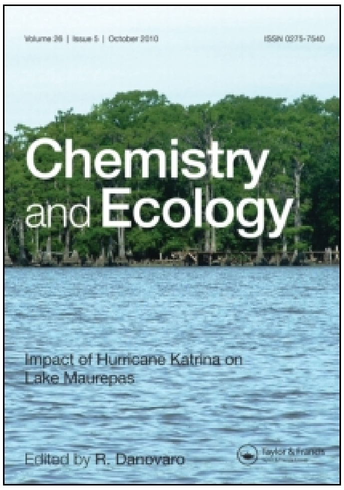

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Changes of nutrient concentrations and phytoplankton communities after morphological modification in the S'Ena Arrubia Lagoon (Central-Western Sardinia)

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Changes of nutrient concentrations and phytoplankton communities after morphological modification in the S'Ena Arrubia Lagoon (Central-Western Sardinia)

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S'Ena Arrubia Lagoon (Central-Western Sardinia) is a eutrophic system and is strongly influenced by human activities. The sea mouth was widened in 2000 to reduce the high trophic levels and improve its hydrodynamics. To study the environmental consequences of this 'reframing', nutrient concentrations and phytoplankton were compared before (1990–1999) and after (2000–2003) the hydrological works. The land–ocean interactions in the coastal zone (LOICZ) biogeochemical model was also applied for some years during the previously mentioned two periods. Results showed significant variations for salinity, Chlorophyll *a* and phytoplanktonic principal classes, and the LOICZ model results indicated that the water residence time was less. However, the expected decrease of nutrient concentration was not observed. Sea-mouth widening is one of the possible management strategies that can be used to reduce the high trophic state of lagoons. It should, however, probably be used in conjunction with watershed management if the objective is also to reduce eutrophication.

Keywords: Coastal lagoon; Environmental management; Eutrophication; Nutrients; Phytoplankton; Engineering works

1. Introduction

One of the major effects of the increase in nutrients in shallow coastal systems all over the world is eutrophication. It is increasing very quickly, especially in the developed world [1–3]. The first effect of this enrichment is high primary production of both phytoplankton and macroalgae [4]. Changes in water quality following eutrophication can have significant economic and social impact [5, 6].

Coastal lagoons provide nursery areas to many marine species and are thus of great importance for the fishing industry. They are also becoming increasingly important for tourism [7, 8]. Coastal lagoons are often characterized not only by large anthropogenic nutrient inputs but also by limited seawater exchange, low water turnover and long residence time [9–12]. This can easily lead to system eutrophication. Owing to the ecological and economic importance

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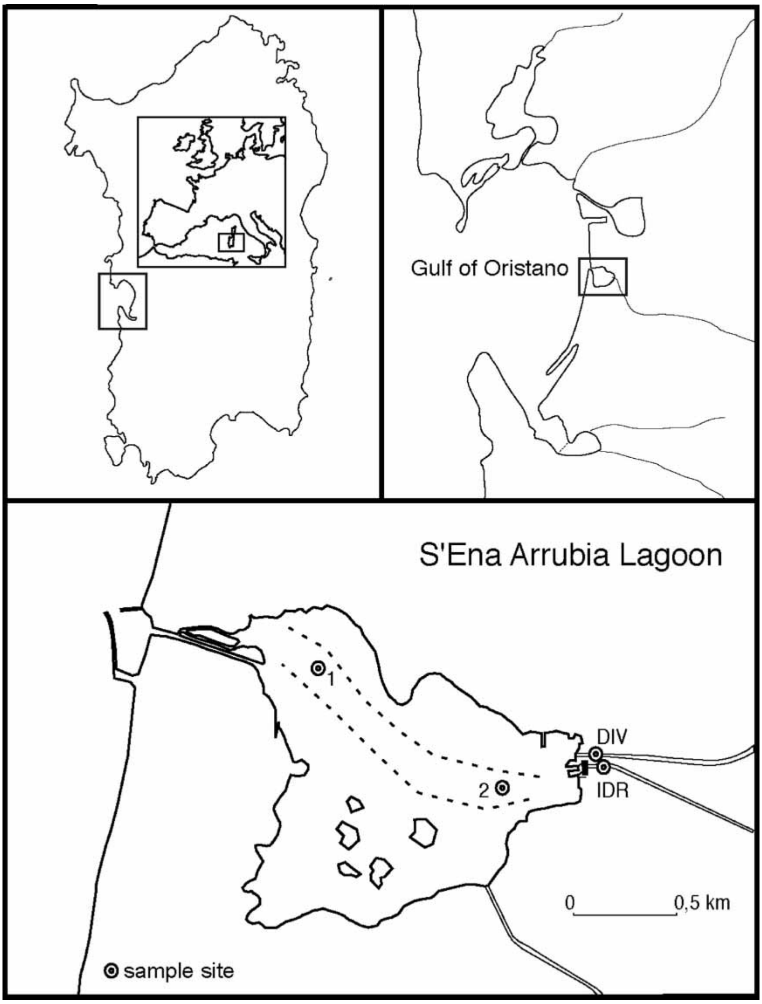

