A TOOL FOR THE DESIGN OPTIMIZATION AND MANAGEMENT OF SUBMARINE OUTFALL PROJECTS: APPLICATION TO A PORTUGUESE CASE-STUDY

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Abstract

The paper presents a risk assessment methodology for operational limit states of submarine outfall projects that considers: the intrinsic nature of the structure, the environmental legislative framework, the climate agents acting on the coastline and prediction of the plume long-term behavior near the coastline, together with the empirical orthogonal functions analysis. The probability of operational failure or stoppage is assessed enabling decision on project design alternatives.

1. Introduction

The use of submarine outfalls has been increasing rapidly (Grace, 2009) and their good working conditions are of mandatory importance to the environment, welfare of populations and economy. These structures are subject to the action of several climate and usage exploitations agents, and must fulfill overall safety and operational criteria.

Despite the fact that high-cost projects of outfalls are a complex task that relies on many disciplines, the risk management is still applied instinctively, with risks remaining implicit.

This work aims to create a consistent methodology for the risk assessment of the project of submarine outfalls following the procedure of the Spanish Recommendations for Maritime Structures, ROM, that is restricted essentially to harbor and coastal protection structures (Puertos del Estado, 2002). This methodology is expected to evaluate safety and operationality, as well as some aspects of the performance of the submarine outfall.

The extreme outcomes of the majority of the agents of the physical environment in a time interval are infrequent occurrences, which must be quantified. They also vary considerably in space. The occurrence and the magnitude or value of the project factor are uncertain from a temporal as well as a spatial perspective, and one way of dealing with this is by applying probability theory.

2. Methodology

The first step of the engineering procedure specifies the requirements and target design levels of these structures in the project phase and is described in Mendonça et al. (2013), together with failure modes and corresponding limit states for submarine outfalls.

The procedure for calculating target design levels determines the safety, serviceability, and exploitation requirements that the project must satisfy (Losada and Benedicto, 2005). This procedure is composed of the following three steps: (1) Evaluation of the indices of economic, social, and environmental repercussion, which define the general and operational intrinsic natures of the structure; (2) Classification of the structure, based on the indices obtained in Step 1; (3) Specification of the target design levels, based on the classification of the structure (Step 2). The identification of these design levels makes it possible to estimate the useful life of the structure, the maximum admissible joint probability of failure against the principal failure modes, the minimum operationality, the admissible average number of technical breakdowns and the maximum admissible duration of an operational stoppage (Puertos del Estado, 2002).

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The risk assessment procedure proposed in Mendonça et al. (2012) is applied for operational limit states (environmental failure modes) focusing on the environmental legislative framework, climate agents on the coast and effluent fate and distribution.

The developed methodology (Figure 1) analyses the plume behavior in each time interval (yearly) with the objective to:

- Calculate the probability of exceeding a representative threshold value whose occurrence may be significant to the operationality of the structure (e.g. fecal coliform concentration);
- Calculate the persistence of the exceedance of that threshold value;
- Calculate the frequency and seasonality;
- Identify the areas with high probability of exceedance of that threshold value;
- Establish a relation between wind forcing and surface currents, finding out if the spatial variability of plumes is primarily determined by atmospheric forcing;
- Quantify the physical forcing mechanisms that govern the variability of plumes in the studied coastal system; and
- Define the plume distribution function and its lower and upper characteristic levels.

The numerical modeling process uses TELEMAC-2D (Galland et al., 1991): (i) to simulate 25 statistically independent event (yearly) scenarios in feasible computation times, using Monte Carlo simulated wind time series as boundary conditions, while (ii) representing the typical annual current conditions.

