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MONOGRAPH

Microbial contamination and management scenarios in a Mediterranean coastal lagoon (Etang de Thau, France): application of a Decision Support System within the Integrated Coastal Zone Management context.

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Abstract

1 - In the Thau lagoon (Southern Mediterranean Coast) the main anthropogenic pressure is represented by the urban development in the watershed, whilst oyster and mussel farming represents one of the main economical activities in the region.

2 - During the last decade, the increasing organic loads from watershed and urban settlements in the lagoon surroundings have caused a diffuse contamination by faecal bacteria. Also toxic algal blooms have been occurring, impairing water quality with major impacts on shellfish farming, fishery and bathing.

3 - In this study, indicators and scenarios identified for the lagoon have been integrated in a Decision Support System (DSS) to evaluate the best solutions for reducing pressures and improving both water quality and ecosystem status.

4 - The watershed has been analysed with reference to indicators of pollution sources and transfer rates to the lagoon. In parallel, socio-economic indicators and descriptors of urban growth and development have been assessed. Numerical models have been run in order to simulate the lagoon hydrodynamics in relation to both meteorological factors and watershed runoff. The impact of faecal bacteria contamination has been evaluated in terms of economical losses and social conflicts, arising from the restriction of shellfish farming and marketing during contamination events. Finally, the DSS prototype has been applied to the lagoon in support to management and future planning.

Keywords: Mediterranean lagoon, watershed, bacteriological contamination, scenario analysis, Integrated Coastal Zone Management (ICZM), Decision Support System (DSS).

Introduction

Mediterranean coastal lagoons are among the most productive aquatic ecosystems with a great biodiversity, but they are also intrinsically fragile and highly sensitive to external forcing (Kierfve, 1994). A brief review of the most common pressures and perturbations occurring in coastal lagoons is reported by Aliaume *et al.*

(this volume). Common features of lagoons in the Southern European Arc are also the strong anthropogenic pressures and severe threats, which pose the question of both sustainable exploitation and environment conservation.

Among the sites considered by the EU Project DITTY, the Thau lagoon (Southern France) has been studied for faecal bacteria contamination in relation with shellfish farming which is one of the main economical activity (www.dittyproject.org). Various scenarios were implemented considering ecological, economical and social implications in the context of both Integrated Coastal Zone Management (ICZM) and sustainable development. Particular attention has been given to the development and application of a Decision Support System (DSS) prototype. The DSS addressed environmental management policies and measures; priority has been given to either the mitigation of bacterial contamination or the recovery of the water quality as well as the improvement of the overall ecological status, with reference to the Water Framework Directive (2000/60/EC)

Study area

Main characteristics and threats

The Thau lagoon is located along the Mediterranean coast of Southern France (Fig. 1; see also Aliaume *et al.*, this volume). The lagoon surface is 75 km^2 with an average depth of 4 m (max 10 m) and a water volume of approximately 280 km^3. The lagoon is connected North to the sea by the “canal of Sète” (90% of sea water exchanges) and South by the “Grau de Pisse Saumes”. The lagoon is under marine influence, and approximately one third of the lagoon water is exchanged with the adjacent sea each year. Hydrodynamics depends mainly on wind, tidal range being very narrow (< 10 cm). Strong North-West winds are blowing for more than 118 days per year, above level 5 on Beaufort scale. On average, water temperature and salinity range from minima of 5 °C and 27 in January and maxima of 29 °C and 40 in August, respectively.

The watershed surface is 280 km^2 and drained by a network of temporary small streams. Only the Vène river is permanent. Rainfalls show large inter-annual variations, from 500 to 1.100 mm y^{-1} (Tournoud *et al.*, 2000).

The watershed is densely populated (130,000 inhabitants, 465 inhabitants km^{-2}) and shows a positive and fast growing trend. Shellfish farming represents the main economical lagoon-based activity with an annual production of 13,000 t of oysters and 2,500 t of mussels . The Thau lagoon accounts for more than 10 % of the national French production of shellfish, the direct income of 750 small-scale producers and cooperatives is of 33,000,000 € y^{-1} (Rey-Valette, 2004).

The watershed-lagoon system is exploited for other activities which are in competition with shellfish farming ; it should be stressed that conflicts are often caused by the lack of resource allocation. Recreational and leisure activities are enhanced by a huge development of traditional and health tourism, water sports, scuba diving and hunting. Industrial and commercial activities are linked to Frontignan and Sète ports, the later being the first fishing port in the Mediterranean coast of France. Finally, the coastal zone is subject to a rapid urbanisation due to the vicinity of Montpellier city, which is of regional importance. Moreover, the Languedoc-Roussillon region is facing the country’s highest population flux.

Identification of environmental threats and related policies

The main environmental concerns for shellfish farming and fishery in the lagoon are the harmful algal blooms of *Alexandrium sp.* and *Dinophysis sp.*, faecal bacteria contamination, anoxia, alien species invasion, biodiversity loss and eutrophication.

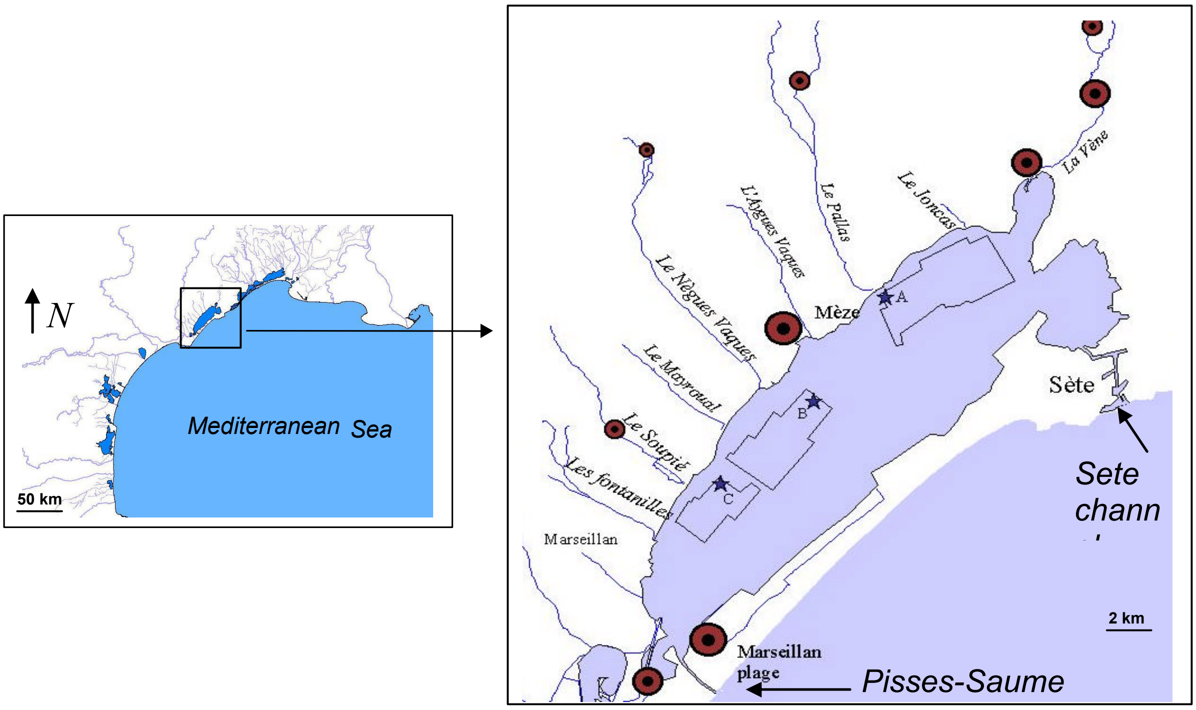


Figure 1. Thau lagoon location and major characteristics : hydrographic network, wastewater treatment plants (circles), shellfish farming zones (A, B and C) and connections to the sea (Sète and Pisse-Saumes channels).

The fact that the development of watershed-based activities could threaten the lagoon has been taken into account in the sector-based policy which was developed in an agreement between 19 municipalities around the Thau lagoon site (Vigne-Etang agreement). During the last decade, bacterial contamination from urban wastewater required an integrated watershed-lagoon management plan, which was established in 1995 (SMVM - Schéma de Mise en Valeur de la Mer). The SMVM focused on shellfish farming among priorities and options for the development of activities in the lagoon and its watershed. In order to reduce the microbial contamination, the implementation of wastewater processing plants was put in the frame of two agreements (Contrat d'Etang) among the main stakeholders. Notwithstanding the above mentioned actions, bacterial contamination of the lagoon water increased as well as gaps in knowledge and shortages in microbiological pollution control. A third contract (Contrat Qualité) was set up and implemented with reference to environmental management procedures (ISO 14001) and to water quality standards for both bathing water quality (regulation IT 178/2002) and production and marketing of bivalve molluscs (2006/7/EC Directive).

An integrated management of the lagoon and its watershed was also developed aiming at a better land use planning (SCOT - Schéma de COhérence Territoriale) and water management (SAGE - Schéma d'Aménagement et de Gestion des Eaux). Furthermore, most of the actions taken in the watershed-lagoon system were in agreement with the goals of the Water Framework Directive (WFD, 2000/60/EC), namely the achievement of a good ecological status of the lagoon ecosystem within 2015.