Figure 1. Location of the S'Ena Arrubia Lagoon and sampling stations.

of lagoons, several attempts have been made to improve water quality in these systems by increasing tidal flushing. This dilutes nutrient concentrations and prevents algae from blooming [13–15]. Restoring the quality of the water body is crucial if fishing and tourism are to be maintained and encouraged. According to Wasserman [16], during the next 10 years, the properties around lagoons may lose up to 50% of their economic value if eutrophication persists. Studies are needed on the effects of the various methods of reducing eutrophy in order to identify which are most efficacious. These are often difficult to do because there is little data available on the situation before the improvements were made.

S'Ena Arrubia Lagoon (Central-Western Sardinia) (figure 1) is eutrophic system because of the intense arable and stock-rearing activities in its watershed [17, 18]. The great quantity of phytoplankton blooms [19] and macroalgae blooms [20] and the dystrophic crises which sometimes kill fish are all evidence of highly trophic conditions.

Engineering works were carried out in 2000 to widen the sea mouth of the lagoon in order to improve tidal flushing and thus reduce its high trophic levels and improve its hydrodynamics. This study assesses the impact of the work on phytoplankton and nutrient concentrations in the lagoon. The changed morphology of the lagoon was expected to improve water exchange, lower nutrient concentrations and limit algal blooms. To study the actual environmental consequences of this 'reframing', nutrient concentrations and phytoplankton were compared before (1990–1999) and after (2000–2003) the hydrological works. The land–ocean interactions in the coastal zone (LOICZ) biogeochemical model [21] and multivariate analyses were used to do this.

2. Study site description

S'Ena Arrubia Lagoon (39.83°N–8.57°E) is located in central-western Sardinia (Italy). It has a surface area of 1.2 km^2 and its depth ranges from 40 to 60 cm. The lagoon is the residual wetland left from the drying up of a larger original lagoon of over 3000 ha. Freshwater inputs come from the catchment area of two canals: Rio Sant'Anna (also called 'Diversivo') which drains an area of 78.4 km^2 and the 'Canale delle Acque Basse' (also called 'Idrovora') which drains 50 km^2. The latter is below sea level and water is pumped into the lagoon. A large part of the catchment area is used for intensive arable farming and cattle breeding, and as a result, the freshwater in the Idrovora canal is very rich in nutrients (table 1).

The water in the lagoon is exchanged with sea water by means of a sea-mouth canal built in the 1970s (length = 230 m, width = 25 m, depth = 1.3 m). This was widened in 2000. The dimensions of the new inlet vary in different places. It is 30 m wide and 0.70 m deep near the lagoon, 60 m wide and 2 m deep in the central part and 32 m wide and 1.30 m deep at the sea mouth.

The lagoon is included in the Ramsar Convention and in the Important Birds Area list. It was recognized as a UE relevant site (SIC, 92/43 CEE) and is considered as a Special Protection Area for the conservation of the species listed in Annex I to the Directive and by the Sardinia Government as a protected area for animals (79/409 CEE).

The principal human activities in this wetland are fishing, outdoor recreation, education and scientific research.

3. Materials and methods

Lagoon samplings were carried out at two stations, monthly from 1990 to 1999 and fortnightly (October–May) or weekly (June–September) from 2000 to 2003. One station was near the freshwater input (St. 2) and the other near the sea mouth (St. 1) (figure 1). Catchment area nutrient sampling (available only after 2000) was carried out fortnightly (October–May) or weekly (June–September) from 2001 to 2002 at a third station located in the Idrovora Channel (Idr.).