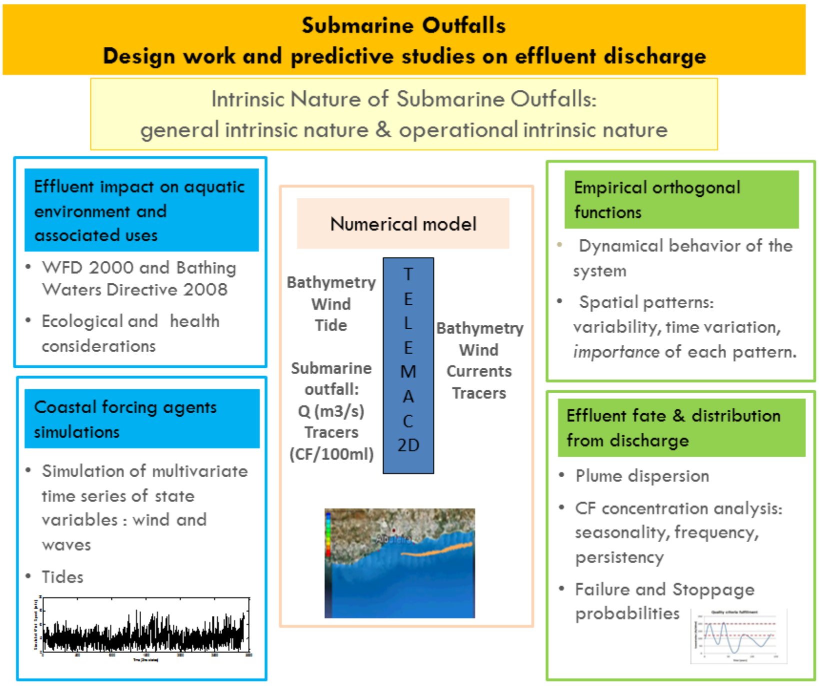


Figure 1. Developed methodology scheme.

Project design alternatives for submarine outfalls should be drawn based on these result analyses with solutions flexible enough to be constantly upgraded and improved in order to fulfill expected environment protection requirements, as the Marine Strategy Framework Directive, and established target design levels of operationality.

Empirical orthogonal functions (EOFs) are used on the TELEMAC-2D results in order to reduce the dimensionality of the system and find the most important patterns of variability.

To illustrate the procedure, an application to a submarine outfall is analyzed and each part of the methodology is described. This outfall is the Vale de Faro outfall, situated in Praia do Inatel, Albufeira, in the south coast of Portugal (Figure 2a).

a) b)

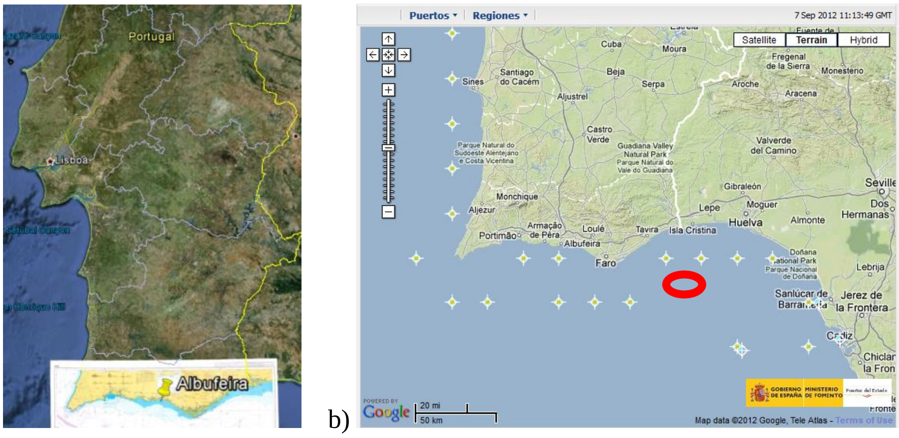


Figure 2. a) Study site: Vale de Faro, Albufeira, Portugal.; b) Puertos del Estado: Point 1050048 (source: www.puertos.es).

3. Study site

The south of Portugal is a region sheltered from the most dominant and important swell source, the North Atlantic. Besides the long travel distance involved, storms generated in the North Atlantic have to circumvent the southern Portuguese continental shelf to reach the coast (Figure 2a). These factors contribute to an important dissipation of storm energy and wave height, which can consequently introduce different patterns into storm variability. The local storm wave climate is also influenced from the southeast by stormy waves originating in the Gibraltar Strait region (Almeida et al., 2011).

These site-specific characteristics and their possible effect on storminess are studied in order to perform simulation of multivariate time series of the state variables that characterize the local predominant forcing agents. Historical and climatic information of physical oceanographic parameters (waves, tides, currents, winds, etc.) is available through the Spanish Port Authorities (www.puertos.es). To illustrate the procedure, an application to the submarine outfall of Vale de Faro, situated in Praia do Inatel, Albufeira, in the south coast of Portugal, is analysed. The case study used time series of WANA point number 1050048 (Figure 2b).

