

RESEARCH ARTICLE

A Multidisciplinary and Ecosystemic Approach in the Oristano Lagoon-Gulf System (Sardinia, Italy) as a Tool in Management Plans

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Abstract

- 1 - This paper provides an overview of some of the research activities carried out in the Oristano Lagoon-Gulf system (western Sardinia, Italy) aimed at assessing the ecological quality of a complex transitional-coastal system renowned for its naturalistic and economical value, but subject to an increasing anthropogenic pressure.
- 2 - Numerical models concerning physical and ecological processes have been applied, including a fully coupled hydrodynamic-ecological model based on the finite element method, suited for application to lagoons and coastal seas. Different scenarios characterized by modified settings of the hydraulic balance between the Gulf of Oristano and the Cabras Lagoon have been considered and numerical simulations have been carried out to predict the evolution of both hydrological and ecological variables within the system under different meteorological forcing.
- 3 - Parallel investigations on the physical and chemical characteristics of the sediments and macrobenthic assemblages have been conducted in the Cabras Lagoon and the adjacent coastal area of the Gulf of Oristano. These studies have shown a close link between the distribution of organic-C bounding fine sediments (<8 µm grain size fractions) and benthic macroinvertebrates, and the water residence times computed from the model. In the Gulf, the structural and functional importance of *Posidonia oceanica* and *Cymodocea nodosa* seagrass meadows in sustaining a high biodiversity and as a natural trapping of fine particles is highlighted.
- 4 - Studies on the effect of hypoxia on ecophysiology, energetics and behaviour have been carried out on the various species of lagoon fishes (*Liza aurata*, *Mugil cephalus* and *Dicentrarchus labrax*), with the specific goal of identifying the thresholds for the effects of hypoxia, a common phenomenon occurring in coastal lagoons, on various physiological and behavioral traits (e.g. swimming energetics, escape performance). The results show that these thresholds ranged from 10 to 50% of air saturation, and were species- and variable-specific.
- 5 - Our multidisciplinary and ecosystemic approach, applicable to other similar systems, is aimed at supporting local administrations in decision making with regard to the management of the transitional and coastal waters of the Oristano Lagoon-Gulf system within the context of the European Water Framework Directive (WFD; EC, 2000).

Keywords: hydrodynamic-ecological modeling, transport, sediments, macrobenthos, fish, ecological indicators, coastal management, Mediterranean coastal lagoons, Water Framework Directive.

Introduction

The Oristano Lagoon-Gulf system comprises the Gulf of Oristano (150 km²; maximum depth 24 m) and several salt marshes and lagoons (which cover a total area of 46 km²) (Fig. 1, Table 1). The salt marshes and lagoons in the Oristano system are shallow eutrophic water bodies (approximately 0.5-2 m depth). The lagoons of the Oristano system are known for their naturalistic value (e.g. several of which are part of the Ramsar Convention on Wetlands and the Natura 2000 network following the EU habitat directive) and economical importance (e.g. artisanal fisheries) (De Falco and Piergallini, 2003). In

addition, the Gulf of Oristano is adjacent to a Marine Protected Area (the MPA of Sinis-Maldiventre), which is an important site for tourism peaking in the summer months.

However, Oristano lagoons have recently experienced high anthropogenic pressure due to massive nutrient loading, reduction of freshwater input from upland, modifications of the inlets and other man-made interventions (Table 2), which have reduced the water exchange with the Gulf of Oristano (Ferrarin and Umgiesser, 2005; Como *et al.* 2007). This has led to periodic environmental crises, with the occurrence of dystrophic events causing

Table 1. Main features of the lagoons connected to the Gulf of Oristano (western Sardinia, Italy).

Lagoon	Surface Km ²	Mean Depth	Max. Depth	Volume Mm ³	Freshwater Inflow	Habitat Type
Cabras	22.3	1.7	3	33.4	Yes	Brackish-Marine
Mistras	4.7	0.5	1	4	No	Marine-Hyperhaline
Santa Giusta	8.4	1.5	1.9	12.6	Yes	Brackish-Marine
S'Ena Arrubia	1.2	0.4	0.8	0.5	Yes	Brackish
Corru de S'Ittiri	1.5	0.8	3	4.5	No	Marine
Marceddi - San Giovanni	8.0	1	2	8	Yes	Brackish

Table 2. Main man-made interventions on the lagoons connected to the Gulf of Oristano (western Sardinia, Italy).

Cabras	Dam construction, digging of the <i>Scolmatore</i> channel, elimination of the pond "Stagno Sa Mardini", water renewal impairment due to barriers, construction of the fish-pond "Sa Mardini", barriers at "Rio Mare e' Foghe".
Mistras	Construction of a fish-pond and aquaculture facilities
Santa Giusta	Separation of the "Pesaria" channel from the Tirso river, direct connection with the sea and construction of a fish catch system; digging and construction of 2 m deep central and peripheral canals; construction of an industrial port and an industrial canal communicating with the sea; construction of a diversion canal of urban wastes.
S'Ena Arrubia	Digging and construction of a central canal and a canal connecting to the sea; construction of various-size barriers and fish-pond.
Corru de S'Ittiri	Construction of barriers and fish-pond.
Marceddi - San Giovanni	Construction of barriers, dams and " <i>lavorieri</i> ".

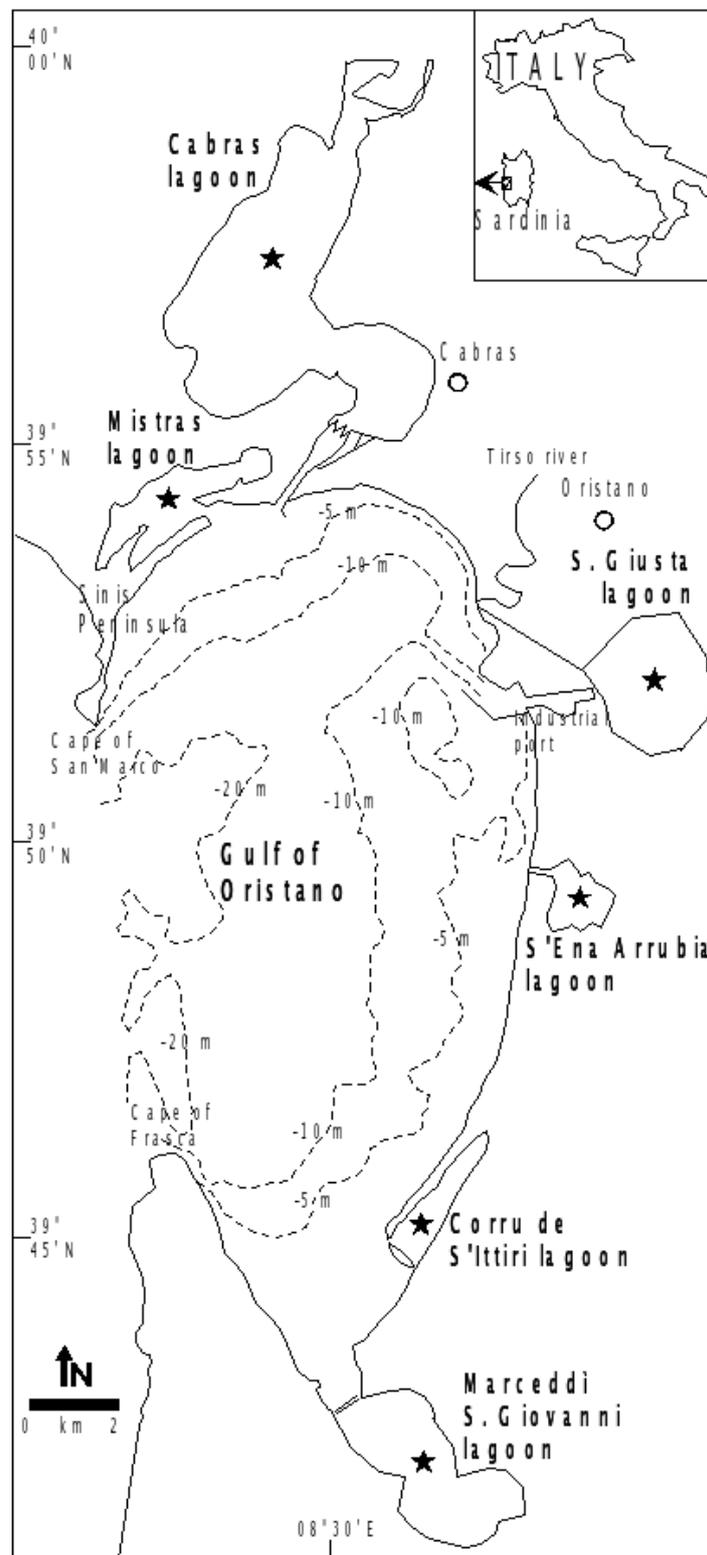


Figure 1. The Oristano Lagoon-Gulf system (western Sardinia, Italy). The six main lagoons connected to the Gulf of Oristano (i.e. from north to south: Cabras, Mistras, Santa Giusta, S'Ena Arrubia, Corru de S'Ittiri, and Marceddi-San Giovanni) are indicated by stars.

massive benthos and fish kill (Murenu *et al.* 2004; Magni *et al.* 2005a; 2008a). In addition, other pollution-related problems posing serious health and management issues have been recently related to the presence of intensive agricultural and dairy activities (Magni *et al.* 2006). Until the early nineties, mining was present in the catchment area of the Gulf of Oristano, particularly in connection with the drainage basin of the Marceddi lagoon in the southernmost sector of the Gulf (Cucco *et al.* 2005; Magni *et al.* 2006). Also, in the Gulf of Oristano, the distribution of *Posidonia oceanica* meadows, which cover about 70% of the total seabed surface (Cancemi *et al.* 2000), is influenced by an anthropogenic impact due to fine-sediment deposition related to dredging and port building (De Falco *et al.* 2000a; 2006). In several lagoons of the Oristano system, grey mullets (Mugilidae) and seabass (*Dicentrarchus labrax*) are the target species of artisanal lagoon fishery which represents the main economic activity in the lagoons (Murenu *et al.* 2004; Magni *et al.* 2008a). The Gulf of Oristano also supports an offshore seabass fishery. Farmed seabass cages are present in the central part of the Gulf. Leisure and recreation attractions for a small tourist industry is provided also by the landscape and the beaches, as well as the local fauna (e.g. bird watching). Management issues between fishermen and conservationists have recently arisen because of the presence of piscivorous birds, particularly cormorants, feeding in high numbers on the lagoon fishes.