Dissolved oxygen and salinity were measured using a multiparameter Idronaut probe (model 401). Ammonia, nitrites and nitrates, reactive phosphorus and total phosphorus concentrations were determined following the method suggested by Strickland and Parsons [22]. Chlorophyll *a* (Chl *a*) analyses were carried out following the method suggested by SCOR-UNESCO [23]. Phytoplankton samples were preserved in both Lugol's solution and formalin 4% and analyzed using Utermöhl's method [24].

Two multivariate analyses were used to compare phytoplankton assemblages and environmental conditions prior to and following lagoon reframing. Matrices of similarity were obtained as follows: the average monthly total for each month of every year before and after the engineering works was calculated and the average results before and after the changes were then compared. The Bray–Curtis similarity coefficient on untransformed data was used for phytoplankton [25], and the Euclidean distance on normalized data was used for chemical data (salinity, dissolved oxygen, total phosphorus, reactive phosphorus, ammonia, nitrates and nitrites). One-way ANOSIM [26] was performed to estimate the variability caused by reframing. This analyzed and compared abiotic and biotic data from the two periods (before and after reframing). Non-metric multidimensional scaling (nMDS) was used to produce two-dimensional ordinations.

Three-way ANOVAs were performed to estimate the temporal variability of abiotic data (DIN as sum of all inorganic nitrogen forms, salinity and total phosphorus). The factors tested were: 'reframing' (before *vs*. after), 'month' (12 levels), treated as fixed and orthogonal factors, and 'year' (three levels), treated as random and nested in 'reframing'. Because data after the reframing were taken for 3 years, 3 years at random were chosen from the 10 year period of sampling before the changes. This was done to balance the design. The two sampling points within the lagoon were used as replicates. Variance homogeneity was checked using Cochran's test and data were transformed whenever necessary.

The LOICZ biogeochemical model (Gordon *et al.*, 1995) was applied to S'Ena Arrubia using the 'one box-one layer' model because of the small size and shallowness of the lagoon [27, 28]. The model – apart from estimating the budgets of non-conservative compounds and evaluating ecosystems functions – allows the advective exchange between the lagoon and the sea and the theoretical water residence time to be calculated.

4. Results

Average monthly salinity (figure 2) ranged from 13‰ to 40‰ before 2000 and from 7‰ to 43‰ in the following years. In 2002, the values were high (from 28‰ to 43‰). From the frequency distribution of salinity data before and after reframing (figure 3), one can see that values of over 30‰ and 35‰ were more frequent after 2000, whereas before 2000, the values ranged from 15‰ to 25‰.

Oxygen dynamics were very variable with frequent oscillations, and the values were occasionally <50%. There was no great difference in the frequency distribution of oxygen between the two periods.

Average total phosphorus concentrations ranged from 101 to 811 mg P m^{-3} until 1999 and from 89 to 1220 mg P m^{-3} after 2000. The frequency of values for total phosphorus concentrations of both >250 mg P m^{-3} and <100 mg P m^{-3} increased after 2000. Reactive phosphorus dynamics frequently oscillated during the whole period, with a peak in 2003. From 1990 to 1999, values ranged from 28 to 393 mg P m^{-3} and after 2000 from 34 to 825 mg P m^{-3}. From 2000 to 2003, values of reactive phosphorus concentrations >250 mg P m^{-3} were more frequent.

Average concentrations ranged from 4 to 732 mg N m^{-3} until 1999 and later between 7 and 632 mg N m^{-3} for ammonia; from 3 to 2798 until 1999 and later 4 and 1099 mg N m^{-3} for nitrate; from 1 to 413 until 1999 and later 1–187 mg N m^{-3} for nitrite. An increase in the frequency of values >150 mg N m^{-3} for nitrates and, conversely, an increase in the frequency of values <50 mg N m^{-3} for ammonia were observed (figure 3).

There were very high concentrations of total and reactive phosphorus and nitrogen inputs in the water from the catchment area (table 1). Total phosphorus ranged from 447 to 1665 mg P m^3, ammonia from 157 to 1204 mg N m^3 and nitrates from 50 to 3213 mg N m^{-3}.

