Operational modelling for hydrodynamics and water quality studies at a river basin scale

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ABSTRACT
In the last years a great effort has been done to make modelling tools available for water resources management at a river basin scale. The European Water Framework Directive encourages the use of these kind of tools. In order to make models usable by all the stakeholders in water resources management process at river basins, these tools must be simple, user-friendly and robust.
Several solutions are being implemented throughout European countries, resulting from the development and integration of different software packages using different integration technologies.
This paper presents a hydroinformatic environment solution particularly designed for the river Cávado basin (Portugal) in order to define, simulate and analyse different hydrodynamics and water quality management scenarios. The solution was designed to be operated in a web environment. Data-bases, implemented using MySQL server, are used to store the geometric features of the river network, hydraulic structures, monitoring stations data and point and non-point pollutant discharges into the river network. The one-dimensional hydrodynamics and water quality models were implemented using SOBEK software. Specific web-based model operation interfaces were developed in order to directly establish the boundary conditions, run the model and visualize model results.
This decision support tool constitutes a robust and efficient technological platform that includes a comprehensive database and detailed one-dimensional hydrodynamic and water quality models of the river basin network.

Keywords: Water Framework Directive, hydrodynamics, hydroinformatics, operational model, river Cávado Basin.

1 INTRODUCTION

Recently a considerable effort has been done for the development of efficient decision support tools for water resources management. The Water Framework Directive (WFD) clearly states that this kind of tools must be developed and used to support decision making, developing water quality diagnostics and to anticipate the impact of the measures that are going to be implemented in order to achieve a good ecological status until 2015 (European Commission, 2000).

The increase of computer capacities, and the need for integrated approaches on water resources management, demands the development of technological platforms that allow the use of different types of models in order to obtain simulations of the different processes involved in the hydrological cycle in an efficient way and, simultaneously, the integration of information that comes from different data sources.

Mathematical modelling is achieving a growing importance as an analysis method and as a forecasting tool of different hydrological cycle processes. This way, developed technological platforms must consider the inclusion of different types of models: hydrological models, hydrodynamic models and water quality models. These models use different kinds of software, selected after a careful assessment of all available options. On a development stage, different dimensionality hydrodynamic and water quality models must be considered: one-dimensional on a horizontal plan (1DH), two-dimensional on a horizontal plan (2DH) and three-dimensional (3D).

In order to facilitate the use of the modelling tools by all the people enrolled in the water management processes at river basins those tools should be simple, friendly and robust. Borowski and Hare (2007) state that water management responsible technicians show strong interest in the use of integrated modelling tools while performing their activities. They point out, however, that the lack of time for learning the proper use of complex systems and the costs of software and hardware, are obstacles that make it difficult to implement and to use these tools in the daily water management tasks.

We can find, under development and implementation, different technological solutions that result from the creation and the integration of distinct software packages using different integration technologies (De Kok et al, 2009).

In this work, the main features of a web based technological platform to support decision making in water management are presented. This platform has three main components: (i) an information system with the ability to present and analyse geographic data; (ii) a modelling system with the possibility of remotely operate hydrological, hydrodynamic and water quality models and also to display online simulations results by different users; and (iii) an analysis system composed by interfaces specifically dedicated to the analysis of water environments (rivers and reservoirs) under different environmental scenarios and considering different operational management measures.

2 TECHNOLOGICAL PLATFORM

This technological platform is mainly based on a database system and a set of hydrological, hydrodynamic and water quality models, operated using web interfaces. It comprises functionalities for query and analysis of the river network (information system), hydrodynamic and water quality models operation (modelling system), and results analysis (analysis system). Besides this, the platform provides the following additional services: user's management, document management and monitoring data store and display. The user's management service allows restricting or not the access to various content, as well as the permissions to run/execute or to view/consult/query the simulations results. The document management service allows the users to perform simple tasks, such as publication of papers and upload/download of work documents. The monitoring data functionalities provides a framework for gauge and water quality stations installed in the river basin, allowing its analysis, validation, and integration using a specifically designed database for this purpose.

The website which is responsible for the system interaction with the end users is divided into four main sections that allow access to the features mentioned above: Project, Information, Modelling and Analysis. These sub-menus are the main options from the navigation menu (Figure 1).
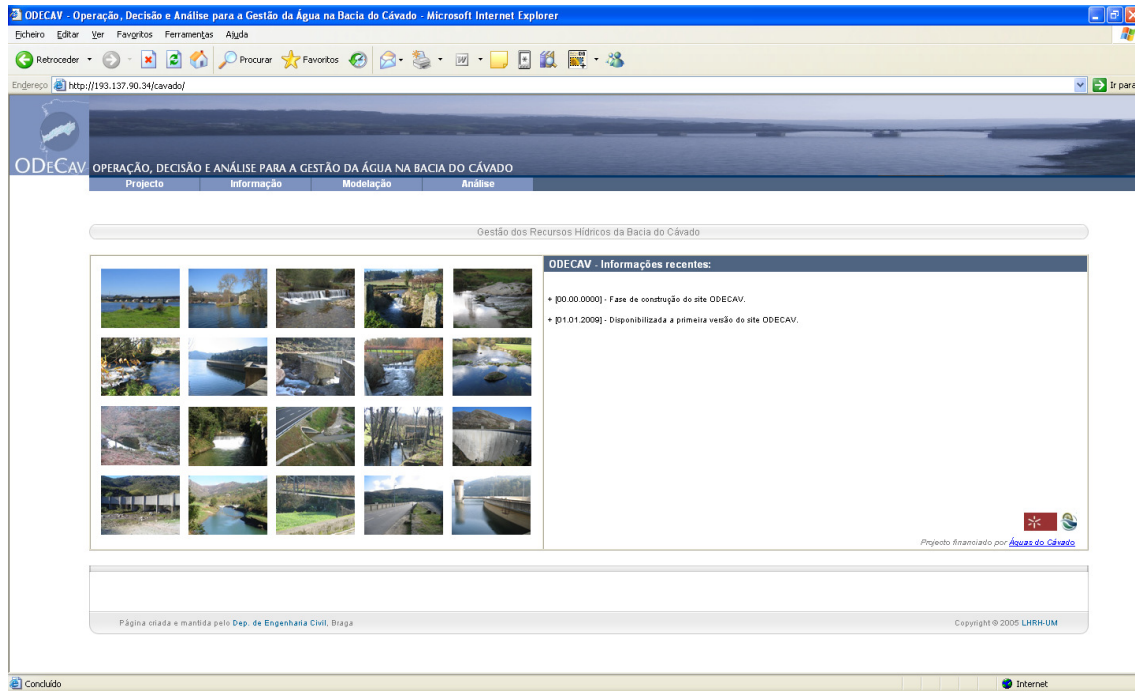
Figure 1 - Main window of the ODeCav modelling system.