This paper aims to provide an overview of the research activities and the multidisciplinary and ecosystemic approach conducted in the Oristano Lagoon-Gulf system (western Sardinia, Italy). Some of the main results are presented and discussed in the light of their potential support to local administrations, as well as their relevance for the monitoring and the ecological quality assessment of Oristano Lagoon-Gulf system within the Water

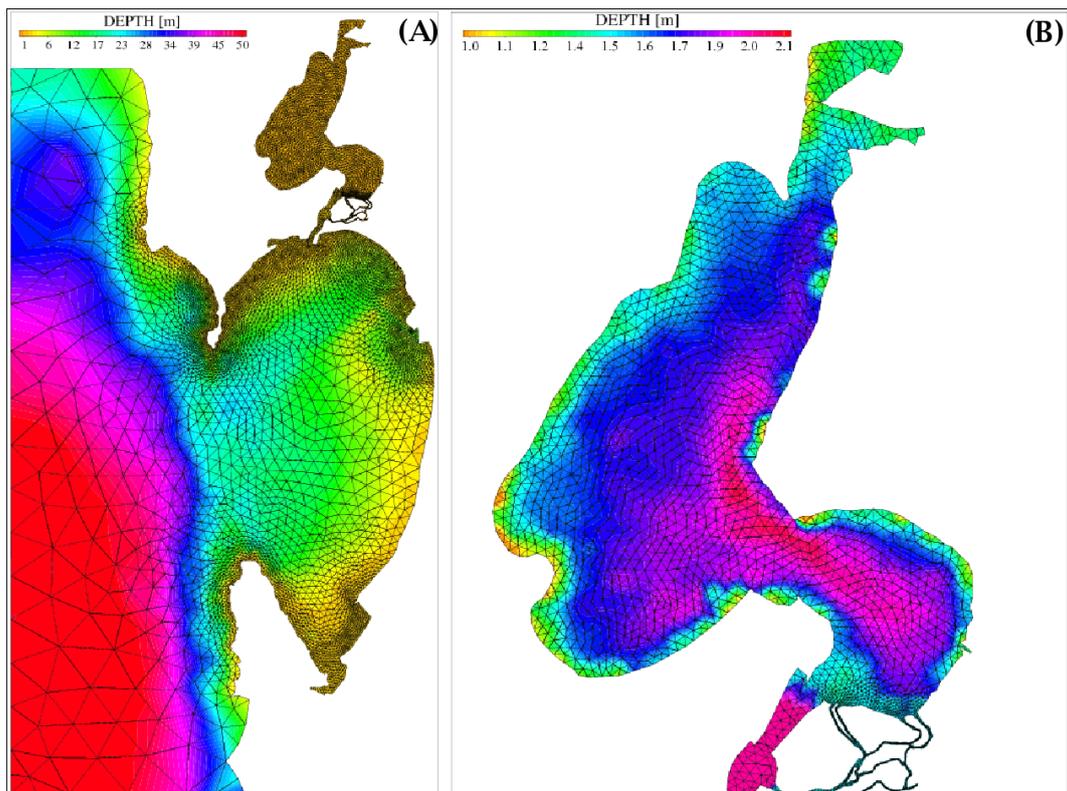
Framework Directive (WFD; EC, 2000).

Materials and Methods

Modeling

The hydrology of the Gulf of Oristano and the Cabras Lagoon was studied by means of numerical models. In particular, a 2D hydrodynamic model, SHYFEM, based on the finite-element method was used. The SHYFEM model is a well-tested hydrodynamic model, applied successfully in numerous coastal basins (Umgiesser *et al.* 2004; Ferrarin and Umgiesser 2005; Cucco and Umgiesser, 2006). The model resolves the vertically integrated shallow-water equations, with water levels and transports. It uses finite elements for spatial integration and a semi-implicit algorithm for integration in time. The terms treated semi-implicitly are the divergence terms in the continuity equation, together with the Coriolis term, and the pressure gradient in the momentum equation. The friction term is treated fully implicitly, while all other terms are treated explicitly. The model is coupled with a transport and diffusion module in order to reproduce the fate of solutes dissolved within the water column. Furthermore, a water quality model WASP (Ambrose *et al.* 1993) is integrated into the hydrodynamic code in order to reproduce the time and space evolution of the main nutrients solutes, oxygen and phytoplankton concentration in the water column. Details of the numerical treatment are given in Umgiesser and Bergamasco (1995), Umgiesser *et al.* (2004), and Cucco and Umgiesser (2006).

Numerical simulations were carried out on a computational domain representing the Gulf of Oristano and the Cabras Lagoon by means of a finite element staggered grid (Fig. 2). The numerical grid is made of about 9000 nodes and 17000 triangular elements with a spatial resolution varying between 2 km for the off-shore areas up to 10 meters for the complicated net of channels connecting the



Figures 2a, b. Numerical grid of the 2D finite element hydrodynamic model used to investigate the water circulation and residence time in the Cabras Lagoon and the Gulf of Oristano (A), and enlarged view of the Cabras Lagoon (B).

Lagoon to the Gulf.

Different simulations were carried out in order to reproduce both water circulation and water residence times within the Cabras Lagoon. Residence times computation was performed following the method proposed by Cucco and Umgiesser (2006). Both wind and tide induced water circulation were investigated. In particular, three different scenarios were considered representing the main meteorological and hydrological regimes of the study site: tide and Sirocco wind, tide and Mistral wind, and finally tide and Libeccio wind induced water circulation. Details of the adopted model boundary conditions and meteo-marine forcing features are given in Cucco *et al.* (2006). For each scenario the water residual circulation over the whole domain and the Cabras Lagoon water residence times were computed

considering both the actual geometry of the main Lagoon inlet which is closed, and a hypothetical geometry in which the main inlet is opened allowing water exchanges between the two basins.

Finally, a whole year simulation was carried out by means of the coupled hydrodynamic and water quality model. Meteorological forcing provided by a local meteorological station and the mainland loads of fresh water and nutrients measured weekly for the whole 2006 were considered in order to simulate the time and space evolution of the main physical water parameters such as temperature, salinity, dissolved oxygen and the main ecological variables such as phytoplankton and nutrient concentrations within the Cabras Lagoon. Numerical results were obtained both by considering the actual Lagoon inlet geometry and the hypothetical

modified inlet geometry.

Benthos

Several investigations on the physical (e.g. porosity, grain size, Eh) and chemical (e.g. acid volatile sulphide, chromium reduced sulphur, organic matter, total organic carbon and total nitrogen) characteristics of sediments and macrobenthic assemblages were conducted in various lagoons (De Falco *et al.* 2004; Magni *et al.* 2004; 2005a,b; 2008a) and the Gulf in the Oristano Lagoon-Gulf system (De Falco *et al.* 2000a; 2006; Magni *et al.* 2006; Como *et al.* 2007; 2008). As a typical phenomenon often occurring in our lagoons, we also investigated the effects of dystrophic events on the temporal changes in the benthic assemblages as well as in the carbon and nitrogen stable isotope composition of various primary producers (macroalgae and angiosperms) and consumers (macroinvertebrate filter/suspension feeders, deposit feeders, detritivores/omnivores and carnivores and fishes) (Magni *et al.* 2008a). In this paper, we focus on a descriptive account of the distribution of fine sediments (<8 µm grain size fractions) and macrobenthos in the Cabras Lagoon (De Falco *et al.* 2004; Magni *et al.* 2004; 2008b), with a comparison with the adjacent coastal areas of the Gulf (Cancemi *et al.* 2000; De Falco *et al.* 2000b; Como *et al.* 2007; 2008). In the Cabras Lagoon, thirty-one stations were selected on a regular square grid and sampled in the spring of 2001 (see for details De Falco *et al.* 2004; Magni *et al.* 2004). At each station, duplicate sediment samples for grain size and organic matter analyses were collected using a manual corer. Subsequently, the surface layer (0-2 cm) of each core sample was carefully sliced off. Samples were dried at 50 °C for 24 hours and the water content was determined as a loss of weight. The organic matter (OM) content in the sediments was determined from a subsample of about 1 g by loss on ignition (LOI) at 500 °C for 3 hours. Another

subsample of about 4 g was used for the grain size analysis. This subsample was suspended on a large volume (500 ml) of distilled water in order to desalinate sediments, treated with hydrogen peroxide (H₂O₂) in order to eliminate organic material and wet sieved through a 64 µm net. The sandy fraction (>64 µm) remaining in the sieve was dried and weighed. The suspension with the mud fraction passing through the 64 µm sieve was diluted up to obtain a sediment concentration ≈ 0.5 mg ml⁻¹ and to further reduce the salt concentration. Ten ml of diluted suspension were treated with Na-Hexametaphosphate 0.6% to avoid particle flocculation. The grain size analysis of the fraction <64 µm was performed using a laser Galai CIS 1 instrument, with specific analytical size intervals of 0.5 µm (Molinaroli *et al.* 2000). At the same stations in the Cabras Lagoon, duplicate sediment samples were collected for the determination of macrozoobenthos using a 216 cm² Ekman-Birge grab. These samples were subsequently sieved on a 0.5 mm mesh size, and the residue was fixed with a buffered formaldehyde solution (final concentration 5%), stained with rose Bengal. In the laboratory, the macrozoobenthos were separated from the residue and transferred into a 75% ethanol and 2.5% ethylene-glycol solution. For each replicate, animals were sorted, counted and identified at the species level when possible.