Mean concentrations of Chl *a* ranged from 2 to 164 mg m^{-3} between 1990 and 1999, whereas values of 2–48 mg m^{-3} were recorded from 2000 until 2003. Values were always <50 mg m^{-3} from 2000 to 2003, whereas during previous years, values were often above this

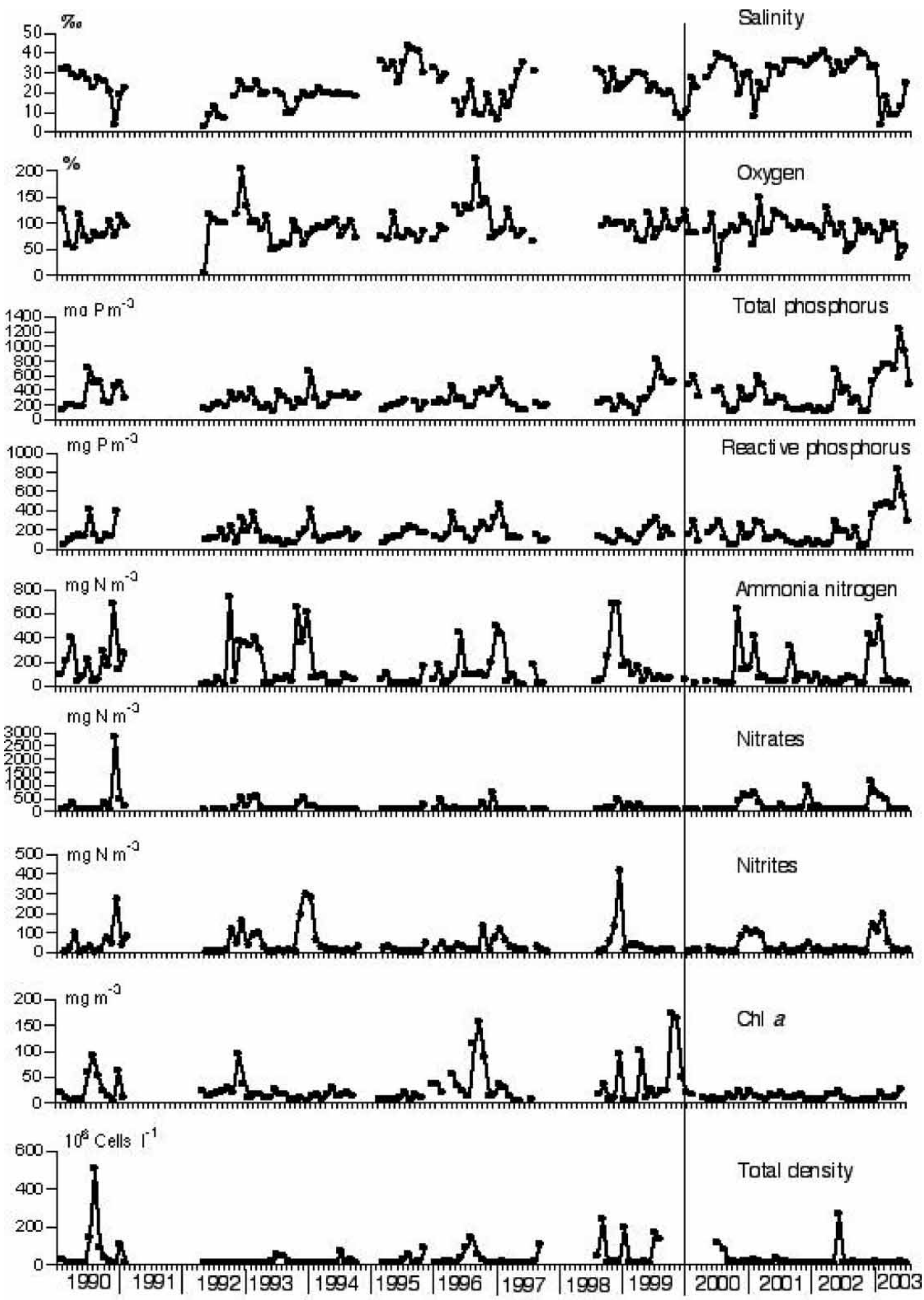

Figure 2. Long-term dynamic of salinity, oxygen dissolved, total phosphorus, reactive phosphorus, ammonia, nitrates, nitrites, Chl *a* and phytoplankton total density (average of the two stations). Straight line indicates reframing.

