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FECAL CONTAMINATION MODELING IN COASTAL WATERS USING A WEB SERVICE APPROACH

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Abstract

In the framework of the Lenvis project, a web service infrastructure able to provide professional users with field data and model results in real time was developed. One of the web services developed (web service model) executes a particle tracking model to simulate the dispersion of sewage discharges. This web service is comprised of a web client with multiple features. The client allows users to explore hydrodynamic forecast results in a GIS environment and define sewer discharges. The web client using the web service model simulates (1 day simulation takes less than 5 minutes to run) the impact over the water quality. The tool was tested for the Estoril coastal area (Lisbon – Portugal), specifically for the Carcavelos, Torre and Oeiras beaches.

Key words: bathing water, fecal, modeling, particle tracking, web services

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1. Introduction

More and more management (e.g. harbors, energy production) or emergency response (e.g. oil spills, sewer discharges) activities depend on numerical model air and water forecasts. Afterward, proper implementation and validation models can be run on a routine basis (e.g. weather forecast models usually run every 6 hours) or sporadically, on demand, for studying specific management scenarios or in emergency situations (e.g. discharges of contaminated water in coastal areas). In the case of emergency scenarios, the available time for collecting data and processing results is short. Additionally, users need a high degree of freedom to simulate several scenarios on demand and efficiently.

Running models on demand is a hard task requiring the compilation of many data sources, and consequently is vulnerable to human mistakes (Jung et al., 2010). The effort demanded and vulnerability to mistakes requires automatic procedures, both for processing input data and model outputs and, in some cases, even for triggering response actions. Software shells must keep human intervention in repetitive tasks to a minimum (Jung et al., 2011). These shells must collect all the input data necessary for specifying boundary and initial conditions, convert them to formats understood by the model, run the model, compare the model's results with field data and publish the results in a format suitable to the end user. The use of these shells is particularly important when the model uses results from other models for specifying boundary or initial conditions due to specific formats and the large amount of data involved.

To tackle the complexity of the activities controlled by each shell, a service approach can be used. Simple shells with very well-defined goals can communicate between themselves by services (or files). A shell always collects some data, processes it and generates an output file that will be assessed by another shell to generate another output file until the completion of all the tasks necessary for obtaining the final result.

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The access to input data and dissemination of the output data are traditionally done via ftp in an ad hoc manner. An alternative is to develop shells with Service Oriented Architecture (SOA) connecters able to communicate with web services (standard "doors" to data). This type of communication ("web services") has the advantage of interoperable machine-to-machine interaction using the XML, SOAP, WSDL and UDDI open standards over an Internet protocol backbone. Typically, the information conveyed uses SOAP protocol encoded with XML tags, while WSDL is used to describe the services available and UDDI is used to list the services' availability. Web services are able to build a distributed system, where the network operations are hidden from client programs.

Open DAP (geophysical grid data), (Gallagher et al., 2005), WMS (maps), WFS (e.g. GML, KML) are well- known web services developed using the Representational State Transfer (REST) architecture, where resources are represented using URI, and HTTP is used to return the current representation of that resource. In the framework of the EU project, Lenvis web services were designed and developed, combining the Simple Object Access Protocol (SOAP) architecture in .net and Java, with REST capabilities for easy consumption by simple clients (ex: JavaScript). This paper describes this development, with a special focus in the web service developed to run a fecal dispersion model on demand via a web client.

One of the main bathing water directive (BWD) principles is the evolution from monitoring to an integral management of water quality (Jung et al., 2011). The previous BWD required very limited action from member states, mostly comprising periodic field surveys. In coherence with the Water Framework Directive (WFD), the BWD promotes the management of the water cycle as a whole, and enforces responses in case of noncompliance with directive standards. These responses may be infrastructural, like the building of water detention tanks, or contingent, like beach closures or warning signs for bathers (Suñer et al., 2008). Another important aspect of the BWD is communication with the public. According to the BWD, the public must be kept informed of water quality. Moreover, when bathing waters are subjected to short-duration pollution events (namely CSO or Combined Sewer Overflows), alert systems with short response times must be put in place (Suñer et al., 2008).