4. Intrinsic Nature of Submarine Outfalls

The importance of a maritime structure or one of its sections, as well as the economic, social, and environmental impact produced in the case of serious damage or destruction or total loss of service and functionality can be evaluated by means of the general intrinsic nature (GIN) of the structure or any of its sections (Figure 3).

The GIN is assessed by selecting the failure mode that gives the highest repercussion value from the principal modes assigned to the ultimate (ULS) and serviceability (SLS) limit states (Puertos del Estado, 2002).

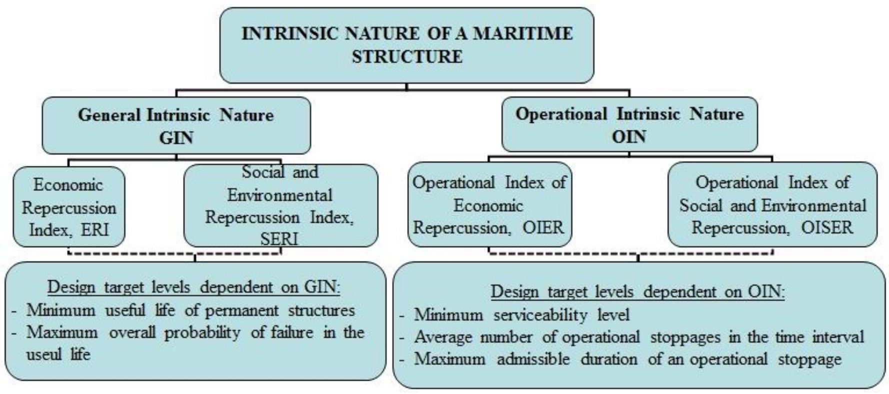


Figure 3. Intrinsic nature of a submarine outfall (Mendonça et al, 2013).

The general intrinsic nature of the structure is a function of the economic repercussion index (ERI) and the social and environmental repercussion index (SERI).
The ensuing economic repercussions and the social and environmental repercussions when the maritime structure stops functioning or reduces its operational level are specified by its operational intrinsic nature (OIN). The OIN is evaluated by selecting the operational stoppage mode that gives the minimum operational level. It is then specified in terms of the operational index of economic repercussion (OIER) and the operational index of social and environmental repercussion (OISER).
The exploitation of any section of a structure can be defined in terms of the following: (i) average number of stoppages (in a time interval linked to social and environmental factors); (ii) minimum levels of operationality (in a specified time period based on previous economic studies); (iii) the maximum admissible duration of a stoppage in a time interval that depends on economic factors and the cycle of demand.

i) Average number of stoppages

In a given time interval (usually a year), and for those cases in which it has not already been specified, the average number of occurrences of all modes assigned to stoppage limit states (N_{stop}) should be lower than the value shown in Table 1. If the operational stoppage has high social and environmental repercussions, four stoppages (per year) are allowed to occur. The submarine outfall should thus always be kept operational, except in the event of extraordinary unforeseen conditions.
The main reasons that submarine outfalls stop operating are the obstruction of the pipe and diffuser, exceedance of the recommended limit values for the effluent discharge and the use of a bypass. Bypasses can pose a direct health risk to people who come into contact with contaminated water. However, they can also indirectly affect people that consume contaminated seafood (e.g. shellfish). Such stoppages mostly occur in periods of heavy rain, when the effluent exceeds the submarine outfall capacity. Information concerning bypasses can help to determine whether operations or maintenance practices need to be improved or if an upgrade of the submarine outfall is required. N_{stop} can be evaluated as follows (Table 1):

$$N_{stop} = \sum_{i=1}^{3} L_i$$

where L_1 represents the exceedance of limit values for the discharge, L_2 the obstruction of the pipe or diffuser and L_3 the bypass of the effluent due to overflow.

Table 1. Parameters defining the average number of stoppages in the time interval.

	L1	L2	L3	$N_{stop} = \sum_{i=1}^{3} L_i$
SERI≤10	8	1	3	12
10<SERI<20	4	1	2	7
SERI≥20	2	1	1	4

ii) Maximum duration of stoppage

During the structure's useful life (and when there are no previous specifications), the probable maximum duration of a stoppage (in hours) cannot exceed the value in Table 2, based on the OIER and OISER of the affected section of the structure.

Table 2. Probable maximum duration of a stoppage mode (hours).