Overall, actions and management options allowed to identify the main threats and their causes. Among these, at present, the bacterial contamination is the main concern and depends on the influence of Mediterranean heavy rainy events associated to wastewaters works malfunctioning.

Considering the regulation context and the strong economic and social pressure on the watershed-lagoon system, the recovery of water quality standards and ecological status of lagoon and adjacent marine ecosystems constitutes a real scientific, technological, socio-economical challenge, that requires the development of new tools and approaches in an Integrated Coastal Zone Management context. Along with sustainable solutions for the main environmental problems, an integrated system for early warning becomes necessary to manage issues which cannot be solved in an economically acceptable fashion.

Most of those issues have been framed and analysed in the DITTY project. Specifically, for the Thau lagoon, the main objective was to support environmental policies and management in order to find out sustainable solutions for shellfish farming and bathing.

Methods and tools

Diagnosis of environmental and economical contexts

Based on the actions and studies mentioned above, the economic activities in the watershed-lagoon system were classified in three categories taking into account their pressures and impacts on lagoon and aquatic resources (Rey-Valette and Valette, 2005) :

- Specific activities related to the exploitation of the lagoon are shellfish farming, professional and non professional fishing, harbour activities, tourism, bathing, but also hunting , water sports, diving, nature discovery and watching,
- Activities in the watershed are mainly linked to agriculture and urban development in relation with the demographic trends and fluxes,
- Commercial and industrial activities are connected to the development of Sète harbour.

The assessment of present status and future trends was performed assuming different socio-economic and environmental factors which are summarised below :

- The urbanisation of the lagoon surroundings is leading to the development of a residential economy which depends on the daily migrations of about 14 % of the population to and from Montpellier city,
- Demographic dynamics vary among areas according to five sub-zones, which foreseen growth rates range from 8 to 72 % until 2020 (Fig. 2), - The lagoon surroundings provide up to 40 % of the tourist accommodation facilities of the Hérault department. An equivalent tourist flux is also related to second houses,
- Life quality and environmental standards are perceived in a different way by different population sectors,
- Agricultural areas cover 44% of the watershed surface, of which 80% are used for vineyards,
- The sanitary standards for waters used for shellfish farming and bathing are the main constraint for the lagoon exploitation. For example, since June 2004, due to faecal bacteria pollution the Thau lagoon was downgraded from A to B sanitary class according to European Directive 91/492/EC; as a consequence, to be put on the market purification of molluscs is compulsory.

Data handling and definition of index of bacterial contamination

Since bacterial contamination has been identified as the main concern for water quality and local economy, the first step in the DITTY project consisted in setting up of a logical scheme which summarises the main issues exposed hereupon (Fig. 3). According to the logical diagram the main factors involved in bacterial contamination were identified and assessed, namely watershed characteristics, typology of meteorological events, identification and characterisation of pollution sources, evaluation of wastewater infrastructures in the watershed, definition of a transfer index of pollutants from the watershed to the lagoon, identification of lagoon areas which are sensitive to bacterial contamination and contaminant transport within the lagoon. Impact and risk assessment, economical evaluation of risks and management options were also considered.

The main goal was to build up a set of indicators to assess the pollutant/bacterial contamination in the watershed and its transfer to the lagoon. The methodology used was based on a Geographical Information System (GIS) application with the support of a multicriteria analysis of the data sets (Fig. 4). A full description of methods used is reported in the technical reports of the DITTY project (www.dittyproject.org).

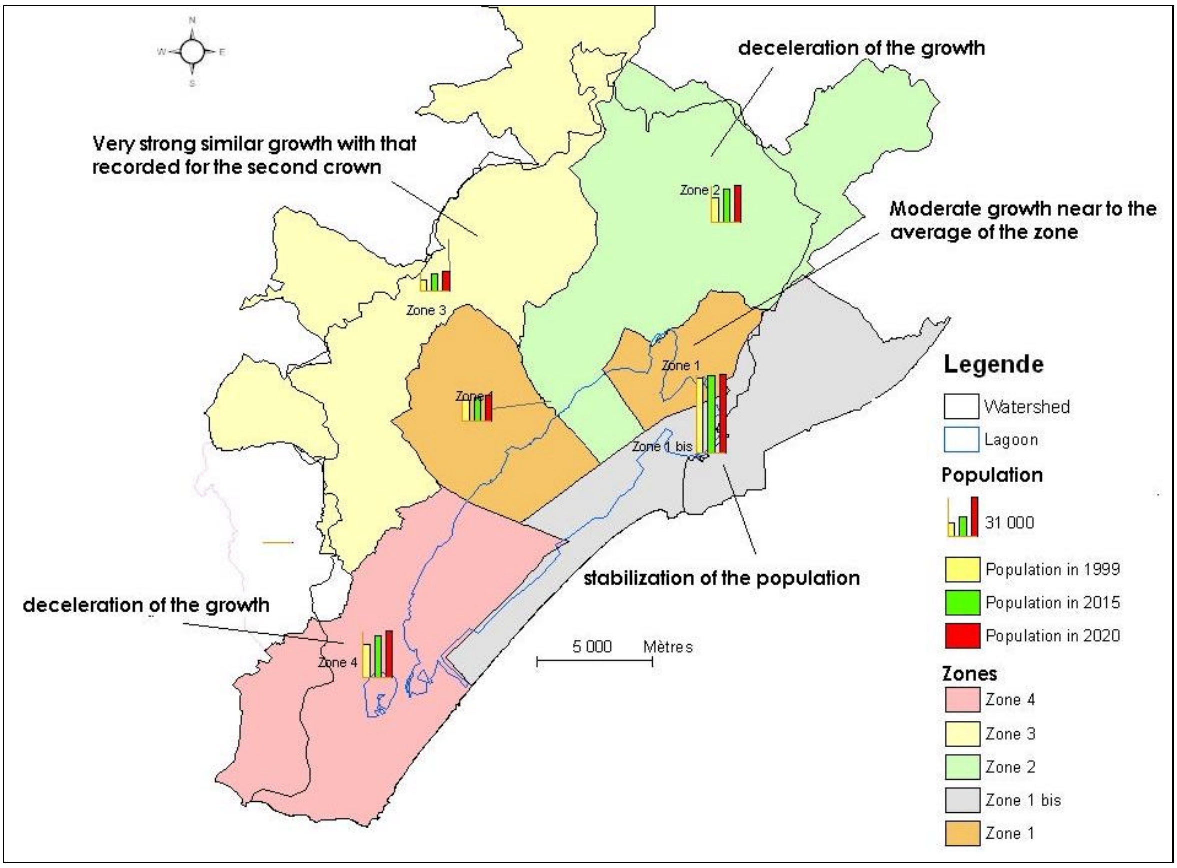


Figure 2. Demographic dynamics in the watershed of the Etang de Thau. Five zones were identified with different trends.

The transfer index of pollutants from watershed to the lagoon was defined by identifying critical environmental issues in the watershed (Musy, 2003). It is based on the availability of a slope map derived from a Digital Terrain Model of the watershed (Fig. 5a) and land use (Fig. 5b) and soils pedology types maps (Fig. 5c). The integration of slope, land use and pedology is realised using spatial analysis with GIS algebraic map computed in raster format (Fig. 5d) in order to obtain a first transfer index to the watershed. This index is then weighed according to the distance from the lagoon using GIS spatial analysis ; distance buffers of one km from the lagoon (Fig. 5e) was computed to produce an integrated transfer index from the watershed to the lagoon (Fig. 5f).

The Thau Basin Agglomeration Community (CABT) and the Northern Basin Community (CCNBT) are the bodies in charge of the wastewater processing for the Thau lagoon. A diagnosis protocol is performed for assessing the critical functioning of water treatment plants, aiming at identifying the infrastructure shortages which lead to sewages releases and bacterial contamination. The inventory and the location of infrastructures susceptible to cause a sanitary impact on the lagoon are archived in a georeferenced database. Using these data, indices of critical functioning have been calculated according to ISO 9001 and 14001 standards and based on the AMDEC methodology (Analyse des Modes de Défaillance, de leurs Effets et leur Criticité). The wastewater infrastructures and their critical indices are then mapped using the cartographic module of the GIS (Fig. 6). The combination of the integrated transfer index with the index of critical functioning gives an index of the lagoon sensitivity to bacterial contamination (Fig. 7). Here, the sensitivity is assessed in terms of potential risk linked to wastewater discharges into the lagoon.