In recent years, sophisticated systems focused on forecasting short-duration pollution events have been developed. Examples of these systems are, for the case of fecal contamination, the COWAMA (Suñer et al., 2008) implemented in a first phase in Barcelona and Saint Jean de Luz (French Basque country), AQUASAFE implemented in Lisbon (Stedman, 2011), for the case of algae blooms, the DSSQUAL implemented in Yong Dam (Jung et al., 2011) in South Korea. These systems control a complex data flow of numerical model results and automatic sensors networks to support decision making for the management of sewer systems, with special focus on the receiving water bodies. These systems focus on the operational needs of water utilities with access to highly-skilled human recourses. Relative to these systems, the web tool presented in this paper can be seen as a lighter version focused on professionals who are not experts in numerical modeling, and needing to understand the possible causes of bad water quality samples. The tool is also suitable in evaluating the impact of sewer emergency discharges.

2. Material and methods

In the framework of the Lenvis Project, a web interface to explore high-resolution hydrodynamic model forecasts in a Geographical Information System (GIS) environment was developed. Additionally, this interface allows a fecal dispersion model to be run to support decision makers in evaluating the impact of a discharge made at a particular point and time frame (e.g. emergency discharges). The concept was tested for the Estoril coastal area, a well-known bathing area located west of Lisbon.

2.2. Web client

The web client allows users to explore hydrodynamic results stored in NetCDF/HDF5 files in a GIS-like environment. This tool only requires the user to have a modern web browser. A WMS (Web Map Service) protocol compatible engine generates geo-referenced images (Fig. 1). The development of the web client was based on the JavaScript libraries jQuery (http://jquery.com/), GeoExt (http://geoext.org/), Ext (http://www.sencha.com/ products/extjs/) and OpenLayers (http://openlayers.org/).

The entry point for the user can be the Lenvis portal (http://portal.lenvis.eu/) or the link http://lenvis.hidromod.com/clients/LenvisModelServiceClient2. Both entry points are linked to the web client interface (Fig. 1). This interface communicates with three web services: Lenvis WMS, GoogleMaps WMS and the Lenvis model web service (Fig. 1). The GoogleMaps WMS is used to provide background images for the GIS view. The Lenvis WMS is used as a mediator between the NetCDF/HDF5 files or OpenDAP server and the JavaScript wms client Open Layers. This web service creates images representing model results (Fig. 1). This tool is an adaptation of the SharpMap GIS engine. SharpMap is an open source mapping library for use in web and desktop applications (http://sharpmap.codeplex.com).

To improve efficiency, the newly generated images are stored in cache (Fig. 1). This way, if the same image is requested twice, it is generated only once. The Lenvis model web service (Fig. 1) is responsible for managing the fecal contamination discharge modeling. After the model is run, the GIS engine automatically generates the images published via the Lenvis WMS (Fig. 1). Layers presented in the JavaScript interface are configured via a XML file.

Users can explore, using GIS standard features, the high-resolution hydrodynamic (spatial step of 30 m) numerical forecasts generated on a daily basis by the Technical Institute of Lisbon (IST) (Viegas et al., 2009). Additionally, this interface allows these hydrodynamic forecasts to be used to simulate the dispersion of sewer discharges on demand.

The user can define the following discharge parameters: location, flow intensity, fecal indicator concentration, time frame and decay rate (T90 in hours). The fecal dispersion model results are the concentration of the fecal indicator for each instant. Moreover, the user has access for each run to the maximum and percentile 95 fields of the fecal indicator corresponding to time frame simulated.

2.3. Model web service

The model web service was developed to run simulations by end users of fecal coliform contaminations. Running simulation models can be complex; the user must define input data and process results. To simplify these tasks, the user-changeable parameters were reduced, focusing the model on the problem (in this case fecal dispersion); in addition, the insertion and validation of input data to the model were automated. The interaction with the end user was done through a web interface where the user could fill in several parameters characterizing the discharge: location, time frame, flow, T90 and fecal indicator concentration. The model is invoked from JavaScript via REST to the model web service.