The *Project* section presents information about the aim of the developed platform and its main characteristics. It also gives access to the document management tool. In the *Information* section it is possible to query the geographical database of the river basin. It includes information about details of the river network, data from monitoring stations and the river basin Geographic Information System. The *Modelling* section allows the users to define new simulations and remotely start the execution of the hydrodynamic and water quality models. This application not only allows the remote operation of the models, but also displays the simulation results from different users. Finally, the *Analysis* section provides access to several simulation results for a posterior detailed analysis and generation of reports. Each one of these sections includes graphical user interfaces, specifically designed and developed for that purpose, considering imposed requisites of its potential users.

Most of the content of the website has conditioned/restricted access. This means that it is available only through user authentication. A user without a valid login can only view/access the information provided under the *Project* menu (Figure 1). Any user who was granted with permissions (which has a user registration and password) will have access to the full content of the interface. However, this does not mean the user has permission to view, use or access all the features, functionalities and tools available in the interface. There are interfaces that differentiate the privileges of users. For example, while some users may start the execution of the models, others may only see theirs results. These permissions are managed by the system administrator. Figure 2 depicts used technologies in the implementation of the modelling platform and their interdependencies.
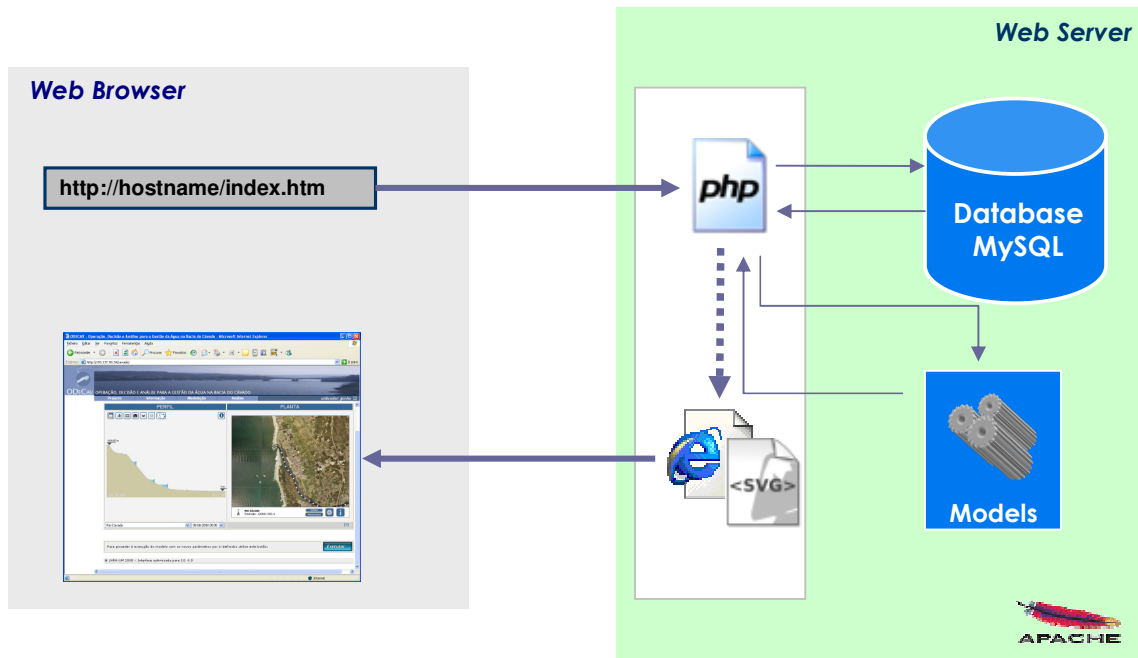
Figure 2 – Adopted technologies for the development of the modelling platform.

This system is supported by a web server that provides all the web pages that are part of the interfaces. The basic task of this web server is to receive HTTP requests and to produce HTTP responses, which are mostly HTML documents or other types, such as images, documents, PDF, SVG vector images and simple text. Apache was the selected web server (due to its portability, wide range of services available, and because is a free web server).

All the information provided by the web server is stored in a relational database supported by MySQL, the world's most popular open source database server. Besides, MySQL provides many features not available in other systems and is completely free for both commercial and private use. It is a fast and robust system that can handle with unlimited number of users and records. Among the main features of this system are: portability (support for practically any platform); compatibility (there are drivers and interface modules for various programming languages); the excellent performance and stability; user friendly; and requires few resources in terms of hardware.

PHP was adopted as the main programming language (used to generate the HTML pages sent to the clients machines), while the JavaScript language was selected to develop code responsible for the interaction between the user and the interface. The Sobek software (Deltares, 2009) was selected for the implementation of mathematical models (hydrodynamic and water quality). This software is applicable for hydrodynamic and water quality modelling in rivers, and it´s composed by seven modules: hydrology, hydrodynamics in channels, hydrodynamics in rivers, sewers, real-time control, water quality and floods. Its integrated approach allows the simultaneously simulation of real problems involving different modules. It is based on a robust and reliable numerical method that allows achieving solutions even for highly complex situations.