Operational index of economic repercussion	Operational index of social and environmental repercussion		
	OISER<20	**20≤OISER<30**	**OISER≥30**
OIER≤5	24	12	6
5<OIER≤20	12	6	3
OIER>20	8	4	2

iii) Minimum operationality

The minimum operationality of a submarine outfall (or each of its sections) depends on the consequences of a stoppage within the context of the operational stoppage limit states that can arise during the serviceability phase, as well as the average number of stoppages and maximum duration of a stoppage. For the serviceability phase, the operational nature of the structure provides an overall evaluation of these consequences. The value, however, cannot be less than the values obtained for the operational index of economic repercussion (OIER) and the operational index of social and environmental repercussion (OISER). In this sense, the structure's operationality should be greater when the economic consequences of operational stoppage are more important. During its useful life, the operationality of the structure or one of its sections in reference to the principal modes assigned to the stoppage limit states in normal working and operating conditions has to be at least the value in Table 3 in accordance with the OIER.

Table 3. Minimum operationality in the useful life of the structure.

Operational index of economic repercussion	Operationality $r_{f,\,OLS}$
OIER≤5	0.90
5<OIER≤20	0.95
OIER>20	0.99

5. Effluent Impact on Aquatic Environment and Associated Uses

Instruments for water resource management have an important role in preventing water-related conflicts, through assessing the resource's spatial and temporal variability on coastal areas. It is therefore important to follow the water policy in order to promote more adequate land use and better protection of water quality and associated ecosystems. In this context, it is also important to relate and integrate water resource management with the prevention of and protection against extreme hydrological conditions. The management of submarine outfalls is tied to:

- **Exceedance of threshold values**: related to the agents of the physical environment (climatic agents);
- **Unacceptable environmental effect or social repercussion**: stoppage modes carried out to avoid damage to people, historical and cultural heritage, and environment;
- **Legal constraints**: stoppage modes carried out to fulfil legal requirements.

According to the legislative framework, submarine outfall monitoring focuses on eight critical stressors/constituents: salinity, pathogens, nutrients, turbidity, heavy metals, natural and organic material, hydrocarbons and pesticides. These eight constituents can be evaluated within the context of four different environmental measurement areas: effluent, water column, sea floor environments, and fish and shellfish.

This study analyses the behaviour of coliform concentration from the effluent considering a worst case scenario where the wastewater treatment plant stops functioning and the submarine outfall is receiving a constant load of $Q=1.18\ m^3/s$ and $1x10^7$ CF/100ml.

6. Coastal Forcing Agents Simulation

For modeling the effluent fate it is required to have the boundary conditions that force the hydrodynamic model. After the astronomical tide, which is a deterministic variable, the main forcing agent is the wind. Then, for applying the probabilistic verification and design procedure proposed in this work, it is necessary to implement a Monte Carlo simulation methodology for wind time series, accounting for both wind speed and wind direction.

In this work a simulation methodology is applied that is based on the use of mixture non-stationary distributions for deseasonalization of the data, and a combination of copula-based and autoregressive models for modeling auto and crosscorrelation of the series. The proposed methodology is based on Solari and Losada (2011) and is summarized as follows:

- Wind speeds are fitted with a parametric probability distribution function. For this a non-stationary mixture model is used, composed of a truncated two-parameter Weibull distribution for the main-mass of the data and a generalized Pareto distribution (GPD) for the upper tail (Solari and Losada, 2011, 2012a, 2012b).
- A copula-based model is used for modeling the autocorrelation of the deseasonalized wind speed time series. For the deseasonalization the Weibull-GPD model is used (Solari and Losada, 2011).
- Wind directions are fitted with a parametric model devised for circular variables (see e.g. Fisher, 1993). In this case a non-stationary mixture model, composed by two Wrapped Student-t distributions, is used (a detail description of this kind of distribution is presented in Solari and Losada (2012c), though they use a mixture of Wrapped Normal distributions).
- Fitting an autoregressive model for the deseasonalized wind directions, using deseasonalized wind velocities as an exogenous variable (ARX model).

Once the four described models are fitted to the original data set, new time series are simulated. For this, wind speed time series are simulated first, using the copula-based dependence model and the Weibull-GPD distribution. Then, wind directions time series are simulated conditional to the wind speed time series previously obtained, using in this case, the ARX model and the mixture of wrapped distributions.

For applying the proposed simulation methodology a hindcast wind time series is used. The data were provided by the Spanish Port Authorities (Puertos del Estado) and correspond to a grid node located in the Atlantic Ocean next to Faro, Portugal (WANA point number 1050048, Figure 2b). Figure 4 shows stretches of the original and the simulated wind speed series.