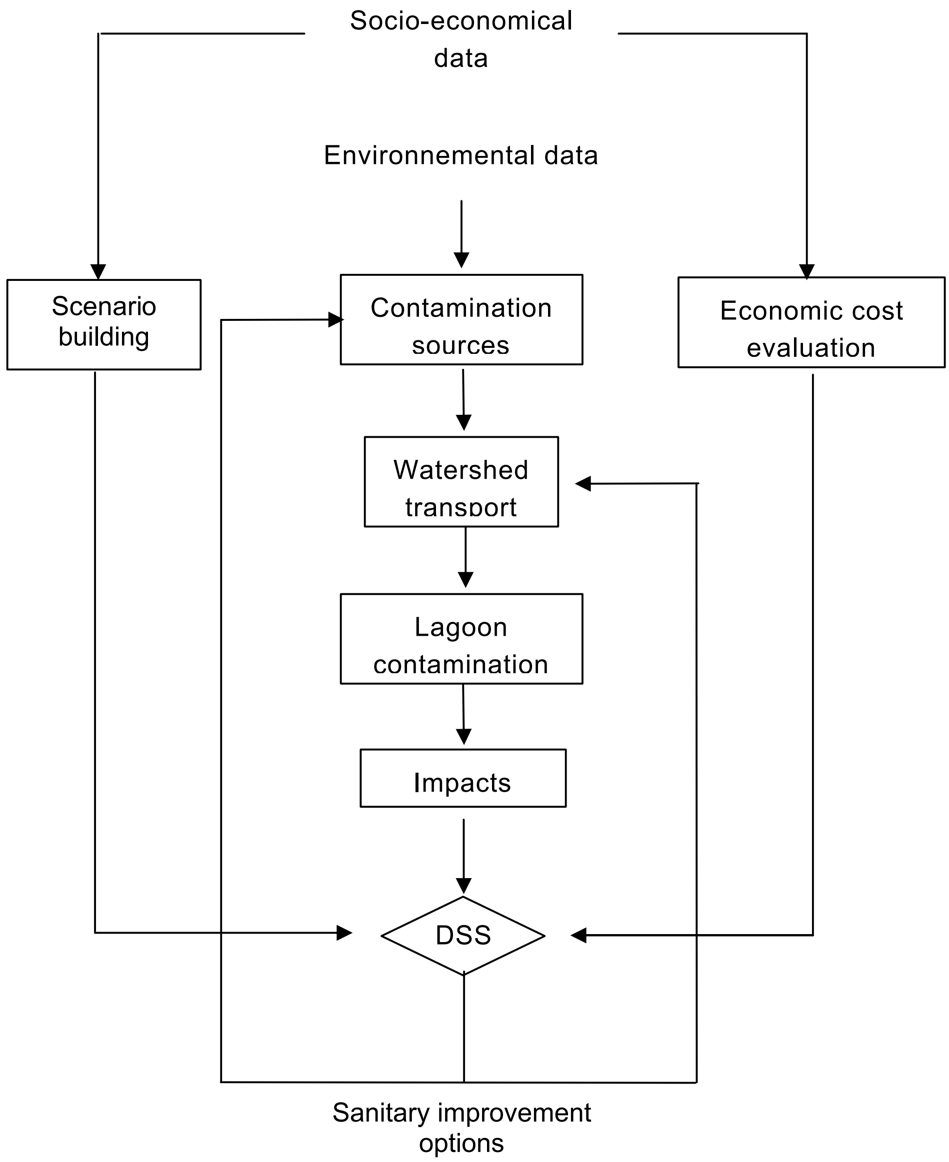


Figure 3. Conceptual scheme representing factors and processes involved in the bacterial contamination of the Thau lagoon.

Integration of socio-economic and demographic data in the environmental context

Pressures and impacts on the lagoon have to be analysed in the context of the recent demographic trend, which has been characterised by an annual average increase of 1500 inhabitants during the last 15 years (Valette and Rey-Valette, 2004). The overall demographic growth corresponds to a supplementary land occupation of 100 ha y^{-1}, of which 90 % is made of urbanised areas. Considering the watershed zones (Fig. 2) and a Business as Usual (BAU) scenario, one can foresee a saturation in the Eastern area and a demographic increase in the Western area which has been basically rural until now (Table 1). Due to the different degree of sensitivity to bacterial contamination, an increase of residential population in the Western area will have a greater impact on the lagoon followed by an increase of water pollution (Fig. 8). We also considered two options, based on different policy targets (Table 2). A more restrictive policy will increase environmental protection, whilst a support to the economic development of this zone, where the unemployment rate is among the highest in the department, will cause further impacts.

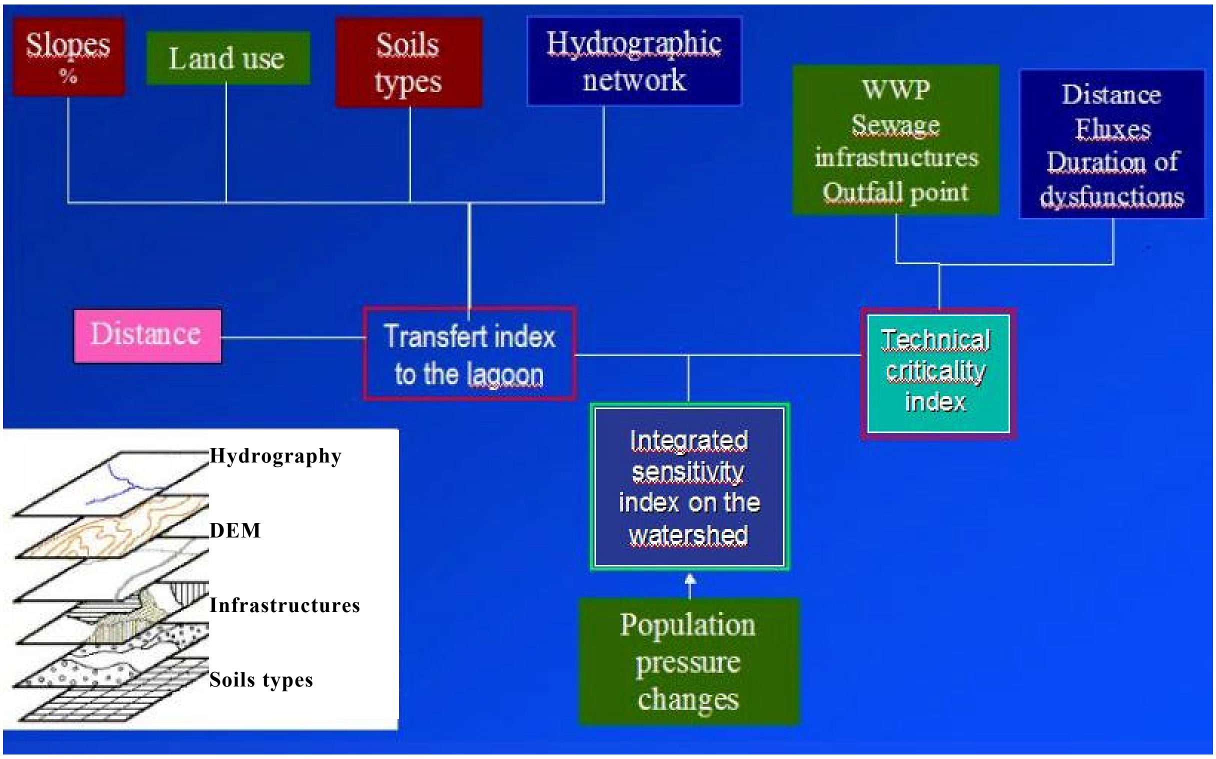


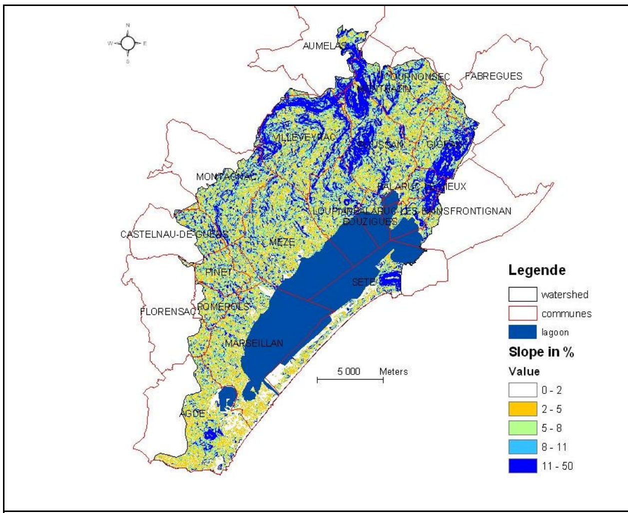
Figure 4. Flow chart describing the methodology developed to define an integrated sensibility index of the watershed.

Table 1. Demographic evolution *vs* wastewaters outlets. N: number of inhabitants, %: relative population increase as percent of the population in 2004.