To deal with the problem of processing the results, the numeric matrix results were converted to graphical layers, and the model web service returns the identification for the newly-created layers. In turn, these layers can be sent to the WMS server and be viewed through JavaScript GIS.

2.4. Study site

The Estoril coastline has a complex morphology characterized by numerous piers, bays, and rocky and sandy beaches. Water circulation patterns are largely determined by the coast's orientation and irregular pattern, where sandy bays are interrupted by rocky geological structures. The Torre beach (Fig. 2) is located near the mouth of Tagus River in an area where flow velocities usually reach higher values (~1.5 m/s).

The hydrodynamic regime is very complex, with meandering tidal currents and eddies in the near coastal section (Viegas et al., 2009). Off the coast of Carcavelos beach (west of Torre) starts an eddy formation in mid ebb that grows to the size of almost all of the Estoril coast at low tide. To the east of Torre (upstream), at Oeiras beach, several eddies form both during ebb and flood. A schematic representation with the general circulation pattern of the area studied is shown in Fig. 2. At the west end of Oeiras beach is a stream which is known to be a sporadic source of fecal contamination.

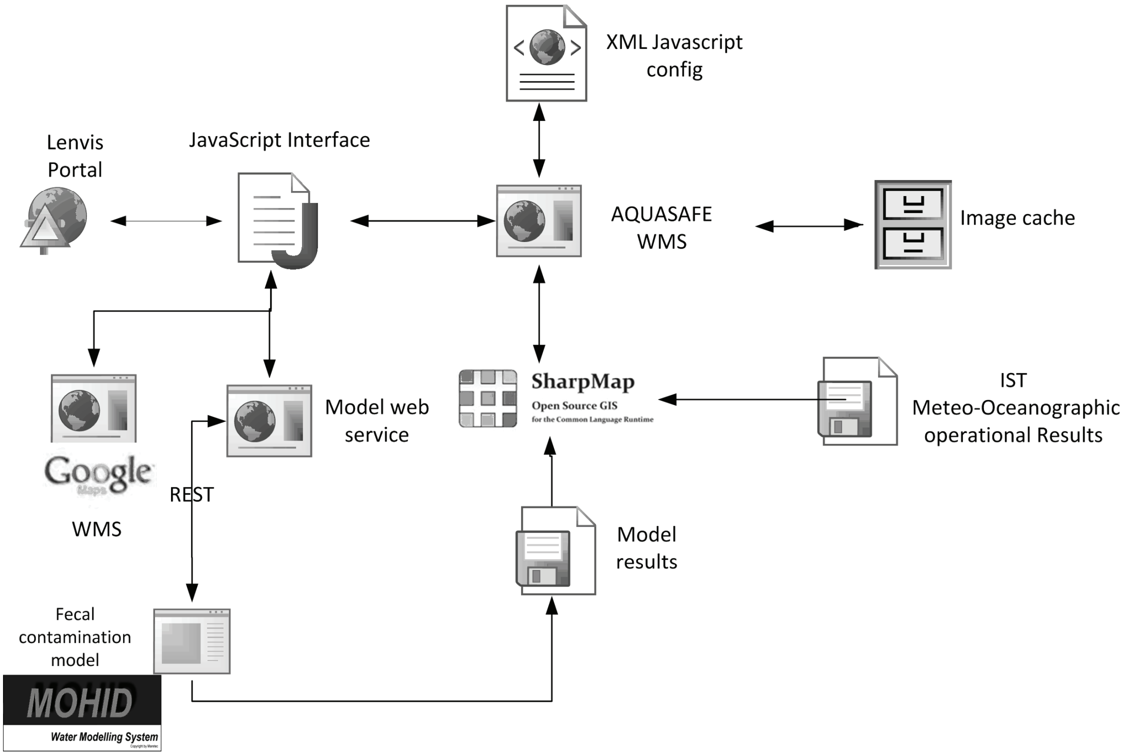

Fig. 1. Web client main components and data flow

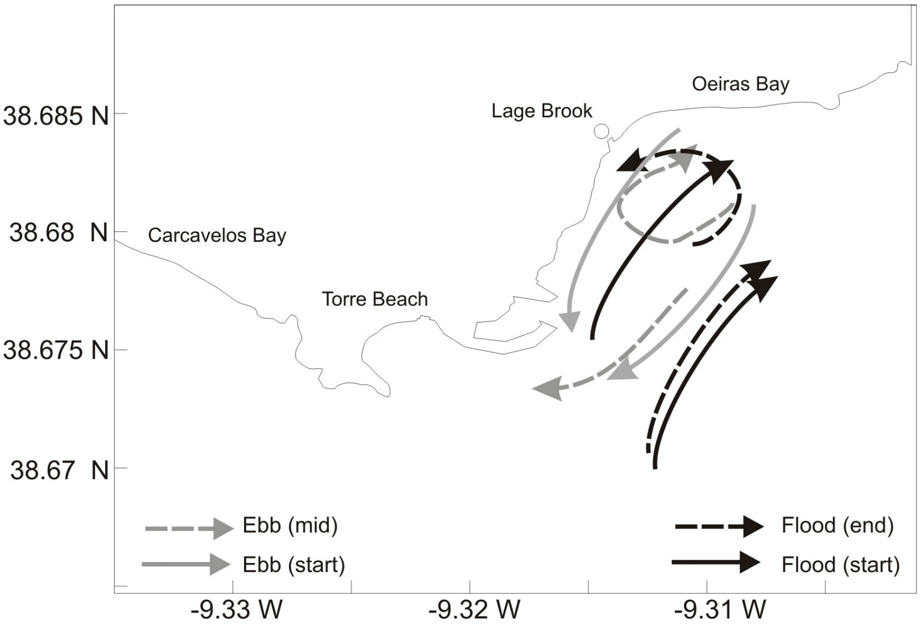

Fig. 2. Study of the site main features and schematic representation of the main hydrodynamic patterns

The dynamic dispersion of its plume is highly controlled by these eddies' characteristics. Torre beach is a small bay between two man-made structures: a marina pier and the surrounding walls of a fort. The near-coast-water regime in this small area consists, basically, of a continuous recirculation, with significant tidal differences.

These are caused 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 from reaching the beach, thereby considerably increasing the water's residence time there.

2.5. Meteo-oceanographic forecast system