The consideration of graphical data within the developed interfaces was considered fundamental for a fast and intuitive understanding of the simulated features. In this case, the choice was the image technology SVG (Scalable Vector Graphics). SVG is an XML specification for graphics and has outstanding features as: ability to make enlargements without loss of resolution, the creation of motion graphics that facilitate presentation of results related to dynamic simulations, allows interactivity with the objects represented and the possibility of associating alphanumeric information to graphics. Beyond that, has a reduced download time, compared to other more conventional types of images.

3 MAIN FEATURES OF THE PLATFORM

3.1 Information System

The platform web map server was developed based on the GeoClient application (Rogers and Rosie, 2001). This application has been improved, and some new features and functionalities were added. Noteworthy, was the translation into Portuguese of all the menus and the inclusion of the possibility of automatic export of features to a Google Earth compatible data format. The information themes are organized into databases. Updates of geographical data, adding and deleting data are operations that should be undertaken by the administrator of the database, in accordance with standard methodologies for databases operations. The map visualized in the client side is defined using a form and is automatically generated by an application developed for this purpose. The database administrator can set pre-defined maps. It is also possible for the user to view the results of water quality simulations available on the modelling system. The user must select the rivers and the instant for which it want to represent the simulation results. The requested map information is communicated to the server and is transferred to the client computer at once. All subsequent operations are dependent on the processing capacity of the client´s machine.

The Geoclient application further developed at University of Minho, and integrated in this platform comprises the following major functionalities (Figure 3): full navigation (zoom in, zoom out and pan); map display of alphanumeric data associated to geographic entities; queries with results in chart or table; set labels display properties, export the map to a file, compliant with the Google Earth application; configurable legend presentation; presentation of a navigation map; selection of display options
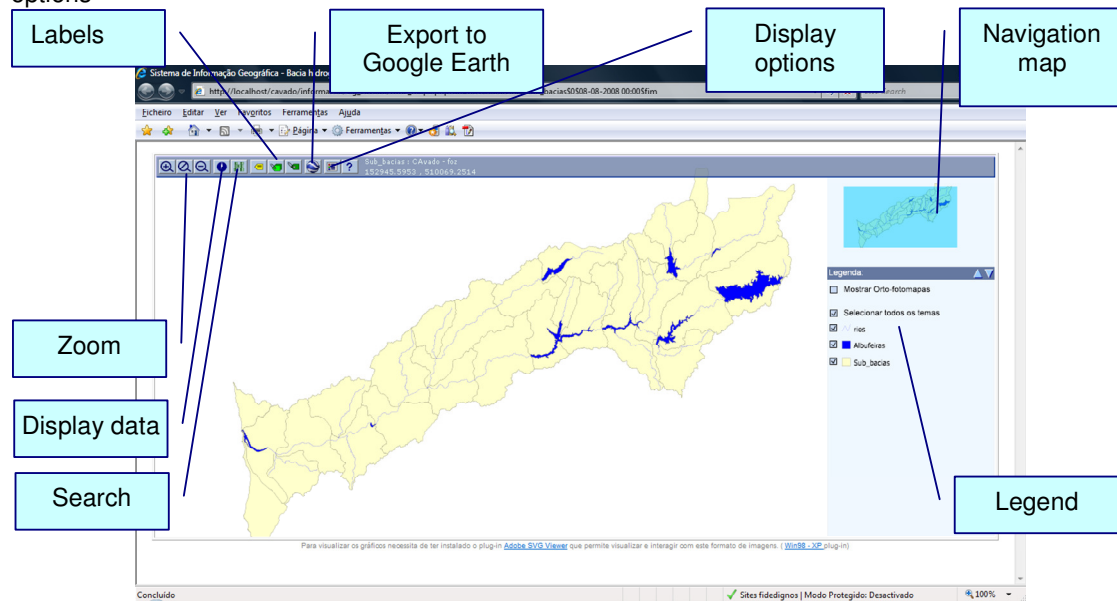

Figure 3 – Web-GIS service for the developed platform.

Navigation on the map is accomplished through some buttons on the toolbar which allow, for example, zoom in, zoom out and restore the original view. The toolbar shows the cursor coordinates and the labels associated to the graphical entities that are under the cursor. The panning can also be accomplished using the navigation map. The data associated with each graphic object are available, once the information button is pressed. The data are shown on a table and it is possible to generate a chart with the numeric values of all occurrences of the displayed map. The search tool allows the identification of objects throughout a table or a graph/chart, which satisfy the given search criteria. This criterion can be based on a comprehensive set of comparison operators. Search results can be quickly identified (by zoom in to the object or by its placement in the central area of the map) (Figure 4).

Map legend can be customized by the user; it's possible to change the colour of the displayed themes, set their classification according the values of numeric fields and show graphics (bars or circles) for numeric fields. For each object represented on the map there is a field associated on the database that is used for representing their labels on the main view. This feature can be assigned automatically for all entities of the map or placed entity by entity. The user has the possibility to define graphical properties of these labels. Finally, the application allows the automatic export of the map for later

viewing on the Google Earth application. The export module is designed to convert the different coordinate data used by the two applications (Figure 5).