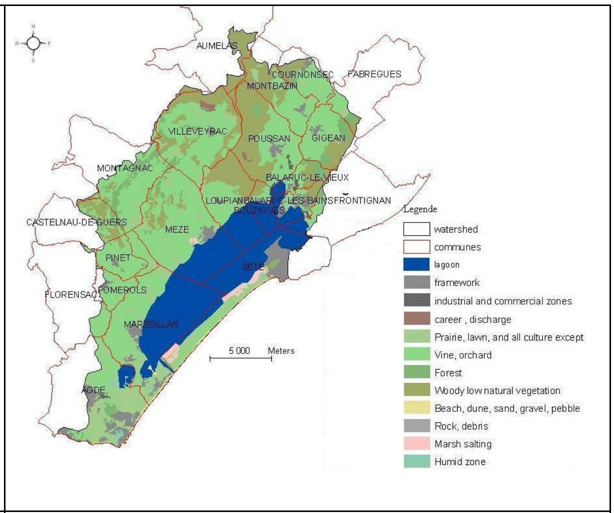
		Wastewaters outlets		Total
		Lagoon	Sea	
Population in 2004	N	36,172	93,333	129,505
Population increase by 2015	N	47,394	104,426	151,820
	%	+ 31	+ 12	+ 17%
Population increase by 2020	N	53,004	109,972	162,977
	%	+ 47	+ 18	+ 26%

Table 2: Demographic trends under different economic development options

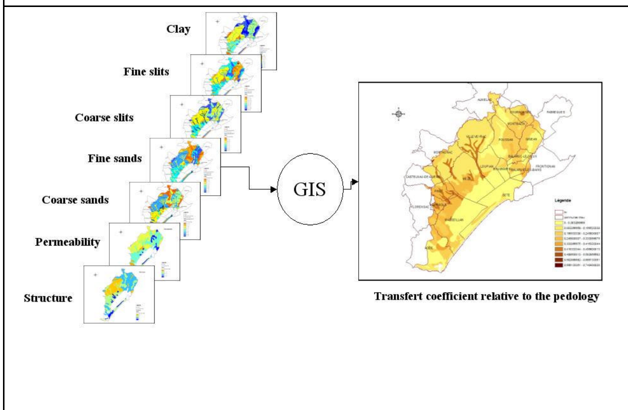
	Economic development	Population forecasts by 2015
Average hypothesis	Business as usual	151,820
Low hypothesis	Environmental issues, low population growth, increase of the social disparities	141,191
High hypothesis	Incentives to economy, strong population growth, employment increase, improvement of socio-economic conditions	182,220



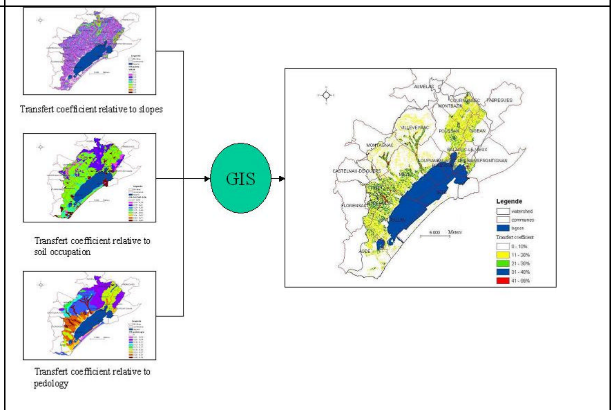
5a . Slope map of the watershed



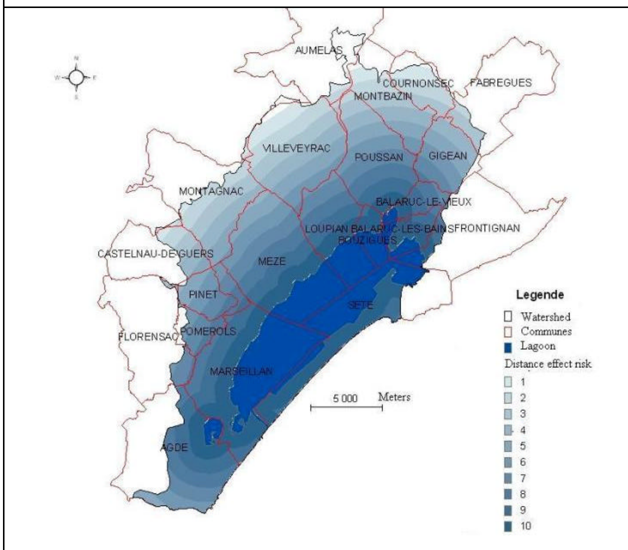
5b. Land use map (IGN data)



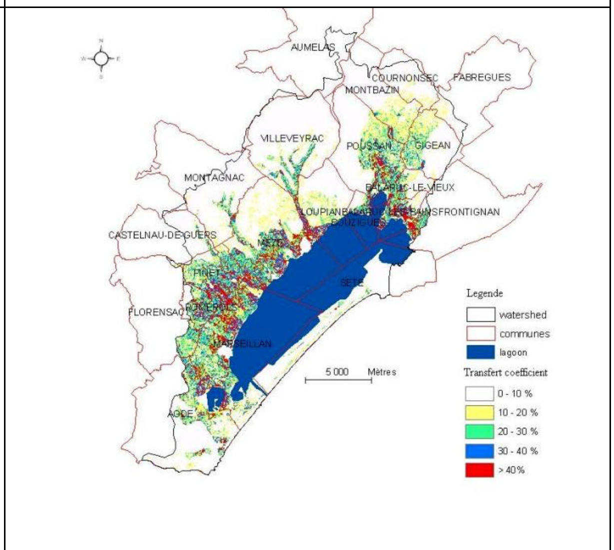
5c. Transfer coefficient related to pedology



5d. Integration of transfer indices (slope, land use, pedology)



5e. Transfer coefficient map related to the distance from the lagoon



5f. Integrated transfer index weighed by the distance from the lagoon

Figure 5. Parameters and different steps developed to achieve the representation of an integrated transfer index from the watershed to the lagoon. The figure displays the highest values of this index, i.e. zones where pollution sources may have a major impact according to the transfer risk to the lagoon.

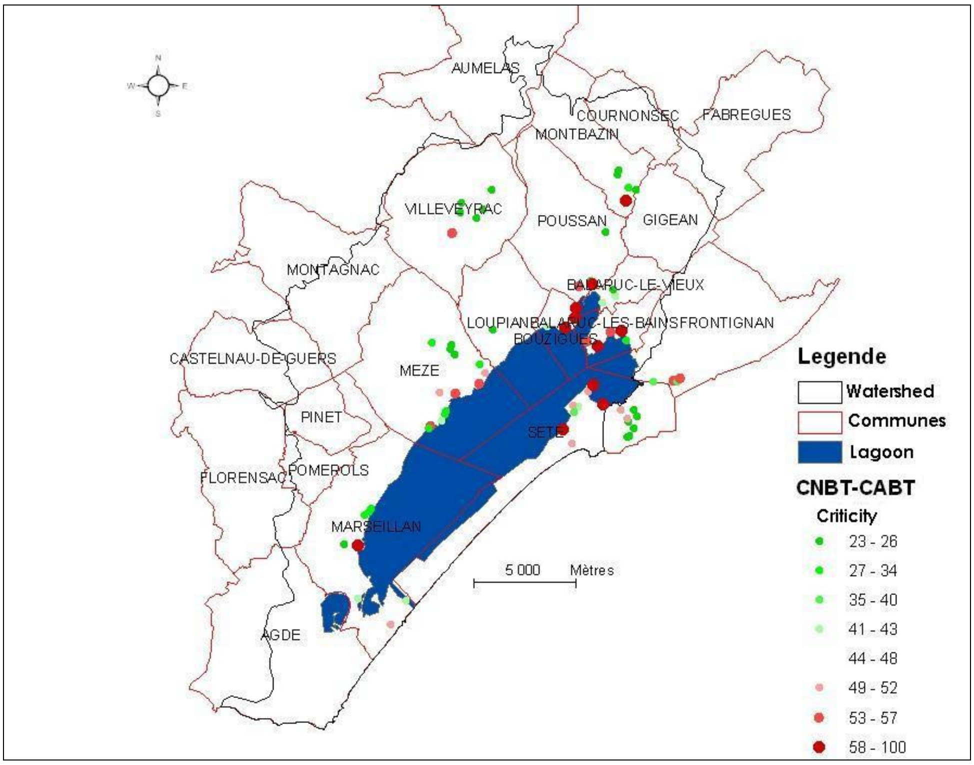


Figure 6. Location of the wastewater treatment infrastructures and their technical critical index. Red dots represent wastewater treatment plants with the highest critical index ; i.e. risk of potential malfunctioning.

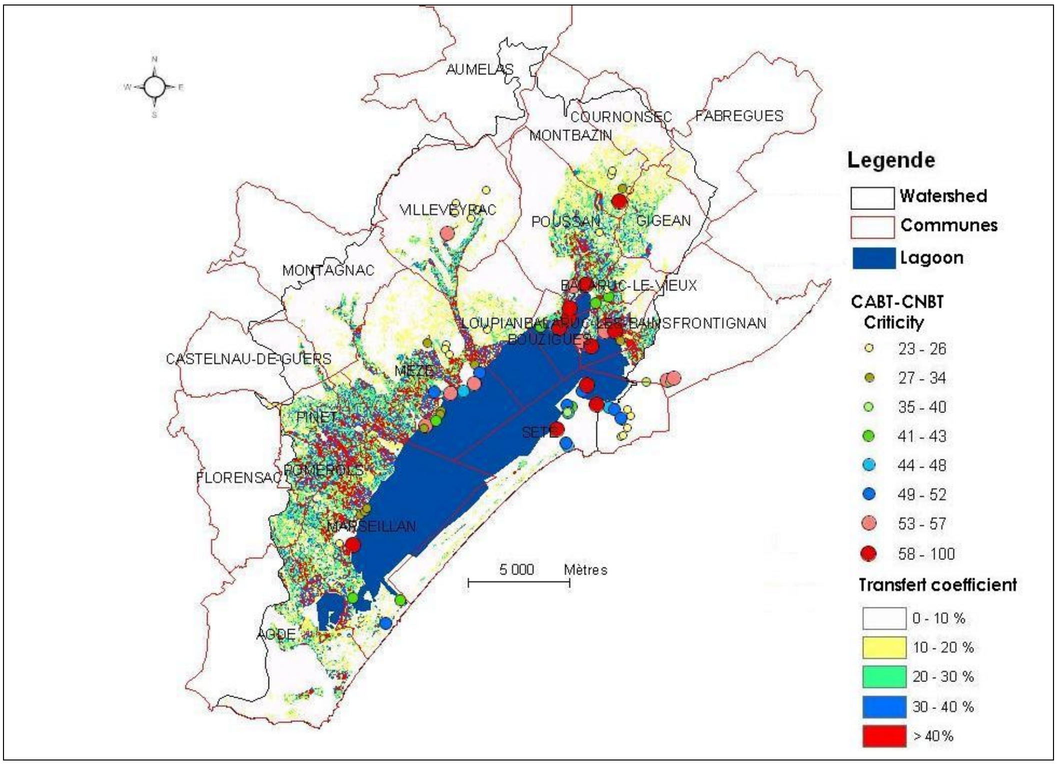


Figure 7. Spatial representation of the lagoon sensitivity to bacterial contamination from watershed.