The same above procedure for collecting and analyzing the sediments and macrobenthic assemblages was adopted in the coastal areas of the Gulf of Oristano adjacent to the Cabras Lagoon. Here, biocenosis maps were also produced using aerial photogrammetry integrated by *in situ* morphostructural measurements as detailed in De Falco *et al.* (2000b). We redirect to our previous published work for methodological and analytical details of this approach (Cancemi *et al.* 2000; De Falco *et al.* 2000b). Shortly, the superficial area (0-10 m depth) of the

whole Gulf of Oristano was mapped, starting from aerial photogrammetry (1:20.000 colour photographs), four aerial colour photographs were digitized (pixel 5 m) in 16.8 million colours. The raster image was analyzed using Multiscope software (Pasqualini *et al.* 1997). Direct observation and ARA diving surveys supported image interpretation.

Fishes

The effects of hypoxia: Behaviours and physiological functions investigated. Above lethal levels, hypoxia induces oxygen distress which in turn affects different functions of the organism. Even if death did not occur, hypoxia is therefore at the origin of changes in behaviours and/or reduction in physiological performances that may affect fish ecological functions such as foraging, growth or survival. First, we investigated the response of *Liza aurata* exposed to hypoxia, and whether or not being in a shoal may play a role in the tolerance to hypoxia. Changes in swimming activity, and aquatic surface respiration (ASR, the active ventilation Mugilidae perform at the surface in order to breath the higher-oxygenated uppermost layers of water) were measured. Second, the stamina was investigated in *M. cephalus* swimming at their optimal swimming speed (i.e. U_{opt} , the speed that implies the lowest amount of energy per unit travelled; Videler, 1993). Hypoxia-related reduction of stamina at U_{opt} would therefore have energetic consequence during activities, such as foraging or habitat exploration when U_{opt} is presumably used. Thirdly, escape performance was investigated in *L. aurata* and *D. labrax*. Escape responses consist of a sudden acceleration in response to startling stimuli such as a predator attack. Any dysfunction in the progress of the escape may increase the fish vulnerability and decrease its probability of survival.

General conditions. The effects of oxygen variations were studied in various species that inhabits Cabras Lagoon: the golden grey

mullet (*Liza aurata*), the flathead grey mullet (*Mugil cephalus*) and the European sea bass (*Dicentrarchus labrax*). Fish were maintained in laboratory conditions at least three weeks before the experiments. They were acclimated to normoxia, as well as constant temperature (20°C unless otherwise indicated) and salinity at 35 PSU. During the experiments, fish were exposed to acute changes in oxygen levels, which ranged between normoxia and 10% AS. During the hypoxia exposure, a set of behaviours and/or physiological functions linked to fish physiological performance were investigated.

Activity in Liza aurata. The activity of single and shoaling *Liza aurata* was investigated at regular intervals from normoxia to 10% AS. Three variable were measured: (i) swimming activity, (ii) ASR and (iii) ventilation frequency (VF), used as an indirect indicator of oxygen consumption. Swimming activity was measured by calculating the average speed of the fish (in total Body lengths s^{-1} ; BL s^{-1}). ASR was calculated as the percentage of time the fish spent gulping at the surface. VF was calculated by counting the number of opercular opening per minute.

Swimming performance and associated energy costs in Mugil cephalus. Stamina was measured in normoxia and at 50%, 25%, 15% AS. Swimming stamina was defined as the time to fatigue at U_{opt} . The experimental set up consisted in a swim-tunnel respirometer, which allowed (i) to control the swimming speed and (ii) to measure oxygen consumption (MO_2). During a stamina test, fish were allowed to swim for 165 min at U_{opt} . If the fish fatigued before this period, the test ended. After the test, the swimming speed was reduced and normoxia reinstated (>80% AS). The post-test MO_2 was then measured to assess the energy costs of the recovery.

Escape performance in Liza aurata and Dicentrarchus labrax. Four levels of air saturation were tested: normoxia (> 85% AS), 50%, 20% and 10% AS. In *L. aurata*, to

prevent ASR at low oxygen saturation, escape performance was also tested without surface access (at 10% AS). Escape responses were elicited using a mechanical stimulus and filmed with a high-speed camera (Redlake PCI 1000S, 500Hz). A set of variables was measured: (i) the responsiveness (i.e. the proportion of responding animals over the total), (ii) the response latency (i.e. the time interval between the stimulus onset and the reaction of the fish), (iii) the directionality, based on the response being oriented away or towards the stimulus, (iv) the locomotor variables (e.g. cumulative distance D , maximum speed V_{max} and maximum acceleration A_{max}) and (v) the response types; single bend (SB, responses consisting of one single muscular contraction, Domenici and Blake 1997) and double bend (DB, responses consisting of two consecutive muscular contractions).

Results and Discussion

Modeling

Tide and Sirocco wind scenario. When the model is forced with tide and a 10 m/s Sirocco wind, the induced water circulation in the Cabras Lagoon is mainly governed by a clockwise motion. In Figure 3a, a snapshot of the water current distribution within the basin is reported. From an hydrological standpoint, the Lagoon can be subdivided into two main sub-basins: a Northern sub-basin, the widest one characterized by a clockwise gyre and a Southern sub-basin, where a one-pair vortex dynamic governs the water circulation. For both sub-basins higher current velocities, up to 20 cm/s, are detected along the edges of each eddy, while lower values are found in the cores of such hydrological structures.

The water residence times (WRTs) distribution within the Lagoon (Fig. 3b) validate the basin zonation obtained by the previous analysis. In particular, a wide North-Central area characterized by high WRTs (up to 45 days), and a southern area characterized by lower

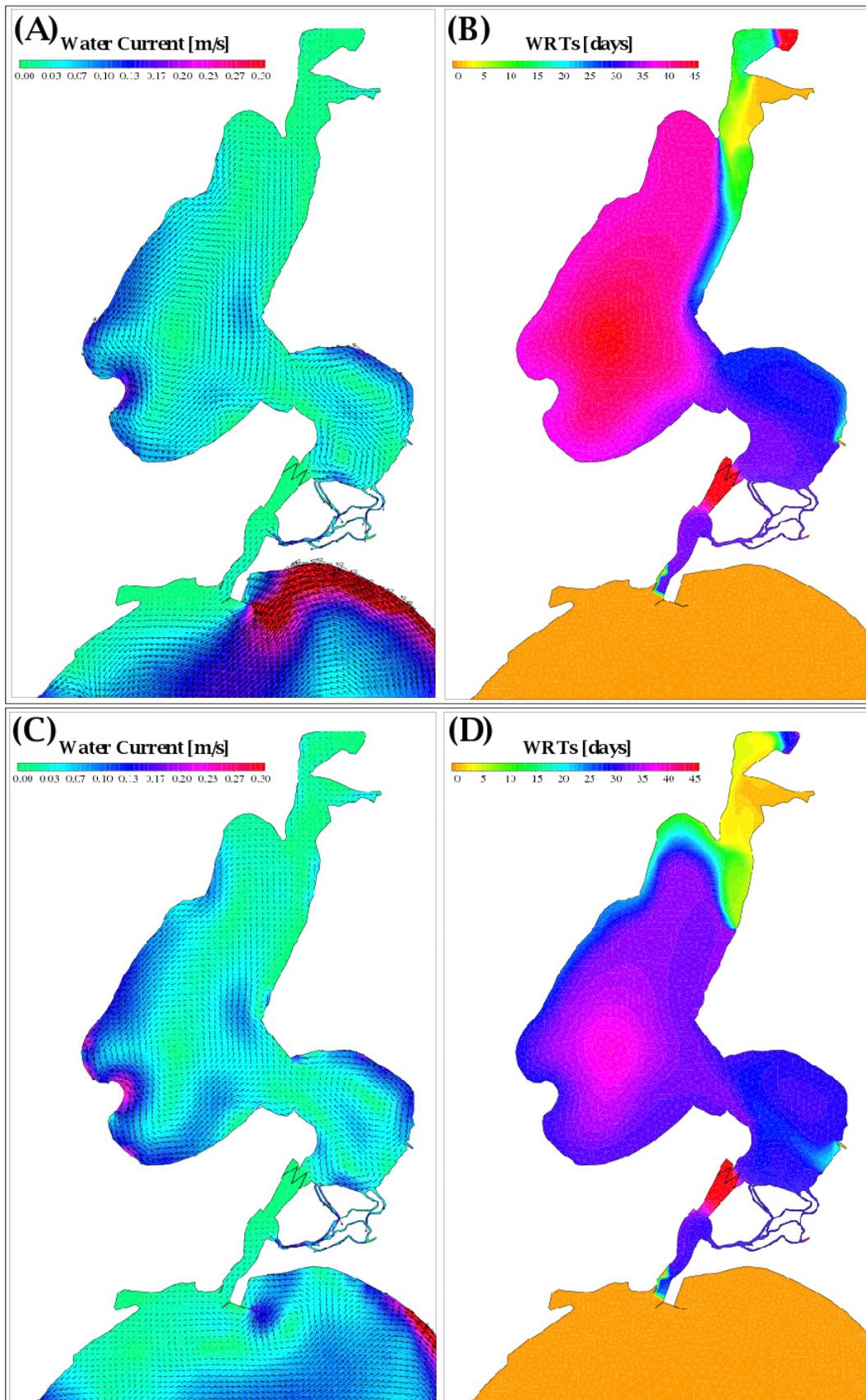
WRTs values (about 20 days) corresponding to the Northern and Southern sub-basins, respectively, can be detected. The WRTs distribution within each sub-basin shapes as function of the water current intensity, with lower values along the eddies edges and higher values within the cores of each eddy.

