bathing water, contrarily to Santo Amaro (figure 5b) where it represents the greater contribution to fecal contamination. Nonetheless, during flood-tide Sasseoios and Marianas streams can also influence significantly bathing water quality in Santo Amaro.

In fact, hydrodynamics play a major role in the dispersion of streams plumes and consequently on bathing water quality in both study areas. On the beginning of ebb-tide streams from the east (Junça, Algés, Jamor and Barcarena, not represented in the graph) are the main features affecting water quality but while tide is ebbing, these contributions decrease and Laje stream contribution increases. This can be explained by the local recirculation that occurs during the ebb tide (Figure 2a) which can difficult the entry of new water and promote recirculation of Laje plume on that location. As the tide changes, streams contribution to water quality will also change, and on the beginning of the flood-tide the discharges from west (Marianas and Sasseoios) are the main features affecting water quality.

A second scenario was simulated for the same day removing Marianas and Sasseoios discharges. This is a typical summer (no rain) situation when dams can prevent these streams from discharging to nearby coastal waters. Same conditions as first scenario were used, except for rainfall and therefore, Marianas and

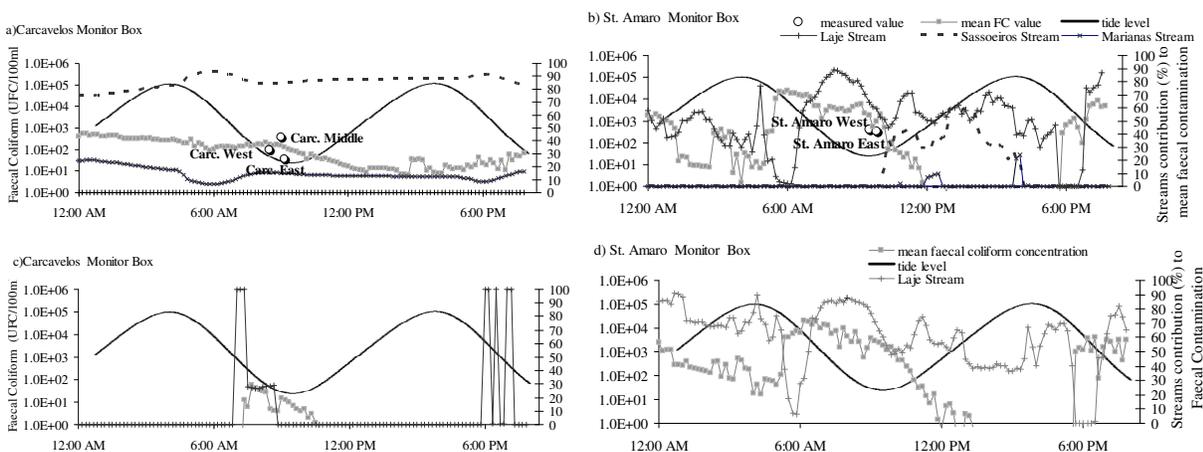


Figure 5- Fecal contamination results from field campaign, and MOHID simulations for April 21st, in Carcavelos (5a) and Santo Amaro (5b); MOHID results for a no rain scenario in Carcavelos (5c) and Santo Amaro (5d). Grey squares represents mean fecal contamination values (FC ufc/100ml) simulated by Mohid; Dashed lines represents Marianas, Sasseoios and Laje Streams contributions to the fecal mean contamination, in percentage; monitoring results are represented with circles; The curvilinear black line represent the tide level.

Sassoeiros contribution. Figures 5c) and 5d) show the model outcome of this simulation. Results represented in figure 5c show clearly lower FC values in Carcavelos monitor box (~100ufc/100ml). Some fecal contamination occurs without the contribution of Laje stream, showing that other streams from east can also reach Carcavelos bathing water, although to a smaller extend. In Santo Amaro (figure 5d), without contributions from Marianas and Sassoeiros, Laje stream discharge represents the highest contribution to bathing water quality, representing nearly 100% of streams contribution during ebb-tide. However, other streams from east can achieve this bathing water, which explains high microbiological values when Laje contribution is low.

CONCLUSIONS

In compliance with the New Bathing Water Directive, the monitoring methodology here presented allows understanding and quantifying streams contribution to bathing water quality and prediction of short-term pollution events. Similar monitoring plan can be applied to other case studies, in the scope of the application of Directive 2006/07/CE.

Bathing water fecal contamination conducts to a recommendable water quality ($100 < FC \leq 2000$ ufc/100ml) considering D.L.236/98 limits. Data obtained in streams, points to a heavily polluted water classification considering INAG limits. Although scarce, water level and flow results allowed determining valid level-discharge ratios for Marianas, Sassoeiros and Laje streams. However, this work should continue in order to validate these relations and to determine a contamination/discharge relation for these streams.

Presently, water level is measured by automatic hydrometric stations in Sassoeiros and Marianas streams, allowing flow estimation. Overflow alerts are also in function, opening the possibility for predicting dam's risk of being passed over and thus creating the basis to have an operational alert system for Carcavelos and Santo Amaro bathing waters, responding to the New Bathing Water Directive demands. Future work includes expansion of this methodology to other streams.

This study also shows that fecal contamination in bathing waters and local hydrodynamic can be simulated using Mohid and that the model can accurately simulate stream plumes dispersion. Monitor boxes approach allows studying bathing waters individually. However, improvements to the model should be considered, namely performing simulations using other parameters (*e. coli* and Enterococci), increasing monitor boxes number and reducing monitor boxes volume. Also, a basin model considering variables like rainfall, infiltration and terrain slope should be used in order to better study rainfall effect in stream dynamics, and consequently bathing water contamination.

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