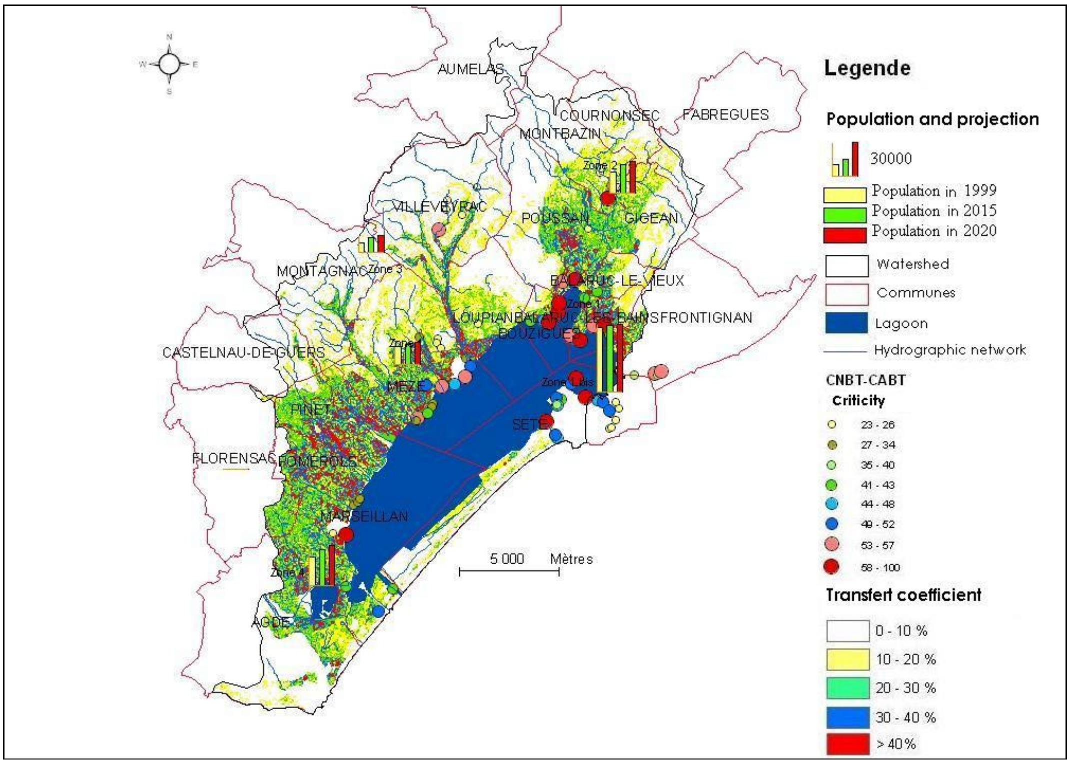


Figure 8: Integrated spatial sensitivity index in the watershed under a business as usual demographic trends.

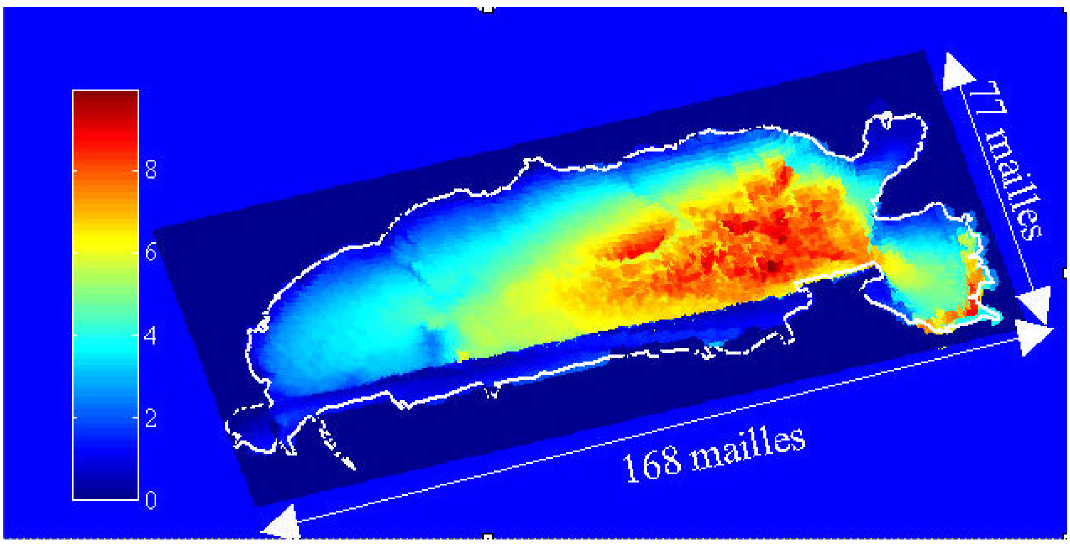


Figure 9. Grid structure (168x77) of the Mars 3D model and bathymetry (m) of the Thau lagoon (SHOM data)

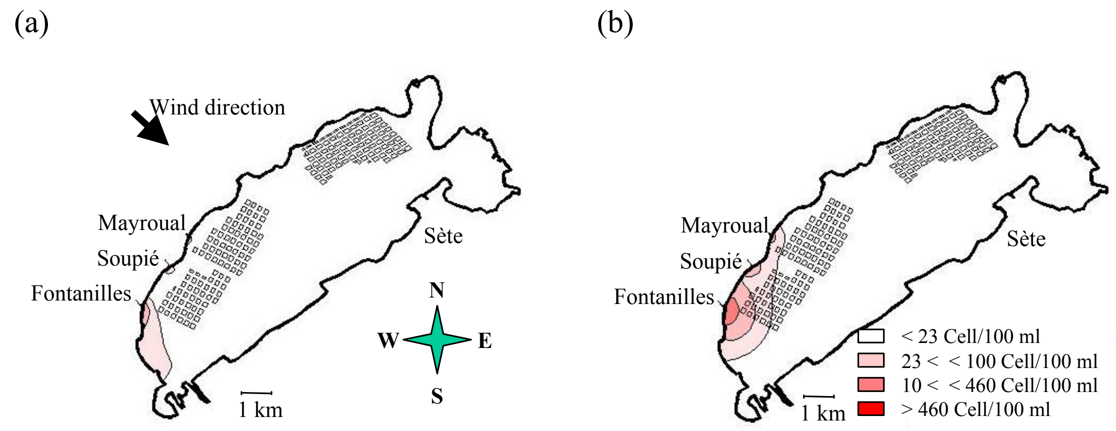


Figure 10. Spreading of bacteria plumes induced by Fontanilles, Soupié and Mayroual rivers. (a): NW wind. (b): No-wind condition. MAF with a NW wind are Fontanilles = 10^8 cells s^{-1}, Soupié = 10^7 cells s^{-1}, Mayroual = 10^7 cells s^{-1}.

Hydrodynamics and biological lagoon models for scenario simulation

The lagoon hydrodynamics was simulated using the MARS 3D hydrodynamic model which was designed to represent the transport and mixing of water masses on time scales varying from hours to days (Lazure, 1992). The model uses a finite difference scheme to solve the primitive equations of fluid mechanics under hydrostatic and Boussinesq approximations, with a barotropic-baroclinic splitting mode. The equations are solved using the technique of internal and external surface modes separation (Blumberg and Mellor, 1987). The external mode solves equations integrated on the vertical, which reproduce gravity waves. The internal mode collects information from the external mode (surface free, integrated currents) and solves equations on the vertical (three-dimensional current structure).

The current version of the Thau lagoon model has a 100 m horizontal resolution with a 77x168 mesh matrix and a 10 levels vertical resolution (Fig. 9). The bathymetric data used to define the calculation grid were collected between 1984 and 1987 (SHOM Data). The wind and pressure data are from Meteo France recorded at the Sète meteorological station.

Only the Sète canal was taken into account for analysing exchanges with the sea. The contribution of Pisse-Saumes canal was reasonably neglected, since it was assumed to be less than 5% of the water volume exchanged through the Sète canal (200 m^3 s^{-1}, CPER, 1997). The Thau watershed is drained by twelve temporary streams (Fig. 1). The available raw data included only daily measurements collected between 1994 and 1996 for the Pallas and the Vène rivers (CPER, 1997). No data are available for the remaining ten streams.