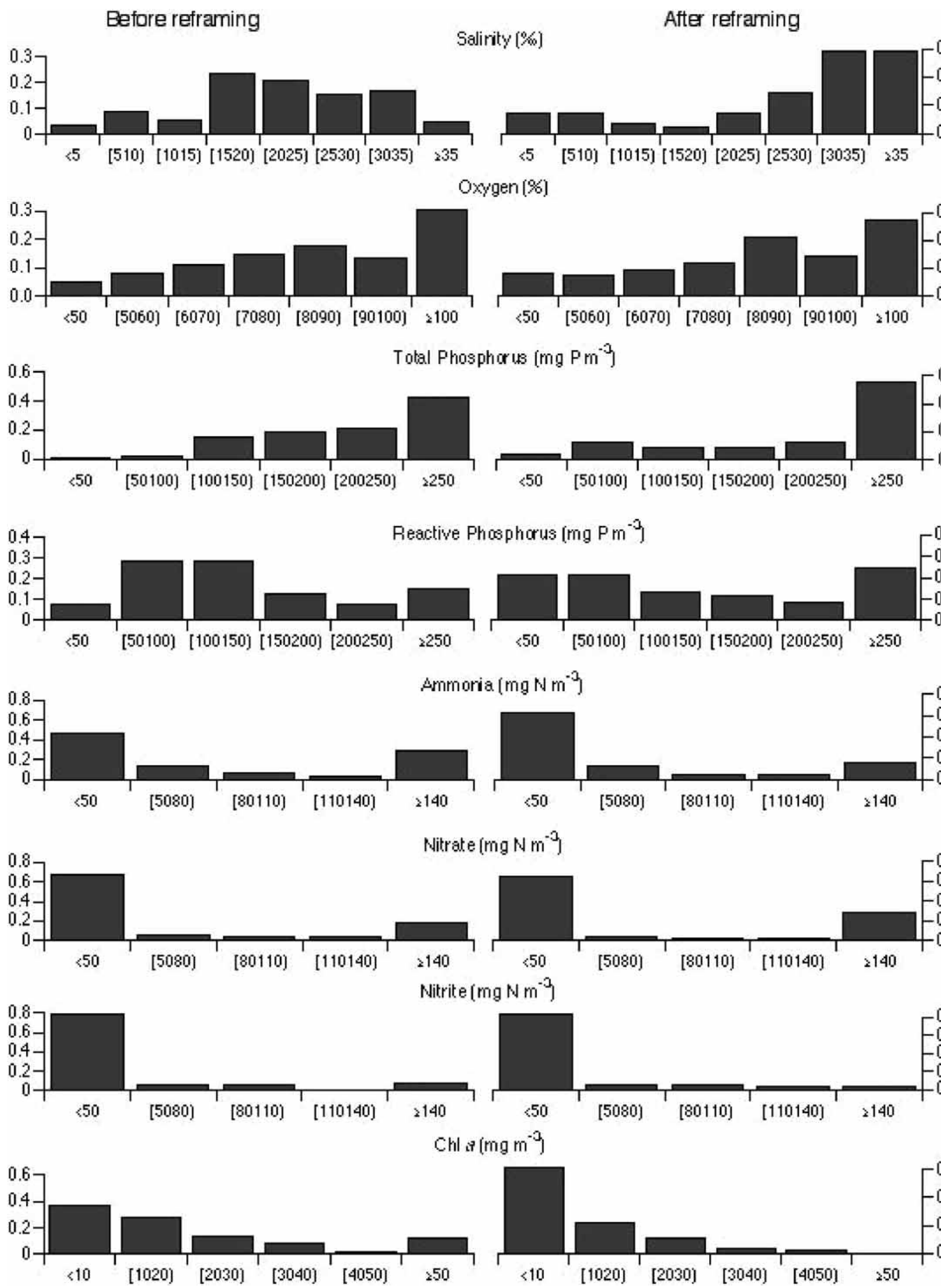

Figure 3. Frequency distribution of salinity, dissolved oxygen, total phosphorus, reactive phosphorus, ammonia, nitrates, nitrites and Chl *a* in the two stations before and after sea-mouth widening.

concentration, with a peak of use 169 mg m^{-3} in 1996 (figure 2). Chl *a* frequency distribution was always <40 mg m^{-3} and an evident dominance of values $\leq$ 10 mg m^{-3} after 2000.