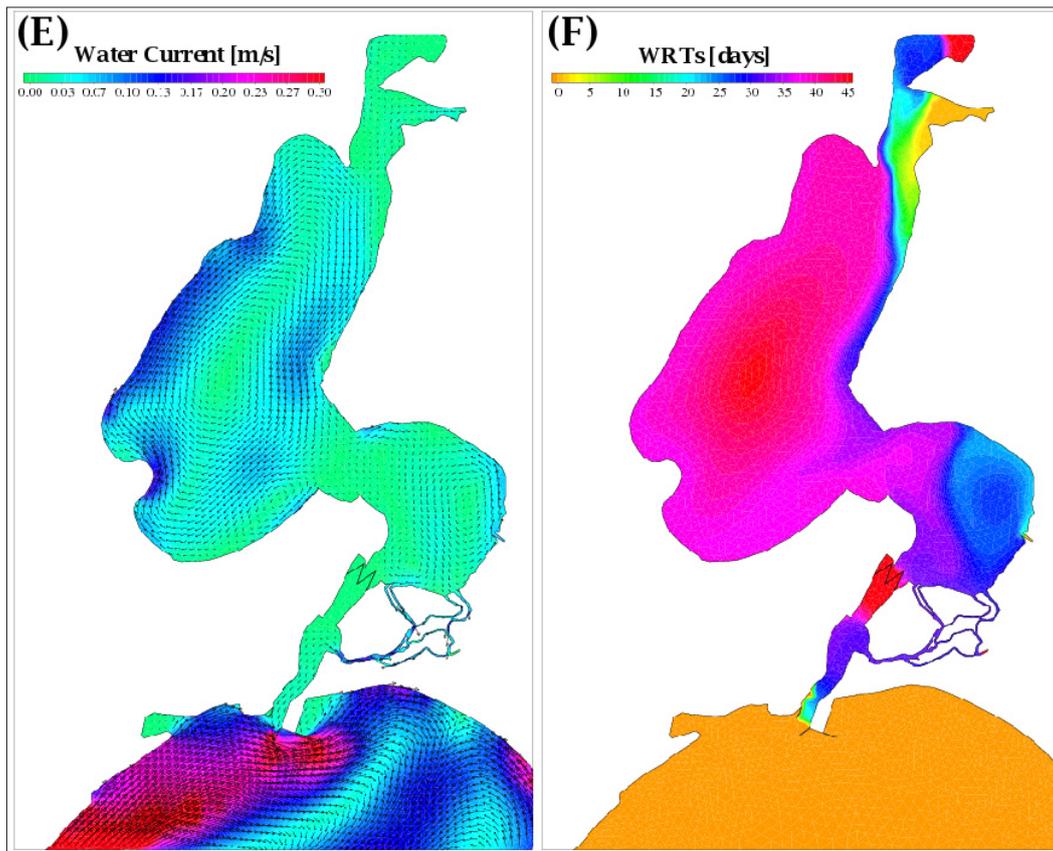
Tide and Mistral wind scenario. When the basin is forced by the tide and a 10 m/s Mistral wind, the water circulation within the two Lagoon sub-basins is characterized by an anticlockwise gyre in the Northern sub-basin and by a one-pair of vortices in Southern sub-basin (Fig. 3c). The same Lagoon zonation can be suggested as for the previous case. Nevertheless, in this scenario the hydrological structures are characterized by rotation wise which is opposite with respect to the one obtained for the Sirocco wind case. Also for the current intensities the obtained results are similar to the results obtained in the previous scenario. In particular, the highest current velocities are detected along the vortices edges (up to 23 cm/s) whereas lower values are found in their core.

The WRTs distribution reveals that the Mistral wind is the most efficient forcing for increasing the renewal capacity of the basin (Fig. 3d). In such case the maximum WRTs values are 30 days and 20 days for the Northern and Southern sub-basins, respectively.

Tide and Libeccio wind scenario. Results obtained by tide and Libeccio wind scenario reveal similar patterns of the induced water circulation within the two sub-basins (Fig. 3e). In particular, a single clockwise gyre is detected in the Northern part whereas a system of three small vortices is found in the Southern sub-basin. Even for this scenario, the top current velocities are located along the gyres edges with values up to 13 cm/s, and the lowest values are found within the cores of such hydrodynamic structures.

Similarly to the previous scenarios, the WRTs distribution (Fig. 3f) is a function of the hydrological features. In particular,





Figures 3a, b, c, d, e, f. Current velocity (left panels) and Water Residence Times (WRTs) (right panels) in the Cabras Lagoon and the adjacent area of the Oristano Gulf obtained by the Tide and Sirocco wind (A and B), the Tide and Mistral wind (C and D), and the Tide and Libeccio wind (E and F) scenario results.

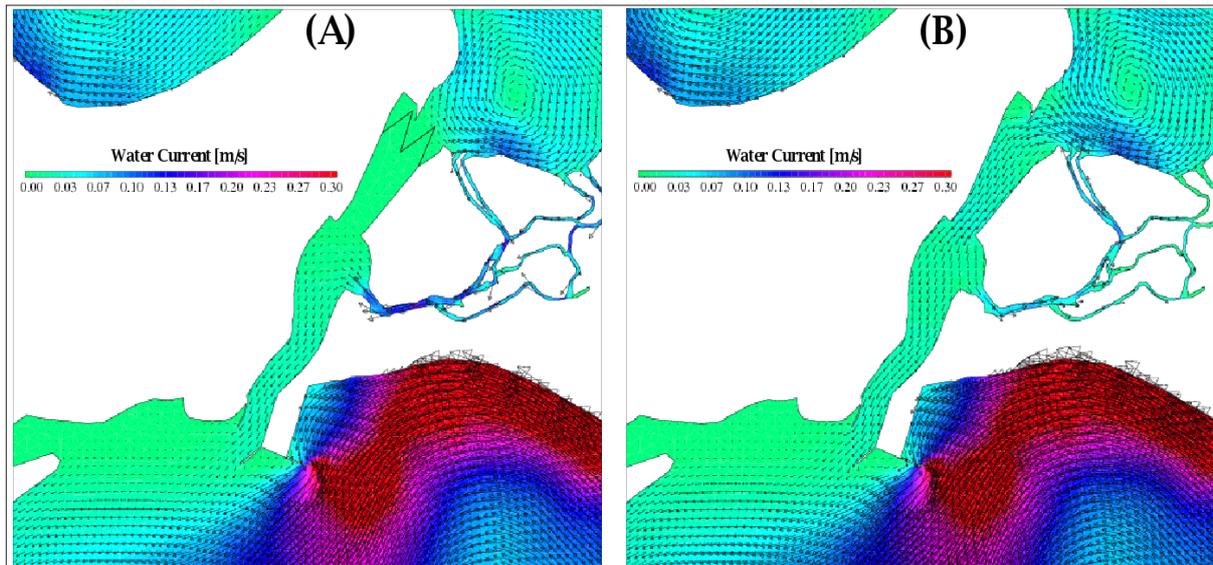
maximum values are found within the cores of the eddies, up to 45 days in the Northern sub-basin, whereas lower values are detected along the Lagoon border and the gyres edges.

Opened inlet scenario. A further analysis was carried in order to verify the modification of water circulation, of the water exchanges between the Gulf and the Lagoon and of the WRTs distribution within the basin induced by the opened Lagoon inlet. For each meteorological scenario a simulation with a modified grid geometry to allow the direct water exchange through out the inlet, was carried out.

In Figure 4, the comparison of the water current distribution in the Lagoon inlet area

with and without the opened inlet is reported for the tide and Sirocco wind scenario, as an example. Results reveal that the opened inlet, allowing direct water exchange, induces an increase of the water fluxes between the Lagoon and the Gulf and modifies locally the water circulation itself both in the Southern sub-basin of the Lagoon and the adjacent coastal area. Similar results (not shown) are found for both Mistral and Libeccio wind scenarios.

The increase of water exchanges between the Lagoon and the Gulf, and the modification of local water circulation induced by the opened inlet, influence the renewal efficiency of the Lagoon basin itself. In particular the modified inlet geometry induces a decrease