Hydrodynamic forecasts are computed using the MOHID model. This model has been used successfully in several numerical studies along the Tagus estuary in the past few years (Mateus and Neves, 2008; Saraiva et al., 2007). A complete description of the model can be found in Martins et al. (2001). Model configuration consists of a downscaling technique (Leitão et al., 2005) with a set of three nesting levels. The first level is provided by PCOMS, an implementation of the MOHID hydrodynamic model covering the entire Portuguese coast run daily by IST in forecast mode (Riflet et al., 2008). The second model domain covers the Tagus Estuary and adjacent coastal waters. The grid has 162 x 162 cells with of 300 meters near Tagus mouth. This level is a 3D model (baroclinic), with 11 z-level layers, that provides hydrodynamic fields, and density gradients (temperature and salinity) for the next level. The atmospheric forcing is based on a forecasting system implemented by IST, using the WRF (Weather Research and Forecasting Model) numerical model, covering the area of Lisbon, with a horizontal resolution of 3 km.

This forecasting system is executed every 6 hours, and generates outputs for a 3-day period with an hourly frequency. The main freshwater discharge in the estuary is the Tagus River. The river flow is imposed using data measured by Portuguese National Water Institute.

The third level is implemented between Carcavelos and Belém – [-9.356o W to -9.2185oW]; [38.669oN to 38.705oN] – and is a very high resolution 3D baroclinic model, with a constant spatial step of 30 m (460 x 120 cells), and a time step of 6 seconds. The vertical discretization has two domains with an interface at 9 m depth. The surface domain has 7 sigma layers, and the bottom one has 5 z-level layers. The atmospheric forcing is the same as level 2. Daily automatic data from hydrometric stations (e.g. Lage stream), and average seasonal freshwater small stream discharges based on climatologic values (obtained from historic measurements in previous years) are imposed along the land boundary.