Total phytoplankton density was more variable in the 1990–1999 period than afterwards. The ranges were 0.1–1771 $\times 10^6$ and 1–262 $\times 10^6$ cells l^{-1}, respectively (figure 2). Chlorophyceae, Bacillariophyceae, Euglenophyceae, Dinophyceae, Cryptophyceae, Chrysophyceae, Haptophyceae, Raphydophyceae and Ultraplancton were the phytoplankton classes found in

Table 1. 'Idrovora Channel' average monthly nutrient.

Idrovora	Total phosphorus (mg P m^{-3})	Reactive phosphorus (mg P m^{-3})	NH_3 (mg P m^{-3})	NO_3 (mg P m^{-3})	NO_3 (mg P m^{-3})
J 01	1665	920	1204	3213	318
F	1294	814	1170	2551	246
M	1325	813	899	1046	245
A	860	473	710	324	115
M	799	485	186	368	100
J	857	472	363	895	86
J	703	441	484	442	77
A	1056	497	406	87	26
S	733	498	262	50	21
O	877	549	521	125	49
N	514	259	276	371	92
D	447	216	383	946	57
J 02	560	212	683	1954	96
F	1001	601	451	1183	110
M	1226	574	320	1023	114
A	1199	383	290	454	103
M	811	321	430	171	64
J	1966	1185	1007	258	159
J	1938	969	448	2195	224
A	1469	1148	439	1744	265
S	1651	993	157	266	27
O	1651	993	157	266	27
N	1246	383	196	373	31
D	685	464	260	2138	306

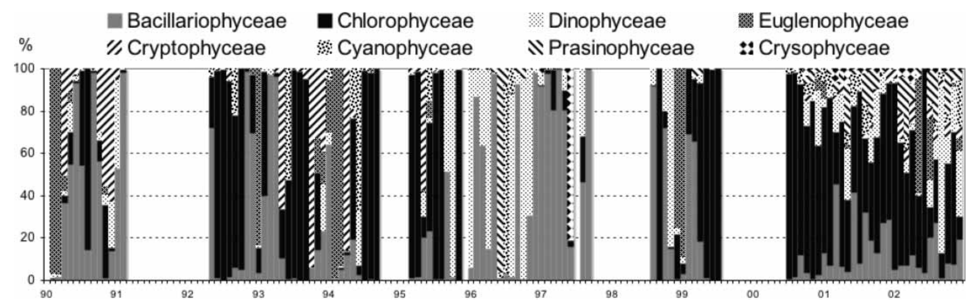

Figure 4. Class percentage abundance of phytoplankton (average of the two stations). Dotted line indicates reframing.

the samples. Class composition within the total density underwent drastic changes. To be precise, after reframing, Chlorophyceae (represented mainly by *Chlorella* sp.) increased and Bacillariophyceae decreased (figure 4).

The phytoplankton species of S'Ena Arrubia were mostly marine and brackish waters, but in several occasions, typical freshwater taxa were found, especially in the station affected by catchment area inputs (*Oscillatoria* sp., *Lyngbya* sp., *Cryptomonas* sp., *Synechoccoccus* sp., *Anabaena* sp. and *Chlamydomonas* sp. were the most frequent species).

MDS ordination plots revealed differences in structure of assemblages between 1990–1999 and 2000–2002 for both chemical data and phytoplankton classes (figure 5). ANOSIM detected significant differences between the two periods: $p = 0.1\%$, $R = 0.341$ and $p = 1\%$, $R = 0.236$ for chemical and phytoplankton data, respectively. SIMPER identified Chlorophyceae