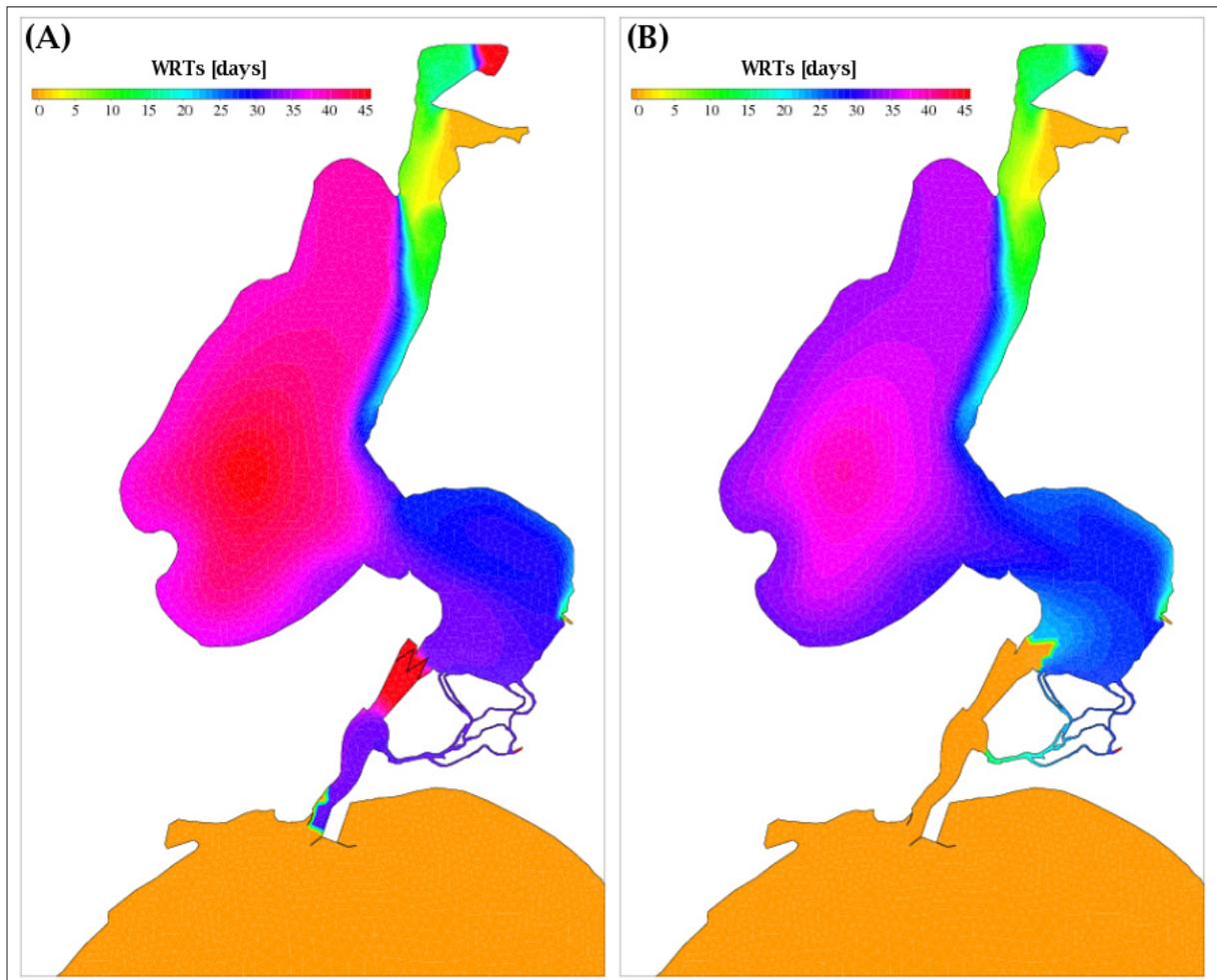
Figures 4a, b. Distribution of the current velocity in the inlet of the Cabras Lagoon obtained by two different simulated scenarios (Tide and Sirocco wind case). A: close inlet scenario (present situation); B: opened inlet scenario. A comparison between the two scenarios reveals an increase of water discharge between the Lagoon and the Gulf, and an increase of the current velocity in the southern Lagoon sub-basin, when the inlet is opened.

of the WRTs over the whole Lagoon basin. In Figure 5 the comparison between the WRTs distribution obtained considering the two inlet geometries are reported for the Tide and the Sirocco wind scenario. The results reveal a decrease of WRTs values both for the Northern and for the Southern sub-basins. In Table 3, the average values of the WRTs computed for the whole Lagoon basin and for each sub-basin are reported for each meteorological scenario and for the two different inlet geometries. The opened inlet induces a decrease of the WRTs, with differences up to 20%, which implies a net increase of the basin renewal efficiency.

In order to verify the effects of opening the inlet on the water physico-chemical features, simulations were carried out by means of the coupled hydrological and water quality model. Results obtained for the actual geometry configuration (closed inlet) were compared with experimental data collected during the year 2006. In this work, comparison focused on salinity, dissolved oxygen and

Table 3. Water Residence Times (WRTs, expressed in days) in the Cabras Lagoon (whole basin, and two sub-basins) obtained by two different scenarios (Scenario 1, present situation: close inlet; Scenario 2: opened inlet) for the tide and Sirocco, Mistral and Libeccio wind forcing conditions, and differences in WRTs between the two scenarios.

Scenario 1 (Close Inlet)	Whole Lagoon	Central sector	Southern sector
Tide	43	40	47
Sirocco	35	36	31
Mistral	29	29	25
Libeccio	35	36	32
Scenario 2 (Opened Inlet)	Whole Lagoon	Central sector	Southern sector
Tide	35	37	31
Sirocco	29	30	25
Mistral	22	24	18
Libeccio	29	31	26
Difference	Whole Lagoon	Central sector	Southern sector
Tide	8	3	16
Sirocco	6	6	6
Mistral	7	5	7
Libeccio	6	5	6

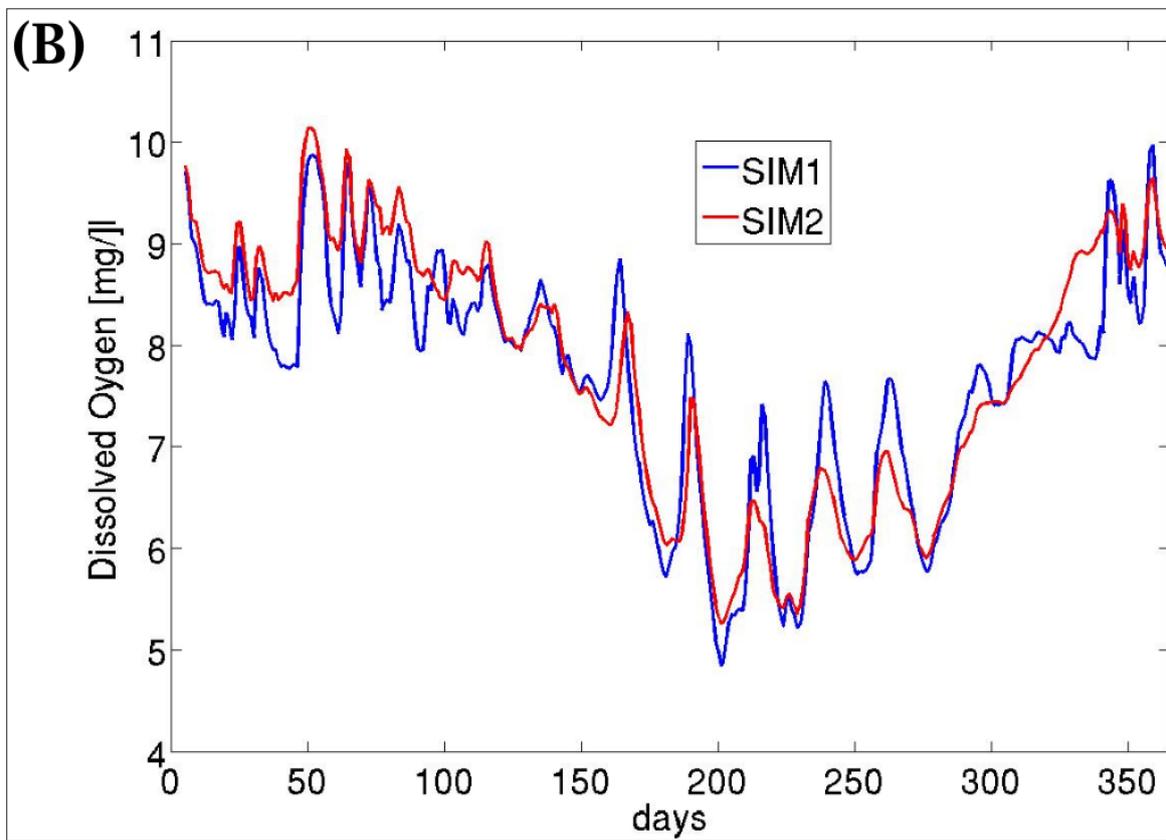
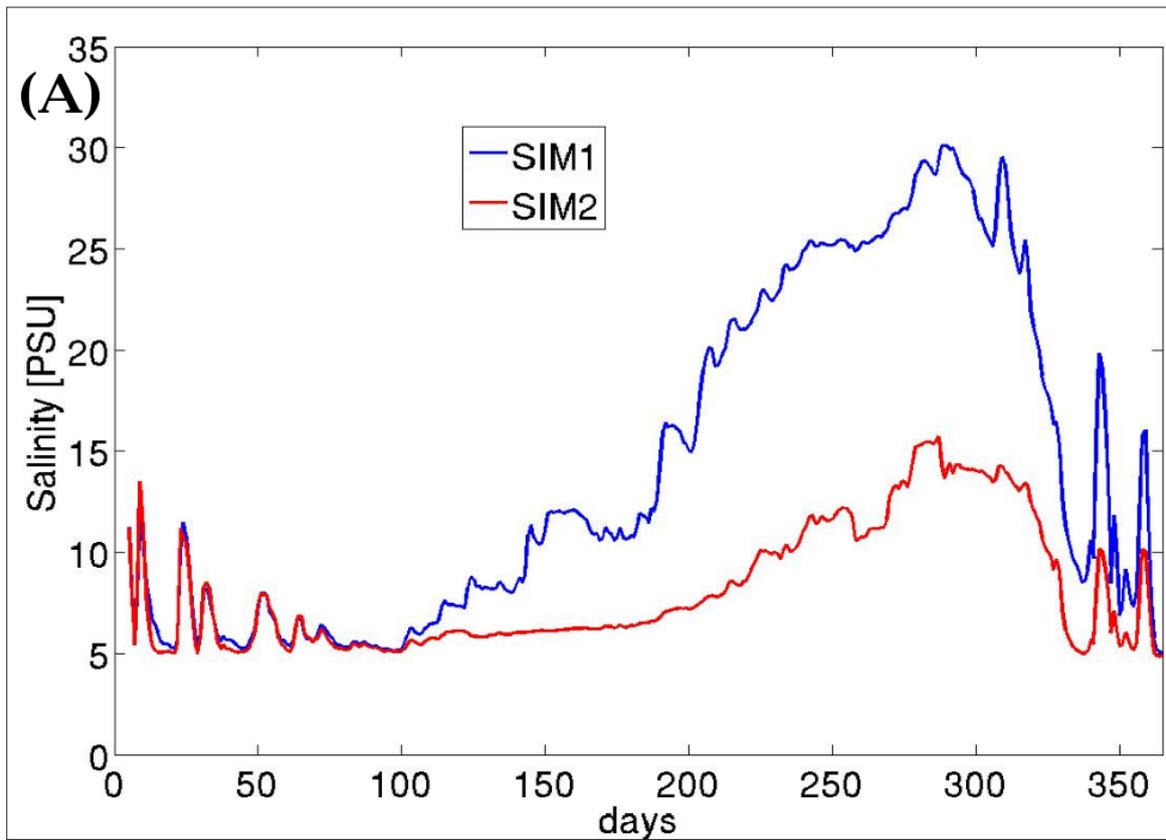