In order to present reliable information, the web client needs to read the forecast data produced. The meteo-oceanographic forecast data is provided by IST via ftp. To get this data, a specific tool called the "Download Manager" connects every day, once a day, to the ftp server and searches for updated data. If the "Download Manager" finds new data, it downloads and stores it in a location where the web client can access it.

After the "Download Manager" execution, a report is created and emailed to pre-selected users, letting them know if the files have been downloaded or if there was any problem. The time of day and the number of times the "Download Manger" runs a work cycle can be customized at any time. The "Download Manager" is maintained in a windows service.

2.6. Fecal dispersion model

A lagrangian (particle tracking) model was used to simulate the dispersion of wastewater in the receiving water body. This model is a subset of the MOHID modeling system. The particle tracking MOHID model has been used to study many subjects of interest; some examples are: pollutants' dispersion (e.g. Gomez-Gesteira et al., 1999), oil spills (Carracedo et al., 2006), water time residence (Malhadas et al., 2010), primary production in the open ocean (Miranda et al., 1999) and larvae transport (Santos et al., 2005).

In this approach, the wastewater plume is discretized using a cloud of particles. Each particle is characterized by a position in space (x,y,z) and time (t), a volume and a concentration of a fecal indicator. The model allows the definition of a discharge flow. Particles are emitted with a frequency equal to the flow intensity divided by the particle volume.

Particle velocity has two components: one resulting from the linear interpolation in space (bilinear horizontally and linear vertically) and in time of the hydrodynamic forecasts described above (level 3 IST forecasts). The second component aims to simulate the turbulence effect over the particles' trajectory. This effect is simulated using a random walk approach. The methodology followed is similar to the one proposed by Allen, (1982). Random displacement is calculated using the mixing length and the standard deviation of the turbulent velocity component, as given by the turbulence closure of the hydrodynamic model. The particles maintain this velocity during the time needed to perform the random movement, which is dependent on the local turbulent mixing length (Allen, 1982). This method is not consistent from the mass balance point of view when the particle tracking model is coupled with a hydrodynamic model having a grid with variable thickness layers. This is the case of the hydrodynamic solution provided by IST (hybrid discretization – sigma and z-level). To overcome this limitation, a correction is used based on the work of Spagnol et al., (2002).

In the first step, the random velocity intensity for each particle is computed (Eq. 1).

$$\left|u_i'\right| = \sqrt{3}u_{i_{sd}}' g_{rand} \qquad (1)$$

where |ui'| is the particle random absolute value and grand a function that returns a random number between 0 and 1 for direction i (three directions – two horizontal – x, y – and one vertical – z).

The second step is to compute the velocity direction (Eqs. 2-3).

$$u_i' = \begin{cases} -\left|u_i'\right|, g_{rand} > \Delta w_i \\ \\ +\left|u_i'\right|, g_{rand} < \Delta w_i \end{cases} \qquad (2)$$

and

$$\Delta w_i = \frac{w_{i_2}}{w_{i_2} + w_{i_1}} \qquad (3)$$

where w_{i1} and w_{i2} are the thickness of the cells adjacent to the particles' position (1 – left cell, 2 – right cell along the *i* direction). This means that if the left cell has the same thickness as the right one, the probability of the random jump going both ways is 50%. If the thickness of the right cell is 3 times the left one, the probability of going right is 75%. In this way, the random transport becomes conservative from the mass balance point of view.

In this application, along with the spatial position and volume, each particle is characterized by the fecal indicator concentration. Total coliforms (TC), fecal coliforms (FC) and *Escherichia coli* (EC) are common fecal indicators used in modeling studies. Total and fecal coliform groups have similar decay rates (Marais, 1974). Fecal mortality is affected by environmental factors such as radiation, temperature and salinity. Mortality rates are a function of these environmental factors, and can be derived from in situ and the laboratory (Canteras et al., 1995; Jung et al., 2010). To maintain simplicity and increase flexibility, the web interface only allows the user to define a constant decay rate as a T90 (time the fecal indicator concentration takes to decrease in order of magnitude due to mortality) in hours. Typical daytime values of T90 are on the order of 3 h, and for nighttime on the order of 12 h in the case of EC (Canteras et al., 1995).