The transport of bacteria was estimated from simulated currents in the same way as for conservative physical tracers (salinity, temperature). The previous work by Martin *et al.* (1998) has been used as a basis for the biological model development. The biological module was then linked to the hydrodynamic model to simulate bacterial dynamics in the water column (mortality, sedimentation,…). Shellfish contamination was estimated with an enrichment factor, which allows to establish a relationship between bacterial concentrations in the water and in the shellfish (Prieur, 1990).

The model resolution is 100 m x 100 m. The meteorological forcing variables take into account air temperature, relative humidity and nebulosity, which are all necessary for the biological module. River discharge was defined with reference to bacterial inputs to the lagoon. It should be stressed that data were available only for the Vène and the Pallas streams, for which contamination by *Escherichia coli* was monitored during the autumn and spring floods.

In the Mediterranean area, sudden and strong rainfall events of short duration are often followed by long dry periods (Neppel *et al.*, 1998). As a consequence, the discharge of small coastal rivers undergoes wide fluctuations from near zero to flood regime. In the Thau watershed, bacterial contamination has been occurring after heavy rainfalls either in autumn or spring. Indeed, sudden floods may cause a washout in wastewater treatments plants as well as they can induce the suspension and transport to the lagoon of bacteria which previously accumulated in the river sediments during dry periods.

Simulation with the coupled 3D and biological models of the spatial distribution and duration of bacterial contamination in the lagoon shows that it is a function of the lagoon hydrodynamics, temporal distribution and intensity of rainfalls and river discharge which in turn influences the water residence time (Fiandrino *et al.*, 2003). During the flood events, due to the great hydraulic discharge the bacterial load is transported by the river plume and dilution processes are not sufficient to reduce the bacterial abundance. When the hydraulic discharge decreases the water retention time plays a major role, favouring bacterial die off through predation and sedimentation. The distance between river mouths and the shellfish farming areas is also a critical factor. When the distance is important, only during a flood event the bacterial load can reach the shellfish area (e.g. Vène river). When the distance between the river mouth and the farming area is short, even low but constant discharges of bacterial polluted waters could lead to a significant contamination of shellfish (e.g. Pallas river).

Based on the model simulations, for each freshwater outlet (of waste water treatment plant, wastewater network, pumping stations…) on the lagoon shoreline we defined a "Maximal Allowable Flux" (MAF) as the threshold above which farming zones are impacted by bacterial contamination (Table 3). According to the European Directive 2006/7/EC and given an enrichment factor 10, a farming zone is considered contaminated when the sanitary category shifts from class A to B. A stronger contamination entails its downgrading from class B to C. The threshold between categories A and B corresponds to an *E. coli* abundance of 23 cells 100 ml^{-1}, which is equivalent to 230 cells 100 g^{-1} of wet weight of shellfish flesh, whilst the limit between B and C are 460 cells 100 ml^{-1} or 46,000 cells 100 g^{-1}, respectively.

Table 3. Bacterial fluxes and their impacts on the lagoon under different wind conditions Numbers represent the power of 10, e.g. 7 correspond to 10^7 cell s^{-1}. Numbers in brackets represent the three main farming areas, namely (1): Bouzigues; (2): Mèze; (3): Marseillan. The Maximal Allowable Flux is highlighted in grey. NW: North-Western wind; NE: North-Eastern wind; SE: South-Eastern wind; NoW: No Wind (speed < 5 $m.s^{-1}$). VE: Vène, PA:Pallas, JO: Joncas, AI: Aiguilles, AY: Aygues Vaques, NEG: Negues Vaques, ME: Mèze, MA: Mayroual, SO: Soupié, FO: Fontanilles, MAV: Marseillan Ville, MAP: Marseillan Plage.

	VE	PA	JO	AI	AV	NE	ME	MA	SO	FO	MAV	MAP
NW	9 (1)	7 (1)	7 (1)	8 (1)	7 (2)	7 (2)	7 (2)	7 (2)	7 (3)(2)	8 (3)	8 (3)	7 (2)
NE	8 (1)	8 (1)	7 (1)	7 (1)	7 (2)	7 (2)	7 (2)	7 (2)	7 (3)(2)	8 (3)(2)	8 (3)	9 (2)(3)
SE	8 (1)	7 (1)	7 (1)	7 (1)	7 (2)	7 (2)	7 (2)	7 (2)	7 (3)(2)	7 (3)	7 (3)	9 (2)(3)
NoW	7 (1)	6 (1)	6 (1)	6 (1)	7 (2)	6 (2)	7 (2)	6 (2)	6 (3)	6 (3)	8 (3)	10 (2)(3)

In semi-enclosed lagoons, bacteria spread depends on wind-induced currents, which drive water mass circulation. Consequently, the MAF threshold has been defined under the worst meteorological conditions, i.e. lowest flux value damaging the shellfish production zone. Relationships between MAF and wind direction and strength are reported in Table 4. No wind conditions occurred over 45% of the year. Winds blowing from North-West occurred with a frequency of 35%, winds from South-East had a frequency of 15%, whilst winds from North-East were less frequent (5%). Since the coupled model is not validated, MAF values given here are not quantitatively reliable. However, a comparison between the bacterial fluxes from each river under the different wind conditions allow to define the worst meteorological condition for each outlet and then, the associated MAF. Since wind induces dispersion and mixing in the whole water column and favour the bacteria decrease, in most of the cases considered, the “no-wind” scenario is the worst. A simulation of two different wind conditions is presented in figure 10, where NE wind entails bacteria plumes to remain along the shore whereas the “no- wind” condition favours bacteria spread over a larger surface area.

Table 4. Economical cost of sales restrictions with reference to bacterial contamination and under different wind conditions. For symbols and acronyms, see table 3.

Period of the year	**Production zone**	**Economical loss (€)**	**No of contamination events per wind type**			
			NW	**NE**	**SE**	**NoW**
Summer	**Bouzigues**	1 246 681	0	2	0	0
	Mèze	576 158	2	1	0	3
	Marseillan	367 327	1	0	0	0
	Total	2 190 166	3	3	0	3
Christmas	**Bouzigues**	1 555 213	2	0	1	1
	Mèze	755 103	0	0	0	0
	Marseillan	501 241	0	0	0	0
	Total	2 811 556	2	0	1	1
Other periods	**Bouzigues**	226 325	0	0	0	1
	Mèze	107 669	0	0	0	0
	Marseillan	70 319	2	0	0	2
	Total	404 313	2	0	0	3

Indicators of bacterial contamination in the lagoon

Bacterial fluxes from rivers and point sources, associated to flood events and the associated MAFs are taken into account in the management options for the watershed. When the modelled bacterial flux is below the MAF, no action is needed; when it exceeds the MAF threshold, management measures have to address the critical steps e.g. in improving the wastewater treatment processes and the implementation of infrastructures. In order to estimate quantitatively the impact of a given bacterial flux on the shellfish production zones, an indicator was calculated ; it is defined by the percentage of the surface area which falls in a given sanitary class. For example, $EI^{B}_{1,2,3,G}$ is the percentage of surface area characterised by by the class B bacteria abundance (range 23-460 cells 100 ml^{-1}), where B is the sanitary class, 1, 2 and 3 correspond respectively to the shellfish production zones of Bouzigues, Mèze, Marseillan, whilst G is the sum of the three areas (General). Similarly, $EI^{C}_{1,2,3,G}$, is the indicator of the sanitary class C which corresponds to the percentage of lagoon surface where bacteria abundances are above 460 cells 100 ml^{-1}. For the MAF calculation and with a given bacteria input flux, the value of $EI^{B,C}_{1,2,3,G}$ depends on the wind conditions (Table 4). For instance, values of environmental indicators EI^{A}_{1} (ie. percentage of the Bouzigues zone's surface classified in A sanitary category: $EI^{A}_{1} = 100 - EI^{B}_{1} - EI^{C}_{1}$) associated to bacterial delivery from the Vène and Pallas rivers measured in 1994, fall between 0% ("no-wind") and 58% (North Western wind). Therefore, the influence of wind direction has to be taken into account as an external forcing factor in the Decision Support System.

Socio-economical indicators related to bacterial contamination of the lagoon

The relationship between bacterial contamination and local economy has been assessed considering the direct effect of commercial loss during shellfish market closure, i.e. when lagoon waters are in class C (Mathé *et al.*, 2006) in relation with the occurrence and duration of bacterial contaminations. This analysis has been performed with data from the national network on microbiological contamination monitoring (REMI) operated by IFREMER. The occurrence of contamination events has been studied from 2000 to 2005, considering marketing periods and production zones in the lagoon. The most important marketing period is November-December, in conjunction with Christmas time. June to September is also an important season for the sales due to summer holidays. During the rest of the year the sales levels were rather low and concerned mainly local and traditional customers. Broadly, the market closures account only for 2% of the surveys performed under REMI over the six years considered where contamination level was higher than 4600 *E. coli* 100 g^{-1}.

Most of the monitoring results were below the threshold limit of class A, ranging from 86% in Mèze to 74% in Marseillan. The major risk was measured in summer, with 12 % of the results exceeding the threshold of 4600 cells 100 g^{-1}, whilst in the rest of the year it was less than 5 %.