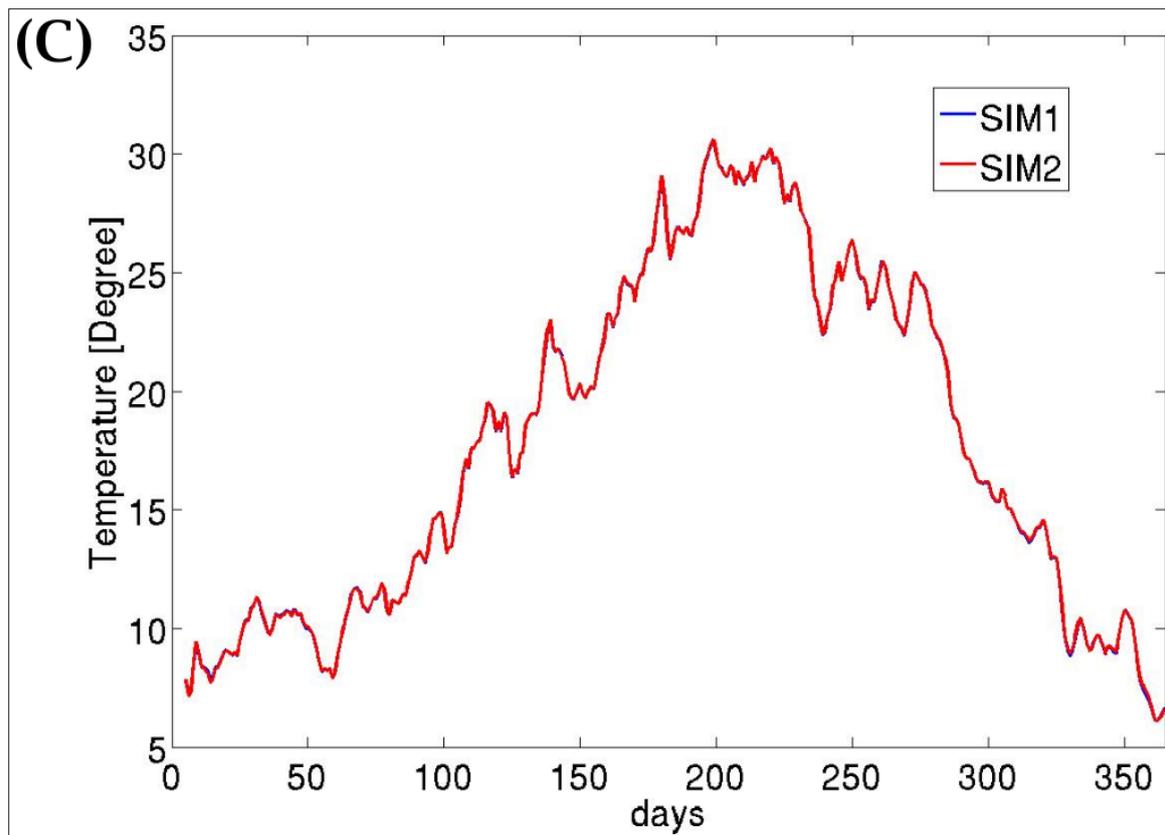
Figures 5a, b. Distribution of the Water Residence Times (WRTs) in the Cabras Lagoon obtained by two different simulated scenarios (Tide and Sirocco wind case). A: close inlet (present situation); B: opened inlet scenario. A comparison between the two scenarios reveals a decrease of the WRTs for the whole Cabras Lagoon basin and the inlet when the inlet is opened.

temperature distribution in order to provide the basic features that characterize the Lagoon environment modified by inlet opening. The results show that the new inlet geometry influences strongly the salinity distribution, whose average value increases more than twice during summer and autumn compared to the actual inlet geometry scenario (Fig. 6a). A general increase in dissolved oxygen concentration is also detected all over the basin during the whole year (Fig. 6b), even if this increase is not as intense as for salinity. Finally, the temperature decreases locally just on the southern Lagoon sub-basin, especially

in the vicinity of the channel mouth, while no significant variation is observed in the whole Lagoon for the whole period simulated (Fig. 6c).

The results obtained demonstrated that the modification of the inlet geometry has strong effects on both physical and chemical features of the Lagoon water. In particular, the increased water exchanges between the Gulf and the Lagoon and the induced changing of salinity and temperature lead to a modification of the oxygen budget of the Lagoon basin itself. Such a model application allows us to predict the potential





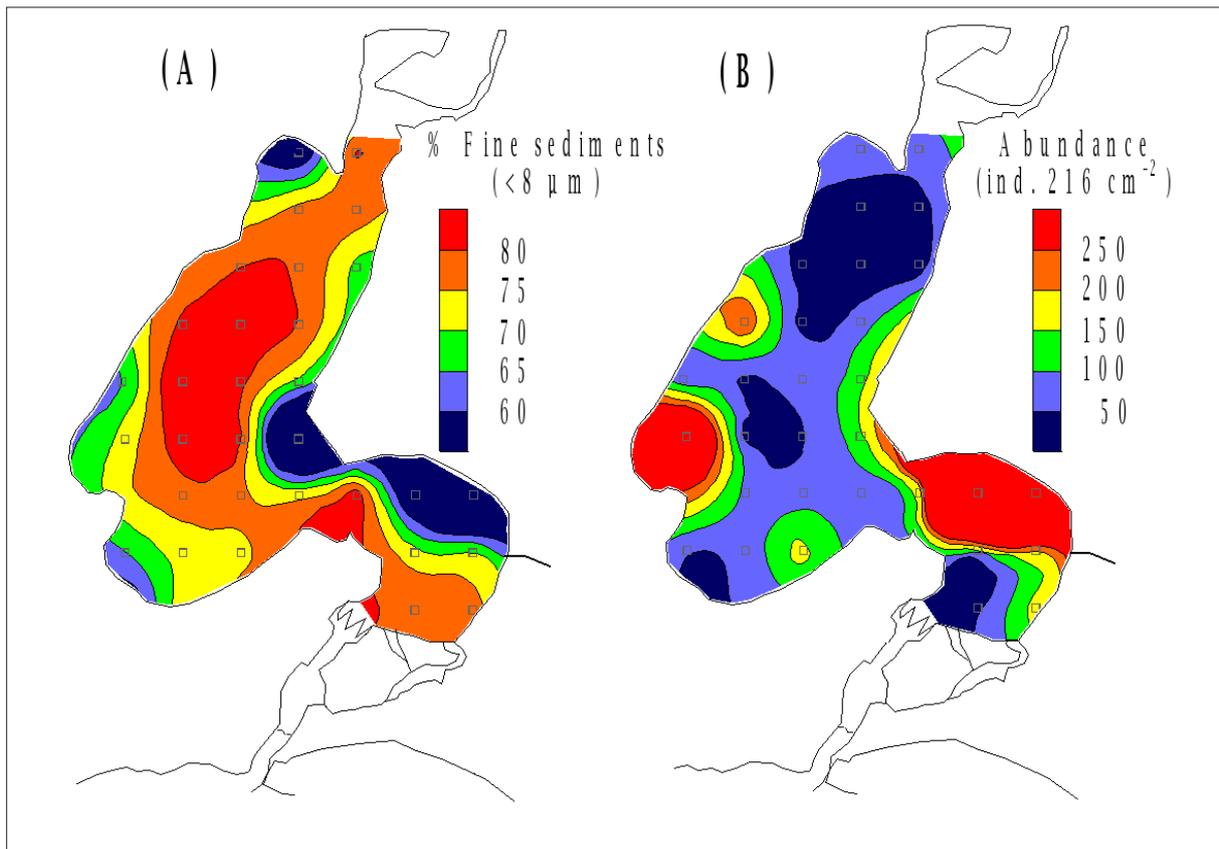
Figures 6a, b, c. Salinity, dissolved oxygen concentration and temperature in the Cabras Lagoon during the whole 2006 obtained from model results. SIM 1: results obtained by simulation considering the opened inlet geometry. SIM 2: results obtained by simulation considering the actual inlet geometry (i.e. close inlet).

effects of anthropic effects on the physical compartment and on the lower trophic levels of the lagoon ecosystem. In order to investigate the effects of such modifications on the dynamics of higher trophic levels, as macrobenthos and fishes, numerical modeling can thus be used to provide and reproduce the spatial distribution and dynamics of the main environmental variables (salinity, temperature and dissolved oxygen), which affect both the habitat and the behavior of organisms investigated.