3. Results and discussion

The main goal of the web client is to allow end users to test hypotheses for the possible origins of bad water quality without being experts in numerical modeling. This tool allows end users to efficiently determine the impact of sewage discharges on bathing water quality. The system was designed so that each fecal dispersion numerical model run takes less than 5 minutes. A typical end user can be a beach manager who wants to understand the possible causes of persistent bad water quality samples for specific conditions. This tool can also be used to demonstrate to stakeholders the impact of sewage discharges on bathing water quality. It is also an efficient method to evaluate the impact of an emergency discharge.

In this chapter, will be describe the tool's features. In a second step, the model results will be explored for an illustrative scenario (a hypothetically non-controlled discharge in the Lage stream).

3.1. Web interface features

The graphical user interface can be divided in 4 areas:

- toolbar located on the top (view 1 - Fig. 3). In the left part of the toolbar, the user has access to normal

GIS features (pan, zoom, measure distance and areas, info). Additionally, the user has a feature to define a spill (or discharge). In the right side of the toolbar, the user has a time slide bar. The user can choose the time of interest;

- the list of layers are divided in three sub-groups: layers – hydrodynamic model forecasts fields, runs – particle tracking model results generated by the user, maps – to provide context background. This component is the left view of the GUI (view 2- Fig. 3);
- center view where mapping images (WMS compliant) are displayed (view 3 - Fig. 3);
- right view displays detailed info for each selected layer (view 4 - Fig. 3). The detailed info also has a specific time slide bar for the selected layer, image opacity or run status (ongoing, ended), discharge characteristics, run start and end time).

To simulate the impact of a sewage discharge, the user should:

- select the starting time of the simulation in the time slide bar;
- click in the icon “Create Point Spill”;
- with the mouse, choose the discharge location in the GIS view. Double click over the push pin, and a popup window will appear;
- define the discharge name, simulation period and discharge characteristics (flow, concentration and T90) and click on the button “Create”;
- select in the “layers – view 2” in the “Runs” sub-group the folder with the name of the discharge;
- click on the “Layer info – view 4” the button “Create Run”. A popup window appears automatically;
- click on the “Start Run” button of the popup window ;
- after the run as started the “info layer – view 4” will display the run status. After less than 5 minutes in the “info layer – view 4”, the information of the run end will be displayed.
- after the run ends, 4 layers will be activated in the “layers – view 2” in the “Runs” sub-group. The layers are as follows: particle position, concentration field of the fecal indicator for each instant (variable in time), field with the 95 percentile of the fecal indicator concentration and field with the maximum concentrations.

3.2. Model results – illustrative scenario

To illustrate the tool’s capabilities, the impact on the bathing water quality of a hypothetic uncontrolled discharge in the Lage stream was simulated. Beaches like Oeiras, where the Lage stream discharges, are challenging from the management point of view. Streams are a potential source of fecal contamination events. These events are usually associated with intense precipitation or illegal sewage discharges. In the first case, the run-off process transports fecal material from the catchment to the stream and combined sewer over (CSO) flows might happen along the stream. During the bathing season, the average Lage stream flow is quite low, and under average conditions, it presents a residual flow, because the water utility responsible for the sewage treatment in this area (SANEST) is able to divert part of the stream flow to the waste water treatment plant (WWTP) located in Cascais (20 km west of the beach). This WWTP discharges the effluent at 40 m depth 2 km off-shore. This methodology minimizes the problem associated with uncontrolled sewage discharges under low flow conditions. However, under strong precipitation events, the Lage stream can be an important source of fecal contamination for the Oeiras beach and eventually nearby beaches like Torre.