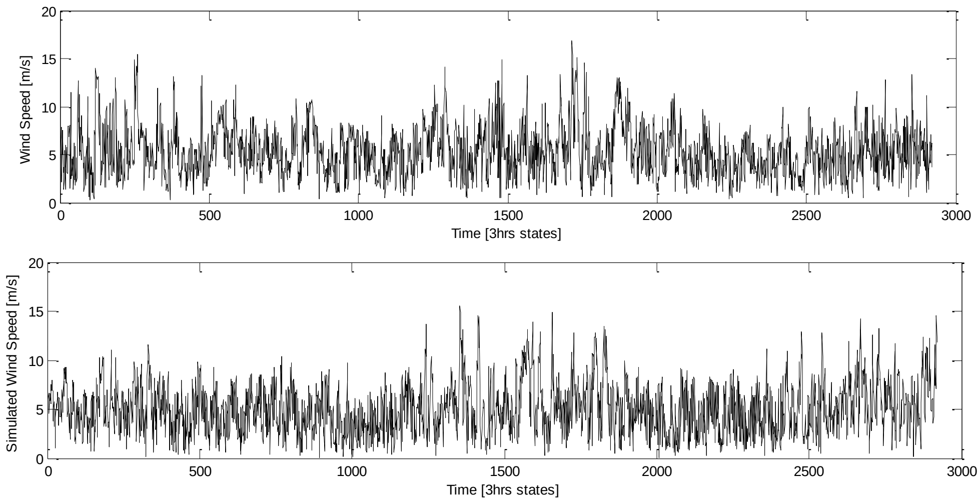


Figure 4. Original (top) and simulated (bottom) wind speed time series.

7. Numerical Model

The important factors that influence the hydrodynamics of the area are the tide, the wind and the currents resulting from the wind and tide action. TELEMAC-2D code is used to represent the current fields generated by the wind and tide and to compute the effluent transport by currents in the studied area.

The TELEMAC-2D code, developed by the National Hydraulics and Environment Laboratory of the Research and Development Directorate of the French Electricity Board (EDF-DRD), solves depth-averaged free surface flow equations as derived first by Barré de Saint-Venant in 1871. The main results at each node of the computational mesh are the depth of water and the depth-averaged velocity components. The main application of TELEMAC-2D is in free-surface maritime or river hydraulics and the program is able to take into account the effects of meteorological phenomena, such as atmospheric pressure and wind, turbulence, entrainment and diffusion of a tracer by currents, including creation and decay terms and particle tracking and computation of Lagrangian

drifts (Galland et al., 1991). With TELEMAC-2D it is possible to take into account the transport of a non-buoyant tracer (i.e. one whose presence has no effect on the hydrodynamics), which may or may not be diffused.
Space is discretized in the form of an unstructured grid of triangular elements, which means that it can be refined, particularly in areas of special interest, facilitating selective refinement to better represent boundaries and small scale features, such as discharge outfalls.
The main steps involved in operating the model are: construction setup, calibration/validation setup, mesh construction, bathymetry and determination of boundary conditions.
This study, as an initial assessment, aims to present a methodology from where it is possible to obtain useful results from a model that is not calibrated (TELEMAC-2D). Model calibration and validation, to proper characterize the field conditions at site, are the next steps of the work.

