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

P. Magni1,*, S. Como2, A. Cucco1, G. De Falco1, P. Domenici1, M. Ghezzo1, C. Lefrançois1,4, S. Simeone2, A. Perilli1

1CNR–IAMC, National Research Council, Institute for Coastal Marine Environment, Località Sa Mardini, Torregrande, 09072 Oristano, Italy;
2IMC, International Marine Centre, Località Sa Mardini, Torregrande, 09072 Oristano, Italy;
3CNR–ISMAR, National Research Council, Institute for Marine Science, Riva Sette Martiri 1364/a, 30122 Venice, Italy;
4University of La Rochelle, Department of Biology, 17000 La Rochelle, France;
*Corresponding Author: paolo.magni@cnr.it; tel.: +39 0783 22027; Fax: +39 0783 22002.

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-Maldiveventre), 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>
<thead>
<tr>
<th>Lagoon</th>
<th>Surface Km²</th>
<th>Mean Depth</th>
<th>Max. Depth</th>
<th>Volume Mm³</th>
<th>Freshwater Inflow</th>
<th>Habitat Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabras</td>
<td>22.3</td>
<td>1.7</td>
<td>3</td>
<td>33.4</td>
<td>Yes</td>
<td>Brackish-Marine</td>
</tr>
<tr>
<td>Mistras</td>
<td>4.7</td>
<td>0.5</td>
<td>1</td>
<td>4</td>
<td>No</td>
<td>Marine-Hyperhaline</td>
</tr>
<tr>
<td>Santa Giusta</td>
<td>8.4</td>
<td>1.5</td>
<td>1.9</td>
<td>12.6</td>
<td>Yes</td>
<td>Brackish-Marine</td>
</tr>
<tr>
<td>S'Ena Arrubia</td>
<td>1.2</td>
<td>0.4</td>
<td>0.8</td>
<td>0.5</td>
<td>Yes</td>
<td>Brackish</td>
</tr>
<tr>
<td>Corru de S'Ittiri</td>
<td>1.5</td>
<td>0.8</td>
<td>3</td>
<td>4.5</td>
<td>No</td>
<td>Marine</td>
</tr>
<tr>
<td>Marceddi – San Giovanni</td>
<td>8.0</td>
<td>1</td>
<td>2</td>
<td>8</td>
<td>Yes</td>
<td>Brackish</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Lagoon</th>
<th>Main features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabras</td>
<td>Dam construction, digging of the Scolmatore 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”.</td>
</tr>
<tr>
<td>Mistras</td>
<td>Construction of a fish-pond and aquaculture facilities</td>
</tr>
<tr>
<td>Santa Giusta</td>
<td>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.</td>
</tr>
<tr>
<td>S’Ena Arrubia</td>
<td>Digging and construction of a central canal and a canal connecting to the sea; construction of various-size barriers and fish-pond.</td>
</tr>
<tr>
<td>Corru de S’Ittiri</td>
<td>Construction of barriers and fish-pond.</td>
</tr>
<tr>
<td>Marceddi – San Giovanni</td>
<td>Construction of barriers, dams and “lavorieri”.</td>
</tr>
</tbody>
</table>

**Table 2.** Main man-made interventions on the lagoons connected to the Gulf of Oristano (western Sardinia, Italy).
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 diary 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 small tourist industry is provided 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
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 scenarios 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_\text{opt}_), the speed that implies the lowest amount of energy per unit travelled; Videler, 1993). Hypoxia-related reduction of stamina at _U_\text{opt} would therefore have energetic consequence during activities, such as foraging or habitat exploration when _U_\text{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_\text{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_\text{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 $V_{\text{max}}$ and maximum acceleration $A_{\text{max}}$) 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 each hydrodynamic structure. 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 vortexes 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 vortexes 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 vortexes 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,
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 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.
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 meteo-marine 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

**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.

**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.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Whole Lagoon</th>
<th>Central sector</th>
<th>Southern sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tide</td>
<td>43</td>
<td>40</td>
<td>47</td>
</tr>
<tr>
<td>Sirocco</td>
<td>35</td>
<td>36</td>
<td>31</td>
</tr>
<tr>
<td>Mistral</td>
<td>29</td>
<td>23</td>
<td>25</td>
</tr>
<tr>
<td>Libeccio</td>
<td>35</td>
<td>36</td>
<td>32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Whole Lagoon</th>
<th>Central sector</th>
<th>Southern sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tide</td>
<td>35</td>
<td>37</td>
<td>31</td>
</tr>
<tr>
<td>Sirocco</td>
<td>29</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Mistral</td>
<td>22</td>
<td>24</td>
<td>18</td>
</tr>
<tr>
<td>Libeccio</td>
<td>29</td>
<td>31</td>
<td>26</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Difference</th>
<th>Whole Lagoon</th>
<th>Central sector</th>
<th>Southern sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tide</td>
<td>0</td>
<td>3</td>
<td>16</td>
</tr>
<tr>
<td>Sirocco</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Mistral</td>
<td>7</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Libeccio</td>
<td>6</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>
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
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...
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 (Gulf).

Figures 7a, b. Spatial distribution of fine sediments (8 µm 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 µm) within the mud (<64 µm) (C) in the southern sector of the Cabras Lagoon (Lagoon) and the adjacent coastal area of the Gulf of Oristano (Gulf).
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-binding 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 fumigate, 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 µm and the <64 µm 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.](image_url)
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 \textit{P. oceanica} and \textit{C. nodosa} seagrass meadows.

\textbf{Fishes}

\textit{Activity in Liza aurata}. During hypoxia, swimming activity of \textit{L. aurata} increased significantly at \(\leq 60\%\) air saturation (AS) compared with normoxia in both solitary and shoaling individuals (Lefrançois \textit{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

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Effect of sub-lethal levels of hypoxia on Mugilidae which perform aquatic surface respiration (ASR). For the different functions studied, signs ↑ and ↓ 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 \textit{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 (\(U_{\text{opt}}\)) and swimming performance, and consequently fitness. The “+” signs within parenthesis are based on these theoretical predictions. Modified after Domenici \textit{et al.} 2007.}
\end{figure}
≤ 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 $U_{\text{opt}}$ 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 $U_{\text{opt}}$ (Fig. 10). Furthermore, after the stamina test, $M_O$, measured in fish tested at 15% AS was significantly higher than the $M_O$ measured in fish tested in normoxia. Increase in $M_O$ 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 $U_{\text{opt}}$. While further work is necessary to establish the extent to which *M. cephalus* use $U_{\text{opt}}$ 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 < $U_{\text{opt}}$, 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 $V_{\text{max}}$ 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).

Acknowledgements

This work was funded by the SIGLA project. (Sistema per il Monitoraggio e la Gestione di Lagune ed Ambiente) of the Italian Ministry for Scientific Research. It was presented at the International Workshop “The implementation of the Water Framework Directive (EC2000/60) in Italy: State of the art on benthic indicators and European experiences.” Ferrara 29 April 2008. We gratefully acknowledge two anonymous referees for their valuable comments on an early version of this manuscript. It is contribution number MPS-08054 of the EU Network of Excellence MarBEF.
References


Randall D 1982. The control of respiration and circulation in fish during exercise and hypoxia.