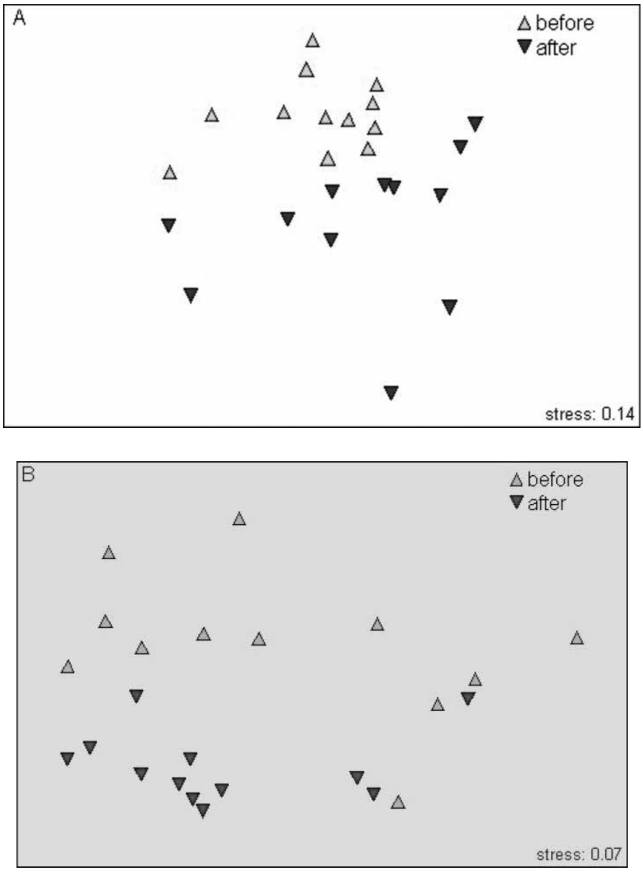

Figure 5. MDS ordination of month centroides, before and after sea-mouth widening, of chemical–physical data (A) and phytoplankton classes (B).

Table 2. Taxa mostly contributing to differences between the periods (SIMPER).

	Average abundance (Cells l^{-1})		
Species	Before	After	Contribution%
Chlorophyceae	38,024,099	14,215,210	55.8
Bacillariophyceae	11,470,326	1,201,813	26.6
Dinophyceae	1,083,066	621,998	6.5
Euglenophyceae	597,855	174,975	4.7

(55.8%) and Bacillariophyceae (26.6%) as the classes that contributed most significantly to the differences between the two periods (table 2).

ANOVA results suggested that the reframing of the lagoon significantly affected salinity, the concentrations being higher after widening the mouth than they were before (table 3). However, the other two environmental variables analyzed were not significantly affected by the period. Cochran's test was significant for salinity and DIN variables. A significant variability at the scale of the year and month was detected for DIN and P tot both before and after reframing.

Results of the LOICZ model for 1994 and 1995 [27] and from 2001 to 2002 [28] were compared: the residence time was reduced (τ) from 3–229 days to 1–8 days (table 4).

Table 3. Three-way ANOVAs on DIN, salinity, P tot: 'reframing' (before *vs*. after), 'month' (12 levels) treated as fixed and orthogonal factors and 'year' (three levels) treated as random and nested in 'reframing'.

		Salinity			DIN			P tot		
	df	MS	F	p-value	MS	F	p-value	MS	F	p-value
Reframing (Re)	1	4911.6	26.03	0.007	837682.5	2.29	0.204	5088.4	0.13	0.7324
Month (Mo)	11	44.28	0.44	0.927	2279235.3	6.67	0.000	61211.5	1.73	0.0982
Year (Ye) (Re)	4	188.72	15.65	0.000	365601.8	8.34	0.000	37841.5	4.28	0.0037
Re × Mo	11	195.06	1.95	0.058	237292.9	0.69	0.736	40860.0	1.15	0.3454
Mo × Ye(Re)	44	100.12	8.30	0.000	341586.9	7.79	0.000	35398.3	4.00	0.0000
Residual	72	12.06			43861.1			8846.80		
Cochran's test			$C = 0.484^{\dagger}$			$C = 0.5033^{\dagger}$			$C = 0.1075$ ns	

Table 4. Comparison of residence time results by LOICZ model application before and after reframing.

Season 1994–1995	Days	Season 2001–2002	Days
Jan–Feb–Mar 94	22	Apr–May–Jun 01	4
Apr–May–Jun 94	17	Jul–Aug–Sep 01	8
Jul–Aug–Sep 94	16	Oct 01	4
Oct–Nov–Dec 94	3	Nov–Dec–01	1
Jan–Feb–Mar 95	10	Jan–Feb–Mar 02	5
Apr–May–Jun 95	51		
Jul–Aug–Sep 95	36		
Oct–Nov 95	229		
Dec 95	6		

5. Discussion and conclusions

Results of this study indicate that some changes occurred in both environmental and biotic conditions after lagoon reframing. Overall, analyses of similarities of chemical data revealed significant differences between the two periods. After lagoon reframing salinity values fluctuated within tighter limits, with more frequent higher values being recorded. In contrast, there were no relevant differences in the total and reactive phosphorus concentrations and in all inorganic nitrogen forms concentrations between the two periods.