8. Empirical Orthogonal Functions

The EOF method analyzes the variability of a single field variable: coliform (CF) concentration. The method finds the spatial patterns of variability, their time variation and gives a measure of the "importance" of each pattern (Björnsson and Venegas, 1997).
Measurements of the variable CF, from the TELEMAC-2D simulations, were considered within an area in the vicinity of the submarine outfall at locations x_1, x_2,..x_p and at times t_1, t_2,...t_n. For each time t_j ($j = 1, ..., n$), the measurements x_i ($i = 1, ..., p$) act as a map or field. Matrix *F* stores this information: each row is one map and each column is a time series of observations for a given location. The EOF analysis is performed using *F* as the data matrix.
The mean is removed from each of the *p* time series in *F*, so that each column has zero mean. The covarianc*e matrix* of *F* is formed by calculating $R = F^t F$, and the eigenvalue problem $RC = C\Lambda$ is solved. Λ is a diagonal matrix containing the eigenvalues λ_i of *R*. The c_i column vectors of *C* are the eigenvectors of *R* corresponding to the eigenvalues λ_i. Both Λ and *C* are of the size *p* by *p*.
For each eigenvalue λ_i chosen, the corresponding eigenvector c_i is found. Each of these eigenvectors can be regarded as a map. These eigenvectors are the EOFs we are looking for. It is assumed that the eigenvectors are ordered according to the size of the eigenvalues. Thus, EOF_1 is the eigenvector associated with the biggest eigenvalue and the one associated with the second biggest eigenvalue is EOF_2, etc. Each eigenvalue λ_i, gives a measure of the fraction of the total variance in *R* explained by the mode.
The pattern obtained when an EOF is plotted as a map represents a standing oscillation. The time evolution of an EOF shows how this pattern oscillates in time. To see how EOF_1 'evolves' in time: $\vec{a}_1 = F\vec{c}_1$.
The *n* components of the vector $\vec{a}_1$ are the projections of the maps in *F* on EOF_1 and the vector is a time series for the evolution of EOF_1. In general, for each calculated EOF_j, a corresponding a_j is found. These are the *principal component time series* (PC's) or the *expansion coefficients* of the EOFs.
Just as the EOFs were uncorrelated in space, the expansion coefficients are uncorrelated in time.
The rationale is that the first *N* eigenvectors are capturing the dynamical behavior of the system and the other eigenvectors (corresponding to the smallest eigenvalues) are just due to random noise.

9. Vale de Faro submarine outfall

Albufeira, in the south of Portugal, has 40,828 inhabitants that triplicate around the summer season due to tourism.
The submarine outfall of Vale de Faro was selected to represent a common type of submarine outfall in Portugal, based on the type of effluent (urban) and importance to the region in terms of tourism and municipal serviceability, **Error! Reference source not found.**.
The submarine outfall, installed in 1986, became under designed due to increasing number of

tourists in the summer season and a new structure was proposed and constructed in 2002. These structures have been monitored and supervised regarding wastewater and environmental characteristics (e.g. topography and bathymetry, bottom materials and morphology) and the description of important and minor failures that have occurred. The system supplies sanitation to about 130,000 P.E. disposing an urban effluent with secondary treatment, plus disinfection in summer. The High Density Polyethylene outfall is 1,020 m long, with a 1,000 mm diameter and discharging at 11 m depth (datum level). The diffuser has 32 ports and is 160 m long.
The submarine outfall was designed to prevent the pollution of bathing waters and its capacity is directly related with the probability of incompliance with the water quality criteria.
The aim is to analyze the plume behavior and coliform concentration in touristic and sensitive areas, near Albufeira, in the summer and winter periods, in case of operational failure. The worst case scenario is represented considering a constant coliform concentration of 1×10^7 CF/100ml.
The hydrodynamic model (TELEMAC-2D) is forced with astronomical and meteorological tides at the oceanic boundary and wind velocity and wind direction on the ocean.

10. Effluent Fate and Distribution from Discharge

Coliforms were studied as the main pollutants at a discharge rate of 1×10^7 CF/100ml in an effluent flow of $1.18 m^3/s$ and dilution of 60.

The computational grid goes from Lagos to Vila Real de Santo António, around 112 km length, and has 12,245 triangular elements and 6,361 nodes (Figure 5a).

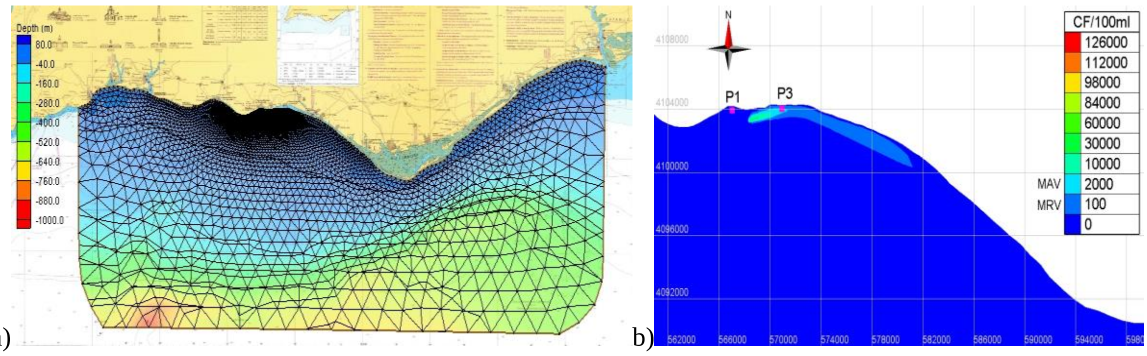
a) b)


Figure 5. a) Computational mesh used in TELEMAC-2D, b) Coliform concentration and plume behavior around Vale de Faro submarine outfall (28th February 2023).