The economic cost of the market closure was assessed according to Mathé *et al.* (2006). The MARS-3D sampling grid was overlayed with shellfish farms cadastre surveys. For each grid the number of "tables" and of "ropes" of mussels and oysters was computed. Then, the production of oysters and mussels was calculated considering their location and data derived from the Evaluation Technical Committee of the lagoon. The model was implemented using zoo-technical characteristics of each farming zone, average annual yield, and oysters/mussels ratio for each zone.

The shellfish production was then translated into monetary value using the sale average price. In turn, prices are function of the marketing channels (wholesalers, retail dealers, markets…) which also depend on the exploitation size. Three size categories were selected according to the number of "tables" used for shellfish culture : small size (1 to 4 tables), medium size (5 to 8 tables) and large size (more than 8 tables). For each grid of the MARS-3D model, "tables" and exploitation typologies were defined so that for each grid cell an average price of sale was estimated and used to calculate the annual turnover. Sales data were also considered seasonally in order to take into account the periods of market closure. Data for each season were then processed in order to obtain the daily turnover. When data were not available for the Thau lagoon, information supplied by OFIMER and from local statistics (Gangnery, 2003) was used.

Based on this procedure, socio-economical indicators were implemented, i.e. $SEI_{1,2,3,G}$. The $SEI_{1,2,3,G}$ indicator was linked to external forcing factor (e.g. wind conditions) for each production area giving an estimate of the total economical costs of sales restrictions. The spatio-temporal distribution of the turnover loss allowed to evaluate the total economic cost of a sale restriction during 15 days, which is statistically significant in the case of Thau lagoon. An example of the estimated costs is given in Table 4.

These indicators are then standardized according to the total cost associated to a market closure (here 8 940 439 €). Standardized indicators are as follows: $SEI^{NW}_1 = 0.35$; $SEI^{NE}_1 = 0.28$; $SEI^{SE}_1 = 0.17$; $SEI^{NoW}_1 = 0.20$. It is then possible to proceed accordingly for all zones and for the whole lagoon.

A relevant socio-economic indicator related to watershed (SEW) was defined to complete the socio-economic description. As the bacteria flux for the Vène river during flood events is 3 orders of magnitude above the MAF, the SEW was defined as the cost of the improvement of the waste water treatment network required to reduce the bacteria flux to the MAF's limit.

Results

Towards a decision support system for the lagoon management under the influence of river basin-runoff

Following the model-based decision support structure developed in the framework of the EU project DITTY (Casini *et al.* 2005; 2007), a Decision Support System (DSS) for the management of the bacterial contamination in the Thau lagoon was implemented. The aim of the DSS is to rank possible future scenarios (each defined by a set of management options) according to given criteria. Each criterion is described by an indicator representing how the scenario performs with respect to that criterion. Multicriteria analysis tools, such as the Analytic Hierarchy Process (AHP), are then used to rank the scenarios when contrasting criteria are taken into account.

In the considered DSS, a scenario is defined by fixing a value of bacteria flux for each outlet. The "Business As Usual" scenario (BAU) corresponds to the current bacteria flux from each outlet. Other scenarios are generated by assuming a decrease of the bacteria flux of a given factor (2, 3,… orders of magnitude) for one or more outlets. The impact of each scenario is simulated using the hydrodynamic-biological model of the lagoon, which provides the microbiological impacts of the twelve main outlets on the whole Thau lagoon, and specifically on the shellfish farming areas. It is stressed that the model is a powerful tool both to understand biological processes and to support environmental management purposes, since it allows to perform sensitivity analysis on a given situation.

Since the actual bacteria fluxes of the BAU scenario are not completely known, we consider a "Reference" scenario based on bacterial outlets measured in 1994 for the Vène (10^{10} cells s^{-1}) and Pallas (10^9 cells s^{-1}) rivers (CPER, 1997). All the other fluxes have been arbitrarily set to zero. Different scenarios could be obtained by evaluating the bacterial fluxes induced by the expected increase of population in the watershed by 2015 (see Table 2).

Description of the decision support system

The decision support system was developed in order to characterise the water quality of the Thau lagoon with respect to bacterial contamination for any given scenario and to select different scenarios that end-users need to test on a hierarchical basis, according to budgetary, socio-economic and environmental constraints.

The conceptual diagram of the DSS is shown in Figure 11. For each of the twelve outlets, the MARS-3D model is run to simulate the impact of various bacterial fluxes. Simulation results are stored in a database. Note that, for any fixed scenario and wind direction, in each cell of the grid the bacterial abundance in the water column is assumed to be the sum of the contributions deriving from each outlet. The "transfer function" (see the transfer function box in Fig. 11) accounting for these contributions is hence the following:

[E.coli](x,y) = [E.coli](x,y)OUTLET1 + [E.coli](x,y)OUTLET2 + [E.coli](x,y)OUTLET3 + …,

where [E.coli](x,y) is the *E.coli* concentration at (x,y)-coordinates of the model grid.

Considering the definition of the socio-economic indicators, shellfish sales restrictions are enforced when the bacterial abundance in the water is above 460 cells 100 ml^{-1} (i.e. 4600 cells 100 g^{-1}) for at least one cell of a considered shellfish farming zone.

The above defined "transfer function" allows one to test an increase in the incoming bacteria fluxes. For instance, the MAF of the Pallas river is equal to 10^6 cells s^{-1} while the Pallas flux corresponding to the sanitary category C in the Thau lagoon is 10^8 cells s^{-1}.

The state of the lagoon with respect to bacterial contamination is described by a vector which contains the values of the considered environmental and socio-economic indicators (see Fig. 11). Wind influence can be taken into account in the definition of the environmental indicators in various ways.

- One can set a particular wind condition. Then, values of environmental indicators are those defined for that specific wind condition. In Mediterranean climate, rainfall events are often associated to South-Eastern wind, while the most frequent is the North-Western wind.
- One can select a "mean year" with respect to meteorological conditions. In this case, statistical analysis based on the distributions of wind direction during past decades allows one to balance the indicator values according to a "weighted wind". For example, during a "mean year" the following weights can be used: 35% for North-Western wind, 5% for North-Eastern wind, 15% for South-Eastern wind, 45% for the "no-wind" condition (speed less than 5 m s^{-1}).

Table 5 shows the surface percentage of the three shellfish production zones which are classified in sanitary class "B" or "C" under the simulation of the "Reference" scenario. It is stressed that environmental indicators have a large variation range depending on the wind direction. For instance, when considering the Bouzigues zone: (EI^B_1;EI^C_1) = (93%; 6%) for the South-Eastern wind condition; (EI^B_1;EI^C_1) = (39%;3%) for the North-Western wind condition; $EI^B_1 = 0.35×39 + 0.15×64 + 0.05×93 + 0.45×30 ≈ 41\%$ and $EI^C_1 = 33\%$ if one is interested in a weighted "mean-year" wind condition.

If bacterial contamination exceeds 4600 cells 100 g^{-1} (sanitary class C), shellfish sales restrictions will occur on the basis of the socio-economic indicators. Values obtained under the three aforementioned wind conditions in the Bouzigues zone are: $SEI_1^{SE} = 0.17$ (South-Eastern wind); $SEI_1^{NW} = 0.35$ (North-Western wind); and $SEI_1^{MeanYear} = 0.72$. Note that $SEI_1^{MeanYear}$ is again the weighted sum of the values of the socio-economic indicator in each particular wind condition (NW, NE, SE, and no wind). The "mean-year" wind condition is the most "constraining", both considering the environmental and the socio-economic indicators, since it takes into account also the worst conditions observed (the "no wind" condition, see Table 5).

Table 5. "Reference" scenario: Percentage of the lagoon surface classified in sanitary class "B" and "C" in each shellfish production zone (Bouzigues, Mèze, and Marseillan) under four wind conditions (NW, NE, SE, no wind). Percentage of surface in "A" category is equal to 100 – $EI^B_{1,2,3}$ – $EI^C_{1,2,3}$.

	Bouzigues		Mèze		Marseillan	
	B	C	B	C	B	C
NW	39	3	11	0	0	0
NE	64	0	83	0	17	0
SE	93	6	0	0	0	0
No Wind	30	70	26	0	0	0

From model results to scenario analysis

Scenario results: vector of indicators

For a given scenario and the corresponding bacteria inputs, the DSS first builds the vector of indicators, which is composed by four socio-economic indicators for the lagoon (SEI_1, SEI_2, SEI_3, SEI_G), six environmental indicators (EI^B_1, EI^C_1, EI^B_2, EI^C_2, EI^B_3, EI^C_3), and one socio-economic indicator for the watershed (SEW), i.e.

I = [SEI_1 SEI_2 SEI_3 SEI_G EI^B_1 EI^C_1 EI^B_2 EI^C_2 EI^B_3 EI^C_3 SEW].

The vector I is representative of both environmental and socio-economic impacts of a particular scenario. For instance, the resulting vector I for the "Reference" scenario and a "mean-year" wind condition turns out to be

I = [0.72 0 0 0.86 41 33 28 0 2 0 0].

The cost related to the watershed is not taken into account, i.e. SEW is set to zero. Moreover, 33% of the farmed surface of the Bouzigues zone is in sanitary category C. Since Mèze and Marseillan zones are never in sanitary category C ($EI^{C}_{2,3}$ = 0), there are no shellfish sales restrictions for these two production zones ($SEI_{2,3}$ = 0). However, all the three production zones have cells in sanitary category B.