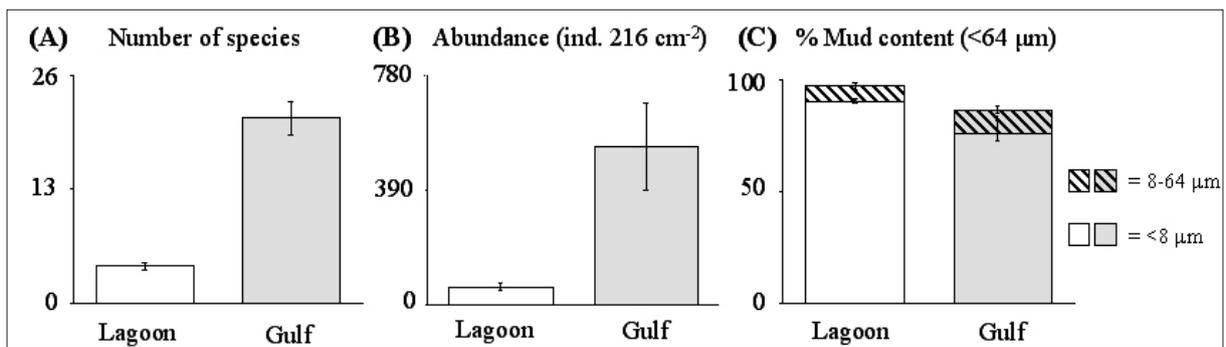
Benthos

Figure 7 shows a major accumulation of fine sediments (<8 μm grain size fractions) in the central sector of the Cabras Lagoon corresponding to a major impoverishment

of benthic assemblages. This fraction of sediments, also known as cohesive or non-sortable sediments (McCave *et al.* 1995), was consistently found to be most tightly correlated with the sedimentary organic matter (De Falco *et al.* 2004; Magni *et al.* 2008b). Here, the opportunistic species *Polydora ciliata* dominated, while *Ficopomatus enigmaticus* and *Corophium sextonae* were relatively abundant and patchily distributed along the shores (Magni *et al.* 2004; 2008b). The distribution of fine sediments and benthic assemblages showed a strong agreement with the results obtained from the 2D hydrodynamic model (Fig. 3). In particular, modeling results consistently indicated the highest WRTs in the central sector of the Lagoon. Therefore, our multidisciplinary approach allowed us



Figures 7a, b. Spatial distribution of fine sediments ($8 \mu\text{m}$ grain size fractions) and macrobenthic abundance in the Cabras Lagoon (based on Magni *et al.* 2008b).



Figures 8a, b, c. Macrobenthic species richness (A) and abundance (B), and percentages of fine sediments ($<8 \mu\text{m}$) within the mud ($<64 \mu\text{m}$) (C) in the southern sector of the Cabras Lagoon (Lagoon) and the adjacent coastal area of the Gulf of Oristano (Gulf).

to assess a high correlation between fine sediment and macrobenthic distribution, organic enrichment and hydrodynamic patterns. Such an approach can be a useful tool to detect the areas that are more at risk

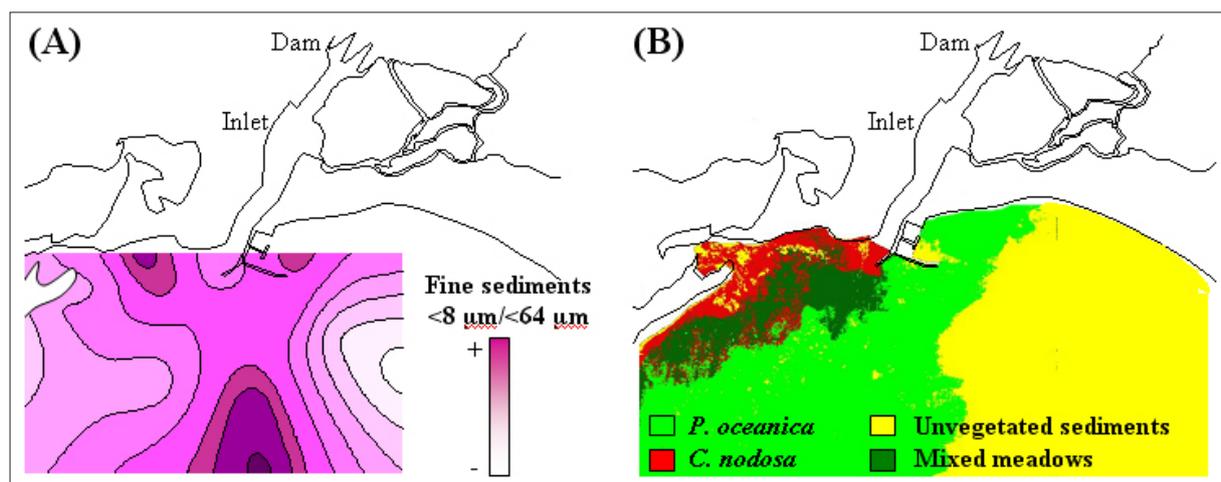
of developing dystrophic crisis.

There were also major differences in sediment composition and benthic assemblage distribution between the Cabras Lagoon and the adjacent coastal area of the Gulf of

Oristano (Fig. 8). Grain size analysis indicated that the Gulf is partially influenced by the deposition of fine sediment particles coming from the Lagoon (Como *et al.* 2007). Also, the adjacent coastal area is rich in refractory organic matter and carbonates, suggesting a supply of detritus from the nearby *Posidonia oceanica* and *Cymodocea nodosa* meadows, as well as from the Cabras Lagoon and the Tirso river (Como *et al.* 2008). Consistent with differences in sediment composition, few opportunistic species (e.g. *Neanthes succinea*) characterized the Lagoon, while a higher diversity, with species commonly found on *P. oceanica* and *C. nodosa* (e.g. *Dexamine spinosa* and *Prionospio cirrifera*), was observed both in the channel and the adjacent marine coastal area (Como *et al.* 2007; 2008). The exchanges of materials and organisms between marine and Lagoon habitats seemed to be rather limited. We suggest that the construction of a dam in the late 70ies in the southern sector of the Lagoon has caused a major change in the sedimentary regime of the Lagoon, associated to internal trapping and re-distribution of organic C-bounding fine sediment particles (De Falco *et al.* 2004; Como *et al.* 2007).

In the coastal area of the Gulf of Oristano adjacent to the Cabras Lagoon, aerial photogrammetry integrated by *in situ* morphostructural measurements showed that *P. oceanica* meadows are the main type of biocenosis (Cancemi *et al.* 2000). This also highlighted that the depositional area of fine sediments coincides with the edge of *P. oceanica* distribution (Fig. 8). Meadows of *C. nodosa* and mixed biocenosis of the two seagrasses are also found near Cabras Lagoon. Unvegetated sediments in the westernmost sector of the study area as well as the current distribution of *P. oceanica* are probably consequences of dredging and port building occurred in the 70ies (De Falco *et al.* 2000b). Consistent with the presence of different habitats within the coastal area of the Gulf of Oristano, major differences were found in the benthic assemblages with some species exclusively found in the two seagrass beds (e.g. the tunicate *Phallusia fumigata*, the polychaete *Syllis garciai* and the decapod *Paguristes syrtensis*), while others were only found in seagrass-derived leaf litter beds (e.g. the bivalves *Abra alba* and *Cerastoderma glaucum*) (Como *et al.* 2008).

Overall, combined modeling and experimental



Figures 9a, b. Spatial distribution of fine sediments, expressed as the ratio between the $<8 \mu\text{m}$ and the $<64 \mu\text{m}$ grain size fractions, in the coastal area of the Gulf of Oristano adjacent to the Cabras Lagoon (A), and benthic mapping of the same coastal area (B, based on Cancemi *et al.* 2000). The depositional area of fine sediments coincides with the edge of *P. oceanica* distribution.

results indicate that the removal of the dam at the inlet of the Cabras Lagoon would favour the water renewal within the Lagoon (Fig. 5), but would also increase the outflow of organic-C rich fine sediments from the Lagoon to the adjacent coastal area of the Gulf (Fig. 8c, 9a). This may have serious consequences on the *P. oceanica* and *C. nodosa* seagrass meadows.

Fishes

Activity in Liza aurata. During hypoxia, swimming activity of *L. aurata* increased

significantly at $\leq 60\%$ air saturation (AS) compared with normoxia in both solitary and shoaling individuals (Lefrançois *et al.* in press). In general, increasing swimming activity may be an efficient response to find better conditions in habitats in which hypoxia is patchily distributed and has been interpreted as an avoidance response (Dizon, 1977). However, such a response also increases energy expenditure and risk of exhaustion. Aquatic surface respiration (ASR) was observed in shoaling and solitary individuals while coping with severe hypoxia