Control points are selected based on their importance to human activities and protected areas (P1 and P3 are observed in Figure 5b). The analysis of results focus on coliform concentration along time, considering the limits established in the Water Framework Directive (maximum admissible value MAV, 2,000 CF/100ml and maximum recommended value, MRV 100 CF/100ml). Special attention is given to the probability of exceeding the coliform concentration value whose occurrence may be significant to the operationality of the structure; persistence of the exceedance of that threshold value; and calculation of the frequency and seasonality. Moreover, spatial and temporal variability of the water quality (based on coliform concentration) in important/sensitive areas is analyzed. Figure 5b presents an example of the plume behavior for Vale de Faro submarine outfall, where its proximity to the coast and beach is observed.
Simulations with TELEMAC-2D reveal that the effluent dispersion caused by currents generated under the influence of wind is greater than the dispersion resulted from the currents generated by the tide only. Also, the area with high probability of exceedance of the MRV (2,000 CF/100ml), that present the greatest evolution of tracer (coliforms) under the tide and wind effects, occurs at location P3.
The 25 year-simulation shows that the failure events occur mainly during the months of February to July and that the failure persistence varies between 1h-3h (Figure 6), probably related to the

wind pattern. Figure 6 represents coliform concentration at control points P1 and P3, for the period of October 2010 to October 2011. In Figure 6a, for point P1, one failure event occurs, i.e., one event for which the coliform concentration exceeds the MAV (2,000 CF/100ml). Figure 6b shows 34 failure events for point P3 that stands for the most affected area in terms of pollution from the submarine outfall.

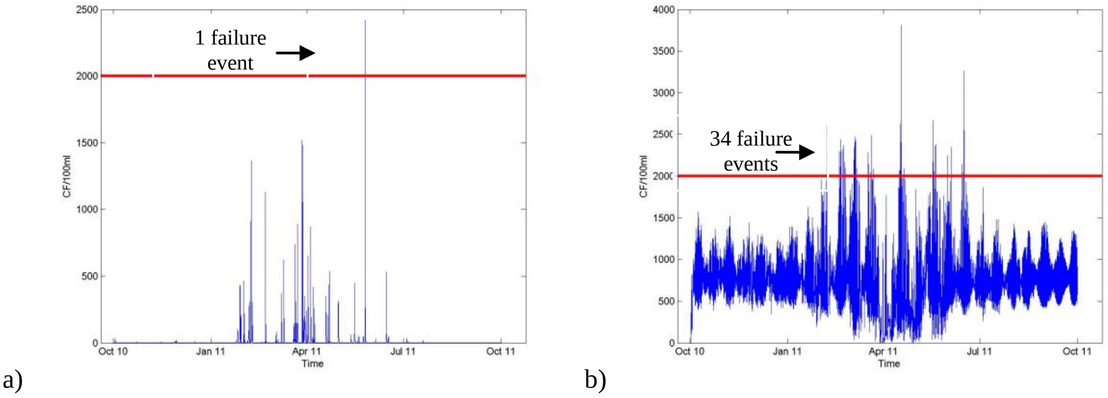


Figure 6. Coliform concentration at control points a) P1 and b) P3.

The EOF method is a 'map-series' method of analysis that takes all the variability in the time evolving field and breaks it into a few standing oscillations and a time series to go with each oscillation. Each of these oscillations (each EOF) is often referred to as a mode of variability and the expansion coefficients of the mode (the PC) show how this mode oscillates in time. The analysis of 25 years (2010-2035) of coliform concentration in Vale de Faro area was performed. The three leading EOF modes together account for 80.64% of the total monthly coliform variance. Individually, they explain 50.19%, 19.12% and 1.33% of the variance. The spatial patterns associated with these three coliform modes are shown in Figure 7 as homogeneous correlation maps $E_1(CF)$, $E_2(CF)$ and $E_3(CF)$.