In addition it was developed an application to present detailed information about the river network. The application allows making a virtual visit to the rivers, enabling to locate relevant features that are relevant for the rivers hydrodynamics (eg. dams, weirs, controlled gates) and water quality (eg. waste water treatment plants, industries). Navigation is driven by selection of river segments. The user selects the river to visualize from an initial map. Then the navigation tools and the interactive legend allow the user to activate/deactivate the selected themes.
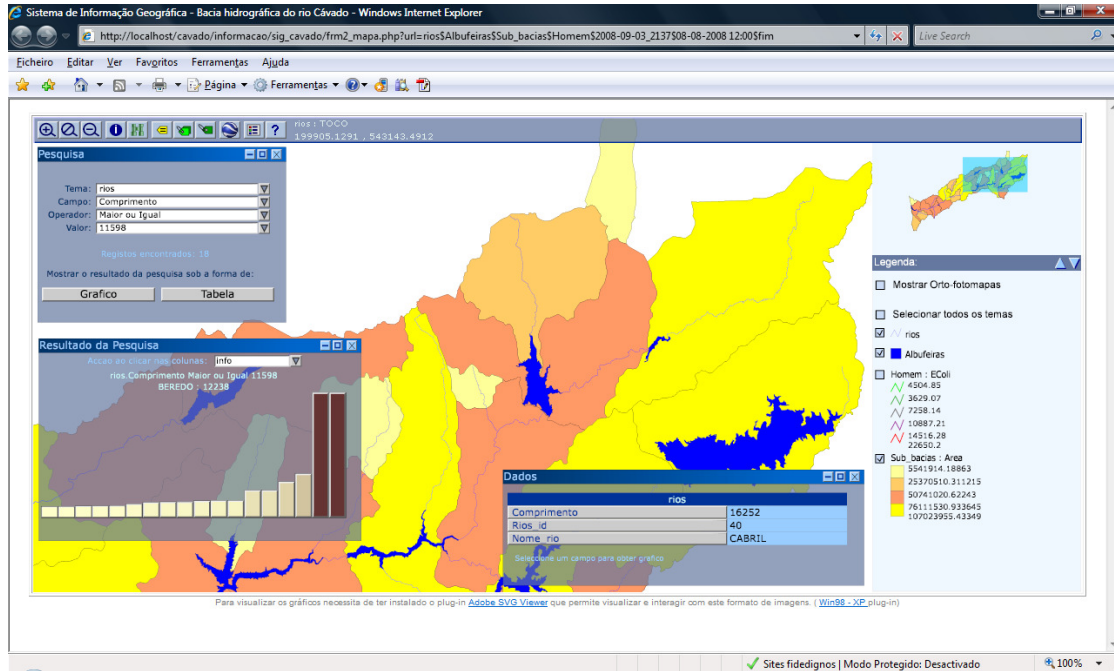

Figure 4 – Search Tool of GeoClient - Web-GIS service application of ODeCav modelling system.
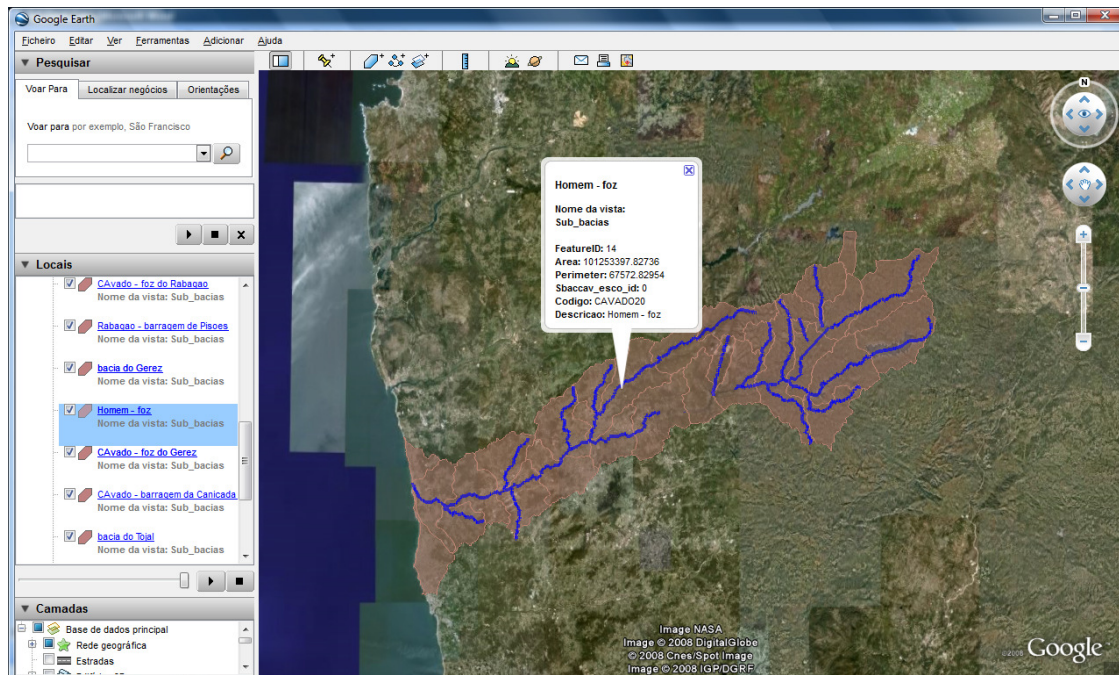

Figure 5 – Export of geographical features to Google Earth compatible data format.

This application allows the visualization of all the alphanumeric data associated with all the entities and to display photos if available. The information management operations are performed on the database. Operations like insert, update, edition, addition or deleting are performed with proper tools for databases management. Aerial photos are stored outside the database in individual and separated files. Only their basic properties are stored in the database.