However, interesting changes were observed for biotic data. Chl *a* concentrations were often higher before the sea-mouth widening than after, as shown by frequency distribution histogram. There were differences in phytoplankton class composition for the two periods. Analysis of similarities revealed differences in the overall structure of assemblages. Chlorophyceae and Bacillariophyceae were the taxa that contributed most to these differences. Finally, LOICZ model highlighted evident differences in the water residence time of the system after the sea-mouth reframing.

Before 2000, fish kills were observed in the lagoon in the summer almost every year, many of them related to anoxic crises and a few, but rarely, to toxic algae. Particularly strong events were recorded in 1989, 1995, 1998 and 1999.

After 2000, there were two partial fish kill: in September 2001 and in October 2002. Although for the latter, neither critical oxygen values nor particularly high nutrients concentrations nor any toxic algal species were found in our data. Possibly, this event was related to the use of some pesticides in the catchment area, but due to the lack of investigation at the time, this can only be hypothesized.

S'Ena Arrubia Lagoon is an ecosystem strongly influenced by human activities and management. As it is small, it is likely to be very sensitive to allochthonous inputs and is probably a suitable site for collecting data. Several actions have been taken to improve the lagoon's trophic condition and, consequently, its fishing yield. In the 1970s, part of the bottom was dredged and more recently wetland phyto-depuration basins were constructed, although they have never been used.

The sea-mouth widening was expected to modify the lagoon's water residence time and thus reduce eutrophication. In particular, as suggested by Cioffi and Gallerano [14], both an increase in nutrient concentration in the sea water and a reduction of that in the lagoon was expected, as well as an increase in the turbulent intensity of the water column with the oxygen exchanges between atmosphere, water column and sediments becoming, as a result, more efficient. In S'Ena Arrubia Lagoon, although variations in residence time, salinity, Chl *a* and phytoplankton composition were observed, the expected reduction in nutrient concentrations was not observed. This is probably because the system is still strongly affected by the heavy inputs of nutrients from the catchment area.

These results have been supported by those of other studies. For example, Delesalle and Sournia [29] suggested that in coral reef lagoons, phytoplankton biomass is controlled by residence time more than nutrient availability. The effects of nutrient loading on phytoplankton in coastal ecosystems have also been shown to depend on other factors including light availability [30–32], sedimentation rates, hydraulic flushing [33] and grazing [34]. It is also well known that plankton populations in brackish-water ecosystems are influenced by the variations of hydrochemical parameters in time and space and tidal dynamics [35, 36] and rapid changes in salinity can determine phytoplankton abundance and composition [37].

Sea-mouth widening is one of the possible ways of reducing high trophic level in critical systems such as S'Ena Arrubia. However, this may make the environmental conditions of the system more similar to marine conditions, which would seriously modify the ecology of the system. Reducing nutrient inputs would probably be a more efficient and conservative way of achieving successful results, although it is a strategy which is difficult to put into practice.

McClelland and Valiela [5] observed how difficult it was to restore habitats altered by the enrichment of nutrients and pointed out that good management must involve first identifying such environments and then developing a suitable prevention policy. Several successful restoration strategies have been adopted for lagoons. For example, Cioffi and Gallerano [4] used models to show that the best management strategy for limiting eutrophication in the Fogliano Lagoon was harvesting the sea-grass biomass, rather than regulating the tidal flow. In another case, Hillsborough Bay (Florida) was successfully restored by reducing the quantity of nutrients from the catchment area [15].

In conclusion, in order to manage a complex ecosystem like S'Ena Arrubia Lagoon correctly, one must first establish what the lagoon is to be used for and then decide on the correct strategies to achieve this. Data on selected important ecosystem variables (chemical and biotic data, sediments, exchange flows with sea and from the catchment area) should be collected. This would (1) enable us to ascertain the correct availability of freshwater and the permissible nutrient input loads for the lagoon if a good level of fish production is to be maintained and (2) define what quantity of water should be exchanged with the sea to achieve good vivification and avoid anoxic conditions. However, when attempting to achieve these objectives, one must always bear in mind the great variability in the structural components, which is characteristic of such environments. These often make it almost impossible to predict with accuracy what will be the precise results and consequences of a particular management strategy.

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