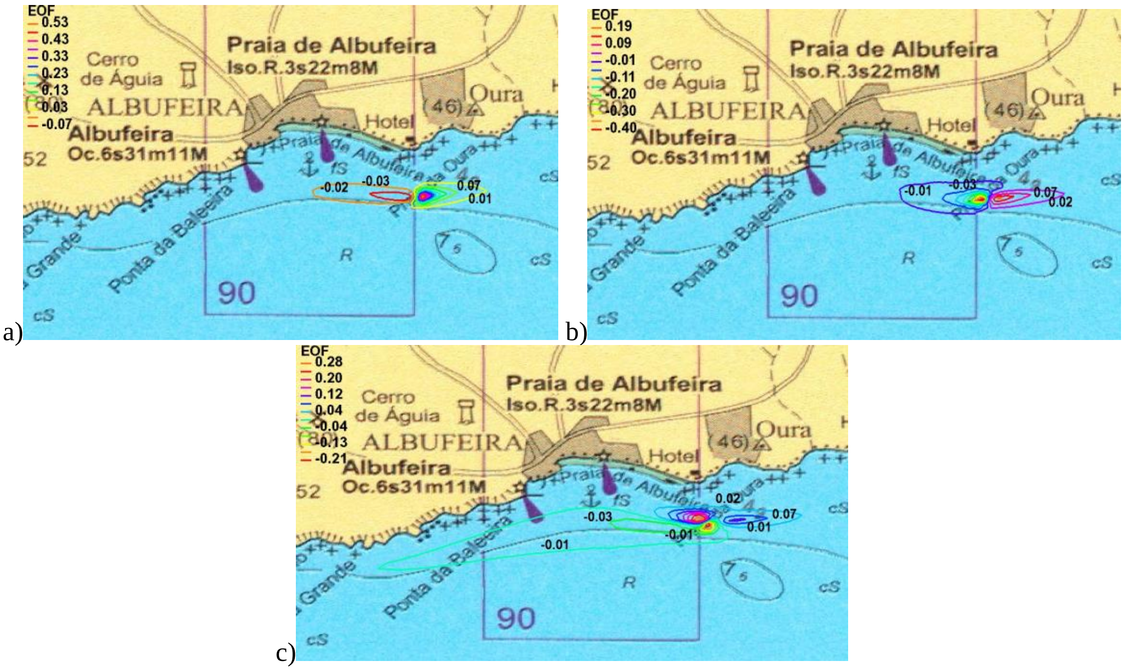


Figure 7. Spatial patterns of the first three EOF modes, presented as homogeneous correlation maps: a) $E_1(CF)$, b) $E_2(CF)$, c) $E_3(CF)$.

E_1(CF) and E_2(CF) exhibit east-west displacements that can be described by the Atlantic wind (Figure 7a) and the tide (Figure 7b). E_3 local variance increases towards the coast, characteristic of the local breeze (Figure 7c). Simulations considering only tide and no wind show the main influence of wind in that area.

11. Conclusion

This research study has described a risk assessment procedure for the project phase of submarine outfalls. The methods and tools used account for randomness and uncertainty, and are also conducive to cost optimization. This paper outlines the steps of a procedure that facilitates decision-making in regards to the target design levels for submarine outfalls, whatever the materials, techniques and elements used in their construction. This procedure is a revised and adapted version of the ROM 0.0 classification of maritime structures in terms of their general and operational intrinsic natures, based on various repercussion indices (Puertos del Estado, 2002; Losada and Benedicto, 2005). These indices evaluate the economic, social and environmental consequences of the most severe failure and stoppage modes.

This procedure was applied to the submarine outfall of Vale the Faro, located on the southern Portuguese coast. The numerical model (TELEMAC-2D) application quantifies the physical forcing mechanisms that govern the variability of the plume, and consequently of pollutants, in the studied coastal system and a relation is established between wind forcing and surface currents, where spatial variability of plumes is primarily determined by atmospheric forcing. The transport of a non-buoyant tracer (coliforms) was analyzed together with the probability of exceeding a representative threshold value whose occurrence may be significant to the operationality of the submarine outfall. Moreover, the persistence of the exceedance of that threshold value, the frequency and seasonality were also considered.

The methodology results are expected to help identifying the structure’s probability of failure or stoppage and the definition of operational target design levels enabling decision on project design alternatives. The outcome allows obtaining optimal yearly failure rates for pollutants and a rational and systematic procedure for the optimal design of submarine outfalls supporting the decision for management.

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