Figure 6 presents, for illustrative purposes, some views of river detailed information at river Cávado basin.
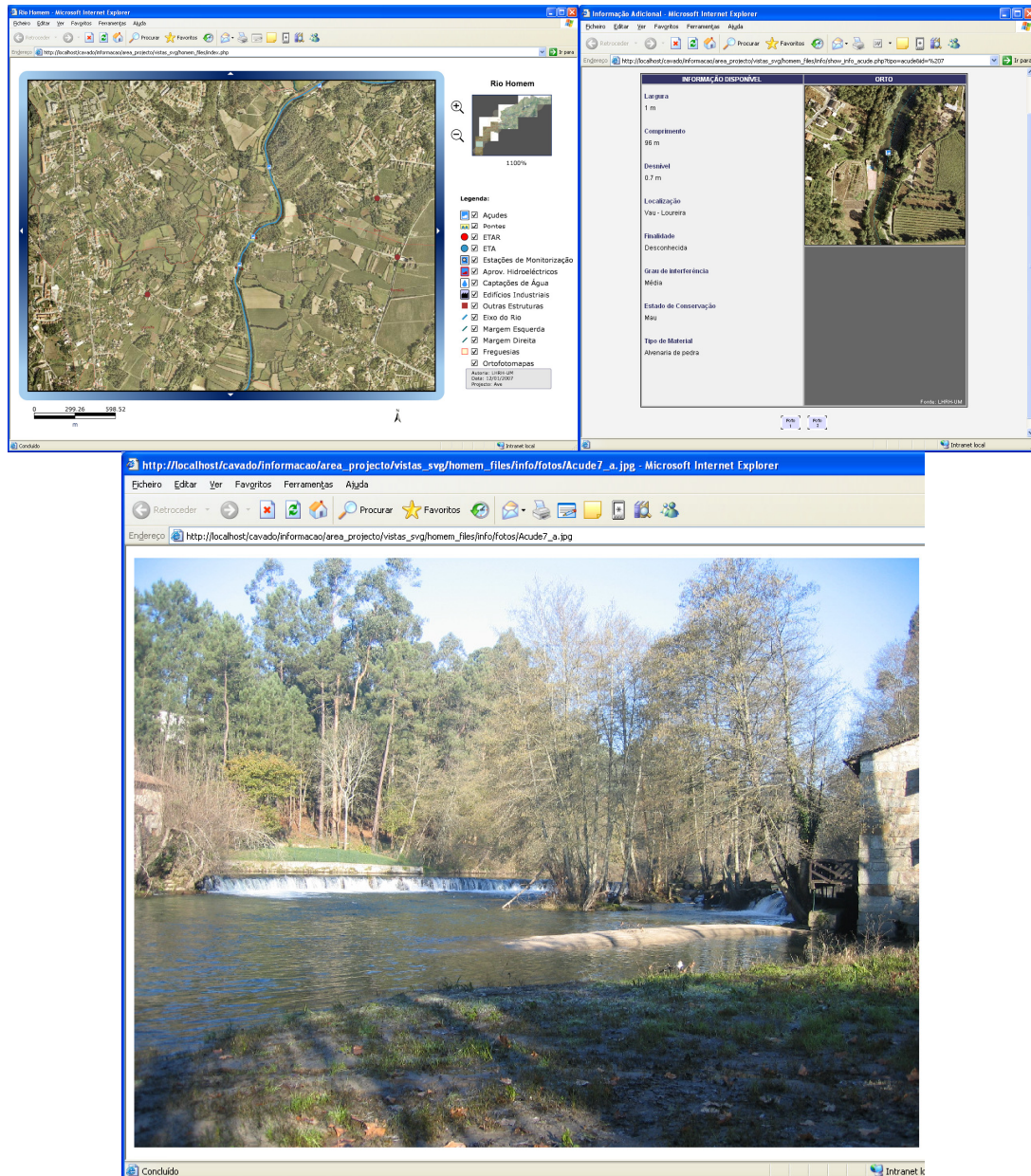

Figure 6 – River detailed information.

Meteorological, hydrometric and water quality information are available on the platform. This database contains historical records of the variables monitored for active monitoring stations. These data are the basis for water quality diagnostics assessment, and to the definition of modelling scenarios to predict the water quality dynamics.

A web application to access monitoring data was developed. The service provided by this application includes the following functionalities: graphical selection of the monitoring station from the map or from a list of available monitoring stations; graphic visualization of the data series for the selected parameter at a given station, data presentation in tabular layout and the possibility of exporting to a file compatible with MS Excel. It also allows the calculation of statistical parameters of the active data series and the automatic generation of a report. After selection of a particular parameter the associated data is displayed in a graphical layout in the client side (Figure 7).
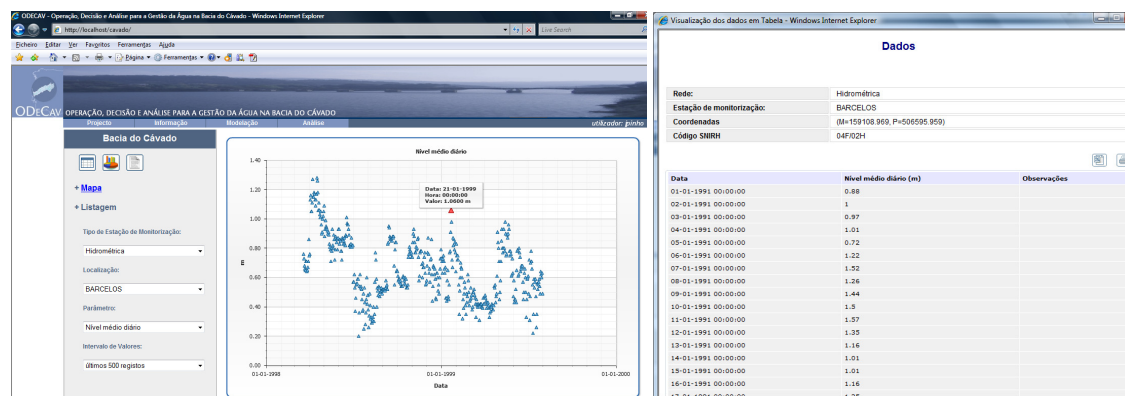

Figure 7 - Monitoring data interface.