The DSS could help the end-user to identify the best way to recover sanitary category A in the whole lagoon. However, to correctly use the DSS results, it is important to acknowledge that the values of environmental indicators are strongly sensitive to the wind conditions. Hence, robustness analysis is always recommended.

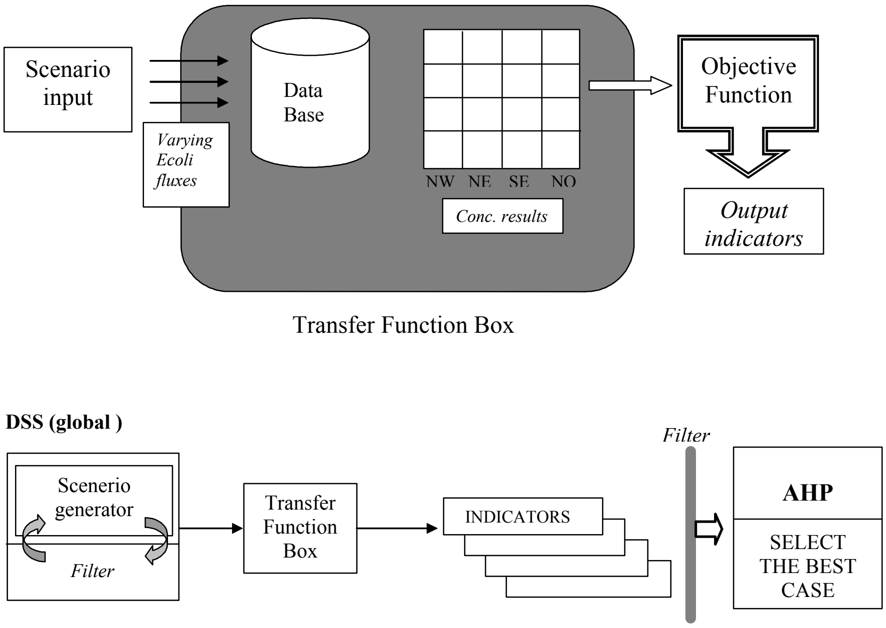


Figure 11. Conceptual diagram of the decision support system for the management of the bacterial contamination in the Thau Lagoon.

Scenario analysis

Different simulated scenarios can be ranked according to the specifications of the end-users by resorting to suitable multi-criteria analysis tools. In the presented application, the AHP was used. In the AHP method (Saaty, 1980), the end-users first have to define the relative importance of the criteria by means of simple pairwise comparisons. Then, the method computes weights for the criteria based on those pairwise comparisons. In the Thau Lagoon, the main goal is to avoid sales restrictions and hence, to have low values of $SEI_{1,2,3,G}$. Then, it becomes important to reduce the bacterial spreading in zones 1, 2 and 3 (following the order of importance). Finally, the improvement of the watershed water quality is the less important criterion.

The AHP method assigns a score to each scenario by a weighted sum of the corresponding values of the environmental and socio-economic indicators. Weights are those defined by the end-users through the pairwise comparisons of the criteria. It is then possible to rank the scenarios by ordering the scores.

For a reliable application of the DSS, it would be needed to estimate also the SEW indicator, i.e. to quantify the cost necessary to decrease bacterial delivery from every sub-watershed. Nevertheless, preliminary simulations foreshadowed interesting results in the simple case of considering only the Vène and Pallas rivers. In this simplified example, it was assumed that the initial bacterial fluxes were 10^{9} cells s^{-1} and 10^{10} cells s^{-1} for the Pallas and Vène rivers, respectively. In addition, it was also assumed that reducing the bacterial fluxes by one order of magnitude costs two units for the Pallas river ($SEW_{Pallas} = 2$) and one unit for the Vène river ($SEW_{Vene} = 1$). Each cell of Fig. 12 describes a possible scenario in which bacterial fluxes due to the Pallas and the Vène river are of the order of magnitude in the corresponding column and row, respectively. The value in each cell is the position in the scenario ranking according to the AHP. Clearly, the best solution corresponds to the maximum reduction of the bacteria fluxes in both rivers, i.e. when the bacteria flux of the Pallas river is reduced to order of magnitude 106 cells s^{-1}, and that of the Vène river is reduced to order of magnitude 10^8 cells s^{-1}. The worst solution (12th in the rank) corresponds to the initial solution. A detailed analysis of the indicators shows that the Thau Lagoon remains in sanitary category B only in the first four ranked scenarios. In still more detail, the Bouzigues zone is never able to recover the sanitary category A, whereas the Mèze zone reaches the A class in the first eight ranked scenarios, and the Marseillan zone is in the A class in the first nine ranked scenarios.

1 u. 1 u. 1 u.

Vène \ Pallas	10^9	10^8	10^7	10^9
10^{10}	12th	9th	8th	7th
10^9	11th	6th	4th	3rd
10^8	10th	5th	2nd	1st

2 u. 2 u

Figure 12. Scenario ranking corresponding to varying bacterial loading in the sub-watersheds of the Vène and Pallas rivers. Labels for rows and columns represent the order of magnitude of *E. coli* fluxes.

General conclusions

This paper introduced a set of results acquired in the framework of the EU Project DITTY, where original methodologies were applied to the setting up of indicators to be used in a DSS with the view to optimise the environmental management of a coastal lagoon under the direct influence of watershed management constraints.

Even if the case study chosen is limited to the bacteriological contamination impacts on the water quality and activities (mainly shellfish culture) of the Thau Lagoon, this paper intends to express the complexity of the issues and to propose some solutions. Solutions derived from the proposed methodology offer the building up of bridges between environmental and socio-economical approaches applied both to the watershed and the lagoon. Of course the actual integration on a territorial point of view (watershed, lagoon, sea) and on a thematic one (natural driving forces, human behaviour, regulations, economy, etc.) is not achieved.

This preliminary study points out the interest of the setting-up of a DSS, even if some improvements are still necessary. Indicators were defined and gathered in a vector defining the socio-economic and environmental state of the system, and summarizing the impacts of bacterial fluxes from the outlets on the Thau lagoon water quality. This first work allowed also to identify relevant indicators as, for instance, the MAFs, which are useful to define priorities among actions to be taken to improve the bacteriological quality of the lagoon and of its sub-areas used as shellfish growing zones. In addition, a possible use of the DSS tool (not detailed here) is to fix constraints on indicators before implementing the scenario analysis in order to select particular scenarios. For instance the end-users can impose to test only scenarios that satisfy i) recovering the sanitary category A for the whole lagoon and ii) the exclusion of any zone in sanitary category C, etc.

However, several improvements are necessary to make the DSS operational. That is why new developments and follow-up actions of the DITTY project have been identified on the Thau Lagoon area. Management tools exposed here are to be set up to reach such goals with reference to the ICZM (Integrated Coastal Zone Management) approach. They will deal with ten main issues :

- a better understanding and modelling of flux transfer from the watershed contamination sources to the lagoon.
- the acquisition of knowledge and measurements of the actual bacterial fluxes reaching the lagoon (BAU scenario), which need to be enhanced before going further.
- the validation of the coupled model in order to estimate realistic MAF for each outlet.
- the validation of the biological model with reference to the benefit for the shellfish of the lagoon water enrichment and microbiological processes.
- an economical evaluation of the waste water processing improvements for all sub-watersheds in order to propose and choose the best solutions as to optimise the quality of the water reaching the lagoon.
- the improvement of the definition of socio-environmental indicators. At present they are based on statistical analysis of the REMI network results. However, these statistics do not take enough into account actual and significant events. They should be extended to a larger period of time and to more type of events (e.g. critical periods).
- the sensitivity of the DSS results to the chosen criteria has to be tested, using various weighting parameters.
- the setting up of management options taking more into account the major driving forces in the area, with reference to the climate change and to the human being prospects.
- the question of the structure of shared operational information database (Barde et al, 2005).
- the question of setting up objective information, representing the various indicators on natural environment, human pressures and trends (Loubersac *et al.*, 2004), and also the question of communicating in an integrated way and in a free access mode, of information to the stakeholders as well as to the general public, within the framework of a participative approach.

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Appendix: Symbols and Acronyms

AHP: Analytic Hierarchy Process
CABT: Communauté d'Agglomération du Bassin de Thau
CCNBT: Communauté de communes du Nord du Bassin de Thau
CPER: Contrat de Plan Etat Région
DITTY: Development of an Information Technology Tool for the Management of European Southern Lagoons under the influence of their watersheds
DSS: Decision Support System
ICZM: Integrated Coastal Zone Management
MAF: Maximal Allowable Flux
OFIMER: Office National Interprofessionnel des Produits de la Mer et de l'Aquaculture (National Interprofessionnal Office for Sea and Mariculture Products)
SAGE: Schéma d'Aménagement et de Gestion des Eaux, (Water Management Plan)
SCOT: Schéma de Cohérence Territoriale (Territorial Coherence Plan)
SHOM: Service Hydrographique et Océanographique de la Marine (Hydrographic and Oceanographic Office Survey)
SMVM: Schéma de Mise en Valeur de la Mer (Marine Activities Development Plan)
WFD: Water Framework Directive
WWI: Waste Water Infrastructure
WWP: Waste Water Plants