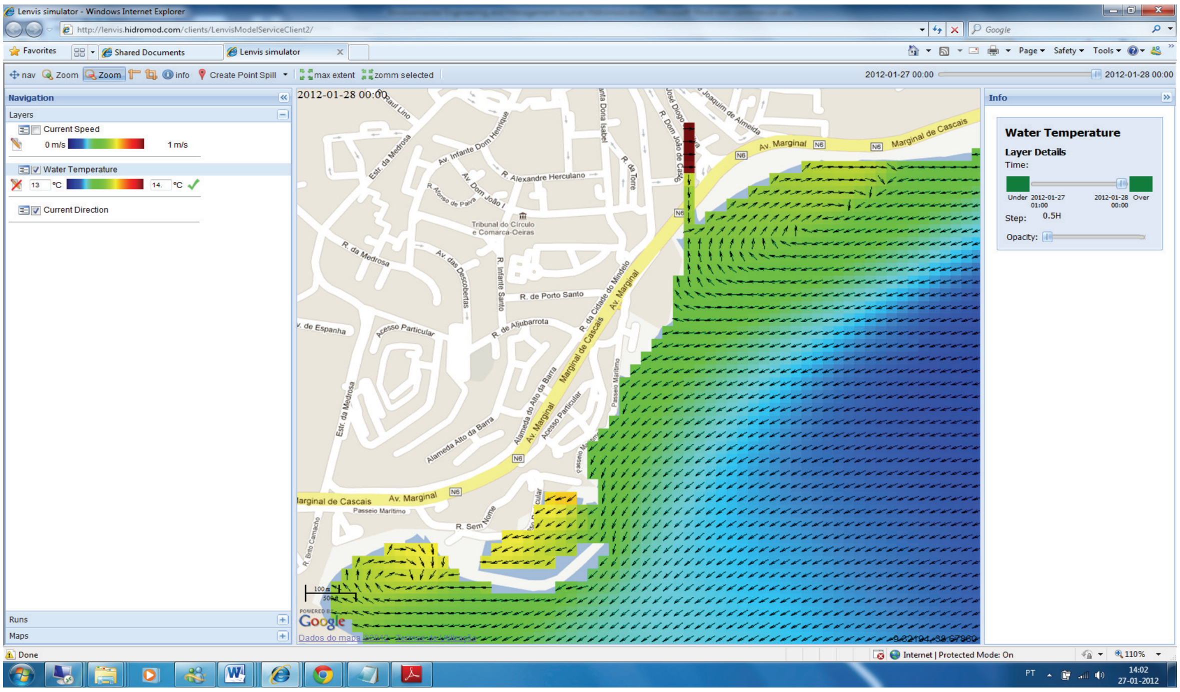

Fig. 3. The different components of the graphical user interface

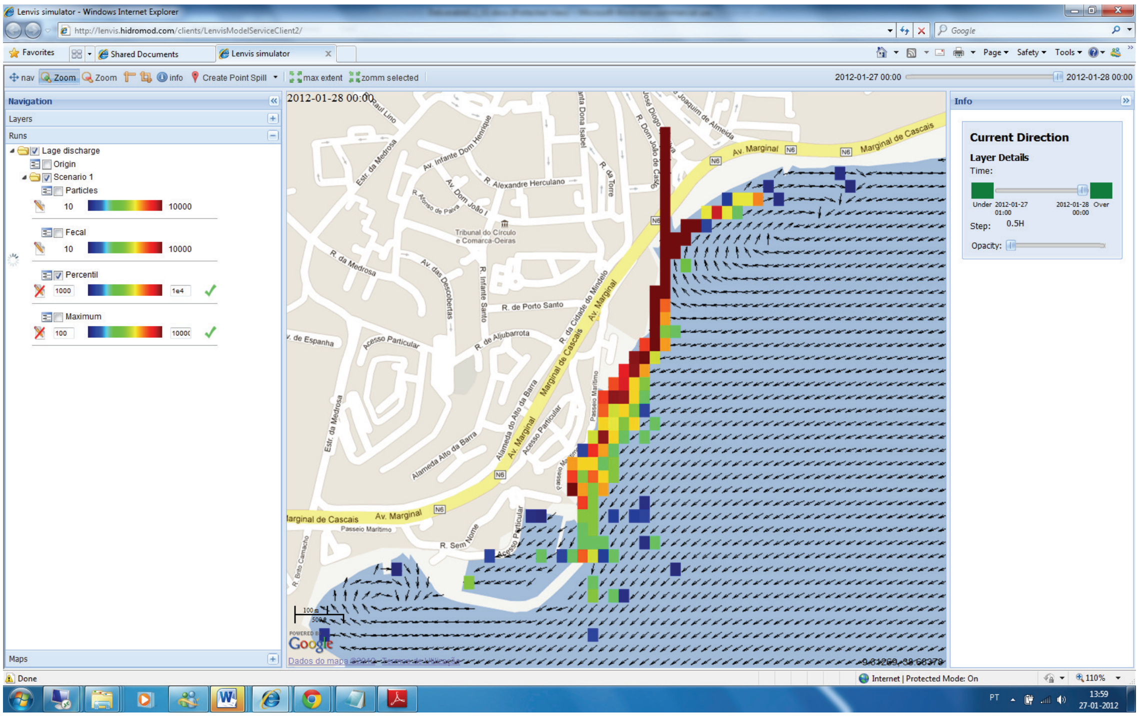

Fig. 4. Percentile 95 of a fecal indicator concentration. The source of the fecal indicator is a discharge in Lage stream with a flow of 100 l/s, a T90 of 3 hours and a concentration of 106 [MPN/100 mL]. Blue represents values of a percentile 95 of 103 [MPN/100 mL] and red represents values above 104 [MPN/100 mL]

The Oeiras, Torre and Carcavelos beaches are under the influence of the Tagus estuary ebb jet, with maximum intensity velocities on the order of 1.5 m/s. The interaction of the jet with the bay structure of these beaches generates eddies that can increase the residence time of fecal contaminations. This is particularly the case of fecal material discharge directly on the beach (e.g. Lage stream). This problem has been characterized in detail by Neves et al., (2010).

To illustrate this problem using the web client, a sewage discharge was defined in the Lage stream with a flow of 100 l/s, a T90 of 3 hours and a fecal indicator concentration of 106 [MPN/100 mL]. The discharge started under high tide conditions. The model was run for 1 day. The analysis of the percentile 95 of the fecal indicator concentration is an efficient way of evaluating the areas more affected by the Lage stream's fecal plume (Figure 4). During the flood period, the fecal material tended to be trapped within the Lage stream. The fecal material is efficiently released to the coastal area during the ebb period. Some of the fecal material follows the Tagus estuary ebb jet's general direction (southwestward). This material can reach the Oeiras marina and even the Torre beach. However, due to the counter-clockwise eddy formed in Oeiras beach during the ebb period (Fig. 2. and Fig. 4.), some fecal material is transported eastward along the beach (Fig. 4).

5. Conclusions

A web client able to explore hydrodynamic forecast results at the beach scale was presented. This tool allows the user to explore model results in a GIS environment. The end user can simulate the dispersion of emergency sewage discharges using a particle tracking model over a high resolution hydrodynamic daily forecast provided by IST to the Estoril Coast. Users can define sewage discharge characteristics: location, time frame, flow, fecal indicator concentration and T90. The results are fecal indicator concentrations in time, maximum and percentile 95.

The tool was designed with the main goal of allowing professional users with no experience in numerical modelling to simulate the impact of a sewage emergency discharge over a bathing water area in less than 5 minutes. The implementation done to the Estoril Coast can easily be replicated for any other water bathing area, if high resolution hydrodynamic forecasts (like the ones provided by IST) are available.

Hydrodynamic forecast data providers are growing in the framework of international initiatives (e.g. GOOS - http://www.ioc-goos.org/ or MyOcean - http://www.myocean.eu.org/). Right now, the bottleneck of these initiatives is the link with end users. The tool presented here is a contribution to bridge the gap between ocean observation systems and end users. In this case, end users are professionals interested in sewage systems and bathing water area management.

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