3.2 Modelling system

The modelling system consists in mathematical models of the rivers network to simulate river water discharge flows and levels (hydrodynamics) and the transport of substances or properties that are used as water quality indicators. River hydrodynamics is simulated based on the one-dimensional mathematical formulations of the equations of mass and momentum conservation for free surface flows. In addition to these equations the models are constructed considering the simulation of discharges at hydraulic structures like bridges, culverts, orifices, pumps, siphons and weirs. In these structures the discharge flow depends on levels upstream and downstream of the structure, their dimensions and from a set of parameters specific for each structure.

Water quality modelling is based on the one-dimensional mass transport equation. The number of equations is equal to the number of water quality variables involved in the simulation. It is possible consider different biogeochemical processes which are relevant to analyse different water quality problems in surface waters. In the developed platform a set of water quality processes were selected, considering either simple processes (such as accidental discharges simulations considering conservative pollutants) or more complex processes (such as organic matter degradation).

Generally, substances in aquatic environments react with other elements and/or substances (resulting in the decrease or increase of concentrations). Bacterial contamination resulting from urban wastewater discharges or diffuse pollutant sources can be modelled by taking a 1st - order decay approach. The behaviour of many other substances (or species) can be approximated by considering the decay or growth according to a second order law, such as biochemical oxygen demand (BOD), and algae. The 1st order laws coefficients values should be established mainly through the available field data or laboratory tests. Dissolved oxygen (DO) is one of the most used environmental parameter to characterize water quality in surface water. Impact assessment of waste water discharges with high concentrations of organic matter can be made in terms of changes in the dissolved oxygen concentrations in the receiving waters.

The river Cávado model was constructed using the software SOBEK (WL, 2009). Figure 8 depicts the river basin and the modelled river network. The model considered the rivers Cávado and Homem and the following main tributaries: Beredo, Borralha, Cabreira, Cabril, Cavadas, Caveiro, Covo, Febras, Gerês, Milhazes, Pontes, Rabagão, Toco, and Tojal.

Cross sections of the river channels considered in the developed model were established using bathymetric and topographic data available for this river basin. The one-dimensional grid comprises 1722 computational nodes, 22 open boundaries, 51 controlled discharges at hydraulic structures and 105 non controlled hydraulic structures. The rivers channels geometry was introduced considering 1854 cross sections. Pollutant sources are simulated considering 84 different locations in the river basin. All hydraulic structures with a significant influence in the rivers flows regime were considered with emphasis for dams and hydropower generation plants.

Figure 8 – River Cávado basin and modelled river network.

A web interface to present model results and operate the model execution was developed. This tool interacts with the model installed on a remote server, and allows setting up and activating new simulations. The user has access to applications that permit change the hydraulic structures operational settings during simulations, define hydropower generation time scheduling, establish tributaries discharge flows under different scenarios and define pollutant concentrations and discharges.

Figures 9 and 10 shows the main view of the designed interface for hydrodynamic and water quality models, where several functionalities are available (graphic display of the river profile, plan view, tables and graphics results and animations). This interface allows either setting up the data needed to define new simulations and viewing the results of a selected simulation. The main window of the interface corresponds to the graphical display of the profile (Figure 10).

Each one of the included icons has one or more PHP modules associated responsible to produce the desirable output. As already mentioned, the developed interface allows both setting up the input data for new model simulations and presenting final results. To define new simulations an intuitive application was developed as depicted in Figure 11. The user has to follow up the successive forms to define all the data involved in a simulation. New simulations are defined using default data associated with the selected one.
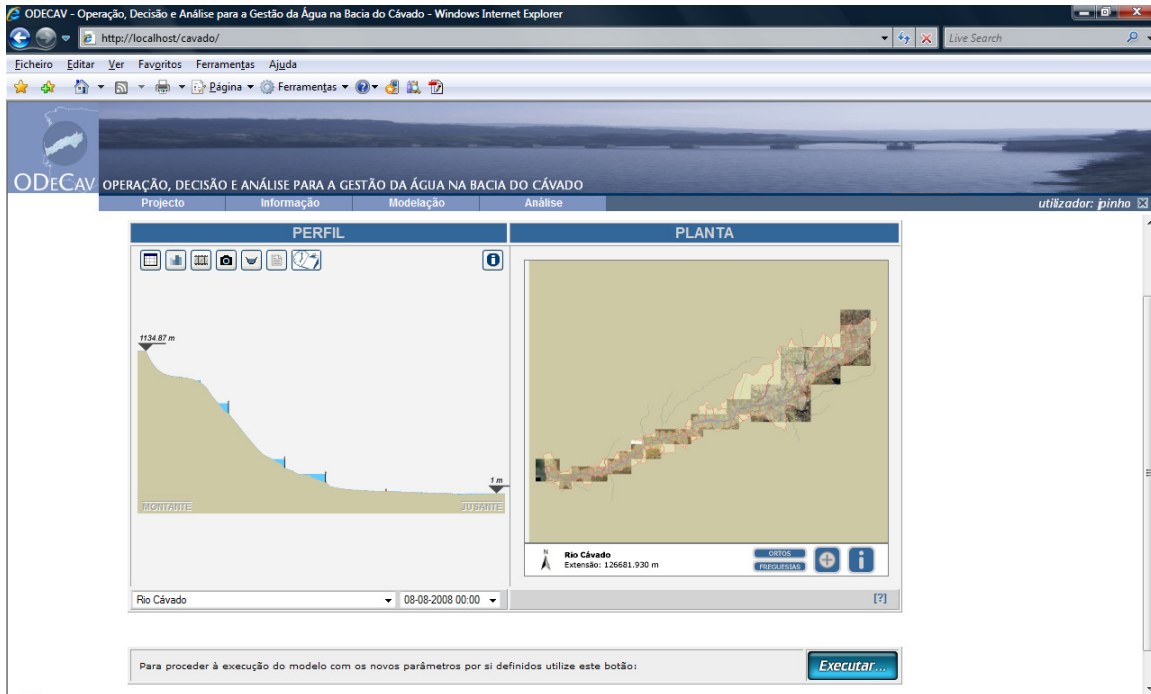
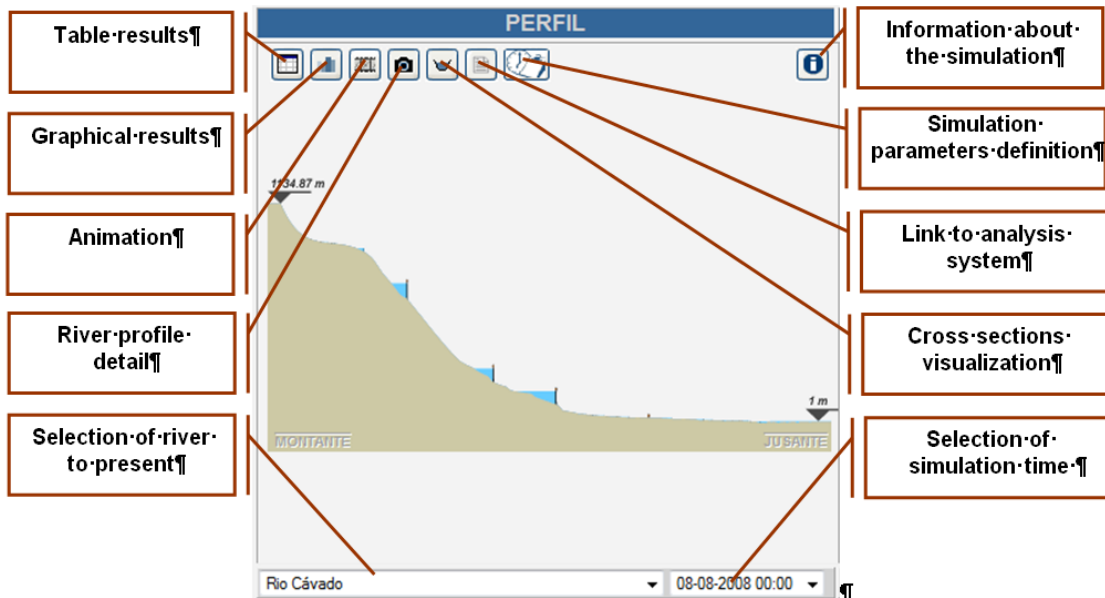**Figure 9** – Web interface for hydrodynamic models.