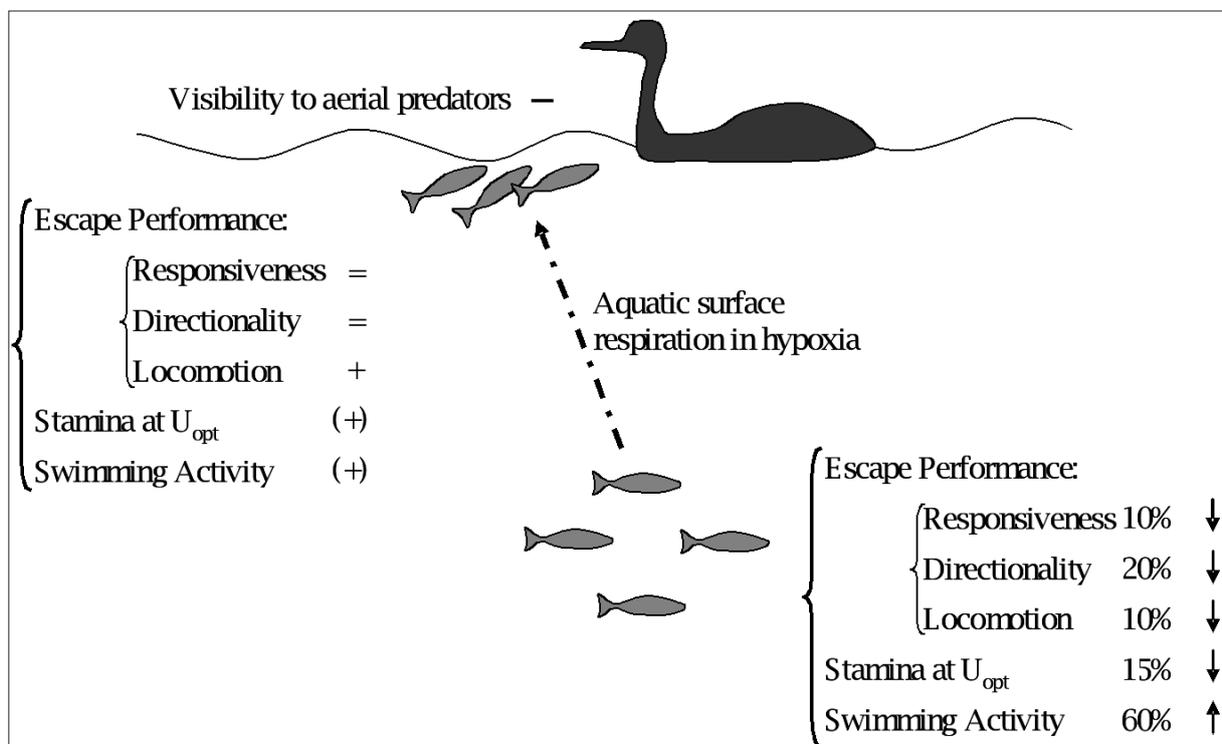


Figure 10. Effect of sub-lethal levels of hypoxia on Mugilidae which perform aquatic surface respiration (ASR). For the different functions studied, signs \uparrow and \downarrow indicate a relative increase and decrease, respectively, in fish exposed to the level of oxygen indicated (in % of air saturation or AS). The signs +, -, = indicate an advantage, a disadvantage and no difference, respectively, when comparing surfacing in hypoxia versus staying in the water column. Surfacing or staying in the water column did not influence responsiveness and directionality, while locomotion performance increases in surfacing fish (Lefrançois *et al.* 2005). However, while surfacing, visibility to aerial predator increases, and consequently the probability of being attacked also increases and the fitness is reduced, hence the sign “-”. On the other hand, performing aquatic respiration allows fish to increase blood oxygenation and aerobic metabolic scope. Aerobic performance is therefore likely to increase, thereby increasing stamina at optimal swimming speed (U_{opt}) and swimming performance, and consequently fitness. The “+” signs within parenthesis are based on these theoretical predictions. Modified after Domenici *et al.* 2007.

$\leq 15\%$ AS. Hypoxia also caused an increase in ventilation frequency (VF) (LeFrançois *et al.* in press). Both ASR and elevated VF contribute to maintain oxygen supply at the gills. However, performing ASR also increases predation risk, since fish close to the water surface are more visible to aerial predators (Fig. 10).

Swimming performance and associated energy costs in Mugil cephalus. Time to fatigue at U_{opt} was significantly affected by hypoxia in fish exposed to 15% AS (Vagner *et al.* 2008). In individuals exposed to hypoxia, certain physiological mechanisms are activated in order to maintain the energy capacity, e.g. augmentation of the gill VF as observed in *L. aurata*, or recruitment of branchial gills (Randall, 1982). In our experimental conditions, the observed decrease in stamina at 15% AS suggests that the oxygen supply was no longer sufficient to maintain a sustained activity at U_{opt} (Fig. 10). Furthermore, after the stamina test, MO_2 measured in fish tested at 15% AS was significantly higher than the MO_2 measured in fish tested in normoxia. Increase in MO_2 illustrates the fish oxygen debt (Hill, 1924), i.e. the energy costs related to the elimination of the end-products of the anaerobic metabolism (e.g. lactate). This suggests that fish probably used anaerobic metabolism to supplement swimming at U_{opt} . While further work is necessary to establish the extent to which *M. cephalus* use U_{opt} during their routine activity, the results unequivocally show that hypoxia can be detrimental for its activity because it reduces the stamina even at low speed. As a consequence fish may swim at speeds $< U_{opt}$, thereby increasing the cost of transport. In addition, reduced activity would decrease habitat exploration and therefore opportunities to find food, to encounter conspecifics and to find better oxygen conditions.

Escape performance in Liza aurata and Dicentrarchus labrax. In both *L. aurata*

and *D. labrax*, responsiveness was affected at 10% AS, but to different extents (37% of responders in seabass and 69% in grey mullets, Lefrançois *et al.* 2005; Lefrançois and Domenici, 2006) (Fig. 10). The hypoxia-induced alteration of responsiveness suggests a reduction of acoustic/visual sensitivity and/or motivation to escape (Domenici *et al.* 2007). This may have important ecological consequences for escape success, since unless predators make an error, the absence of an escape attempt leads unavoidably to prey capture. When responding, *L. aurata* showed a disorientation only at oxygen level as low as 20% AS (i.e. a significant proportion of the fish initially escaped in the direction of the stimulus, Lefrançois *et al.* 2005), while sea bass (*D. labrax*) showed a disorientation when oxygen level was 50% AS (Lefrançois and Domenici, 2006). Bending towards the predator at the initiation of the fast start may induce a significant delay in the effort of the prey to escape away from the predator. Since the first milliseconds of the escape response may be crucial for surviving a predator attack, response towards the threat may contribute to an increase in prey vulnerability. Furthermore, D and V_{max} during escape responses were reduced in *L. aurata* at 10% of AS (Fig. 10). This decrease in performance was associated with an increasing proportion of single bend responses (Lefrançois *et al.* 2005). Hypoxia-related increase in occurrence of low performance responses (i.e. single bend) may be due to changes in the balance between the oxygen distress and the need to escape from a predator attack. It is worth noticing that such effects were mitigated when mullet performed ASR. In contrast, *D. labrax* did not show any reduction in locomotor performance while exposed to hypoxia (Lefrançois and Domenici, 2006).

Conclusions

The application of numerical modeling was proven to be a useful tool in the

ecosystem quality assessment of the Oristano Lagoon-Gulf system. It provided the main hydrodynamic features, such as water currents and water residence times (WRTs), of both Cabras Lagoon and the Gulf of Oristano under different meteorological scenarios and considering different Lagoon inlet geometries. In the Cabras Lagoon, the distribution of fine sediments (<8 μm fraction) and macrobenthic assemblages matched model predictions, that is a major accumulation of fine sediments and impoverished assemblages in areas characterized by the highest WRTs. The opening of the Lagoon inlet would allow an increase of the water exchanges between the Cabras Lagoon and the Gulf and, therefore, a reduction of the WRTs inside the Lagoon. However, this would also increase the outflow of organic-C bounding fine particles from the Lagoon to the adjacent coastal area, with possible serious consequences on the *P. oceanica* and *C. nodosa* seagrass meadows, and the rich and diverse benthic assemblages.

Numerical modeling also demonstrates that the modification of the inlet geometry induces an increase of both salinity and dissolved oxygen concentration within the Lagoon basin, whereas it leads to a decrease of the water temperature. Environmental variation can have a profound effect on fish behavior and energetics. Our work shows that the thresholds at which modifications on fish behaviours can occur, are much higher than the lethal threshold of oxygen concentration (Fig. 10). In particular, Mugilidae, the most common family found in all the lagoons of the Oristano region, are faced with a number of trade-offs illustrated in Fig. 10. In hypoxia, Mugilidae can either stay in the water column, away from the surface, and face the detrimental effects of hypoxia (such as lower scope for movement for foraging, and lower escape performance), or they can swim to the surface to avoid hypoxia, but face a higher risk of predation by piscivorous birds. A full

understanding of how fish behave when facing this trade off, and how this is modulated by environmental conditions, is central for our ability to manage the local fisheries in relation to the increased occurrence of hypoxia episodes.

We recognize that, beside the importance of lagoons and coastal waters within the WFD, there are difficulties in detecting the ecological status of transitional waters using the biotic indices proposed within the WFD (Munari and Mistri, 2008). This is consistent with the fact that the mechanisms and the processes occurring in transitional waters (e.g. spatio-temporal variability, organic enrichment, productive activities) make it difficult to translate the assessment and the conservation strategies into management recommendations (Munari and Mistri, 2008). We thus emphasize the importance and support of such a multidisciplinary and ecosystemic approach as that we demonstrated for the Oristano Lagoon-Gulf system in detecting, for example, priority areas (i.e. areas subjected to dystrophic events, with anoxia and sulphide development) for future remediation measures.

Extrapolating our study within the broader context of human-impacted coastal lagoons of the Mediterranean Sea, we highlight the following concluding remarks:

- 1) the need for a multidisciplinary monitoring approach, which could give integrated results from different disciplines, such as analysis of sediment characteristics (e.g. grain size composition and partitioning, sulphide and organic matter concentrations) in relation to the composition and distribution of the biotic components (e.g. macrobenthic assemblages) (Magni *et al.* 2008a,b). This also includes an organismic approach aimed at testing behavioural thresholds below which fish and other organisms will show suboptimal behaviour. These thresholds are likely to be sublethal for most environmental variables, and we suggest that this concept of

sublethal thresholds affecting the behaviour of organisms should be used for identifying “danger zones” revealed by monitoring programs (Domenici *et al.* 2007).

2) the need for an ecosystemic approach (e.g. a coupled sea-lagoon research), including the application of numerical modeling, to investigate changes (and scenarios) in hydrological, biological and ecological features, since the maintenance and the conservation of lagoon and coastal environments need careful attention and specific actions based on appropriate biological and ecological knowledge (Cognetti and Maltagliati, 2008).

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