Figure 10 - Main functionalities of the hydrodynamic models web interface: profile view**.**

Figure 11 – Main form for definition of new simulations data (left) and interface to define data time series related to hydraulic structures (right).

The script used by this interface is responsible for setting the starting date and duration of the simulations. The presented form allows the definition of the values of river flows at the most upstream open boundaries. It is possible to define a constant value for the entire simulation or a variable law over that period. The image of a dam (as well as images for other hydraulic structures) on the form gives access to a specific new form for setting the opening laws of the gates and orifices (Figure 11 right). Completed the previous steps, the user can execute the model with these new parameters, pressing the "Run" button, located at the bottom of the main window (Figure 9).

3.3 Analysis system

The main purpose of this system is to simplify the analysis process of complex water systems through presentation of organized results information and tools for evaluation of the different management alternatives. The complexity of environmental systems is related to the uncertainty of the system behaviour caused by lack of essential information to describe natural phenomena and due to the simplifications adopted by mathematical models. This complexity is often intensified by the fact that, there are several actors with shared responsibility in solving the existing problems but usually these actors do not work together.

In the design of the analysis system it was considered the integration of different scales involved in the water resources management problems in a simple and intuitive manner, allowing moving from basin scale to the scale of hydraulic structures within the same application. The analysis of management measures under various environmental scenarios, results in a set of simulations that can be stored by the manager of the developed platform. These stored simulations can be used by different users of the modelling system.

Through a specific interface (Figure 12) it is possible to manage (store, consult and remove) different simulations generated in the modelling system. This information is organized by rivers and the analysis is carried out through reports available online. Two separated applications were considered for system analysis: one dedicated to the exploration and analysis of results from hydrodynamic simulations and the second committed to the analysis and exploration of results of water quality. The design and features included in the two interfaces are identical, differing only in the type of results available. This division is justified by the expected use of two distinct groups of users (one group focused on quantitative analysis and the other more interested in qualitative analysis).
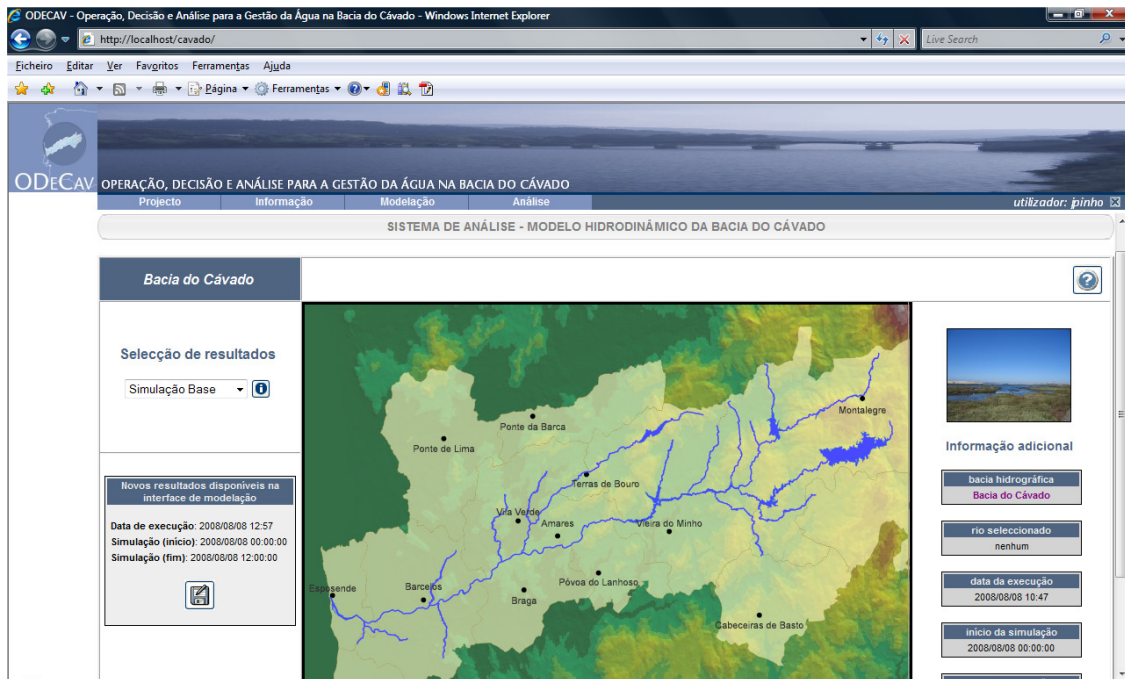
Figure 12 - Main interface of the analysis system.

The main window displays a list box with the available simulations results. It also provides an area with indication of possible simulations available for storage (if the user has permission to store simulations) and an area with additional information about the selected river and simulation data. After selecting the river to be analysed, a plan view of the river is displayed with graphical features that represents river reaches, nodes and hydraulic structures (Figure 13).
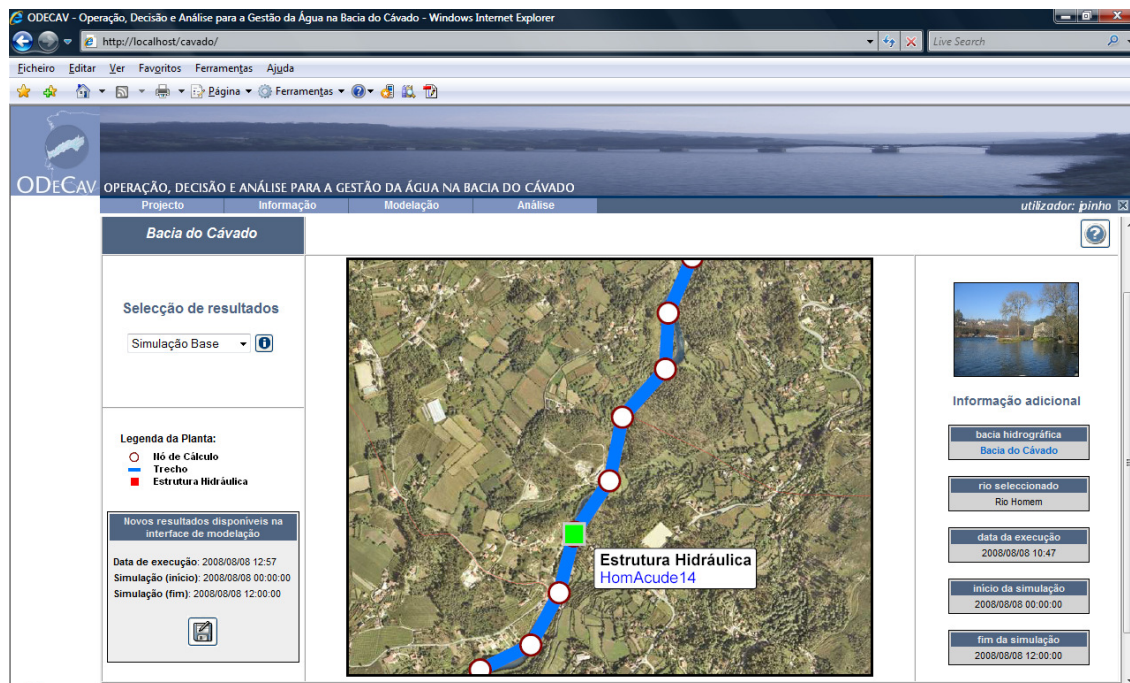

Figure 13 – Plan view for selection of river features in the analysis system.

The plan view, also allows visualization of aerial photos, location names and the river name that are used as auxiliary information for easily locate the conceptual elements of the model (nodes, reaches and hydraulic structures). Based on these elements it is possible to automatically generate a report with results of the selected simulation. The report consists of: general information about the simulation and information about the nodes, reaches or hydraulic structures, plant and profile location of the selected element; representation of the profile view at the initial time, intermediate instant and at the final instant of the simulation; table of results for the active element; graph of results for all variables associated with the selected element and a statistical summary of these variables over the simulation period.

4 RESULTS AND CONCLUSION

The developed operational modelling platform allows the simulation of an unlimited number of scenarios. Several scenarios were implemented in order to evaluate its performance after a judicious effort for model calibration and validation.

Main obtained results (a detailed paper about obtained results is in preparation) for the rivers within the basin reveal an almost uniform longitudinal profile for BOD concentration with a good agreement between observed and simulated results. The installed wastewater treatment capacity in the watershed (domestic and industrial wastewater) is reflected in the observed values leading to low concentrations of BOD. However, a quite different situation is observed for bacteriological indicators. In the lower part of the basin, concentrations results for all simulated scenarios are always lower than the observed ones even in the dry season. The reason for this fact can be the existence of untreated discharges or the lack of disinfection in WWTP.

The presented decision support tool for the river Cávado basin constitutes a robust and efficient technological platform to support water management at a river basin scale. Obtained results allow predicting that this new tool will be extremely effective and important to achieve the objectives of water management at river basin scale. In the next years, the use of all the potentialities of this kind of platforms in practical situations under different water management problems constitutes a major challenge for the evaluation of the developed tool. Moreover, water authorities once decide to use this kind of management tools will certainly see improved their analysis capabilities, strengthening their technological skills for the adoption of more sustainable water management policies.

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