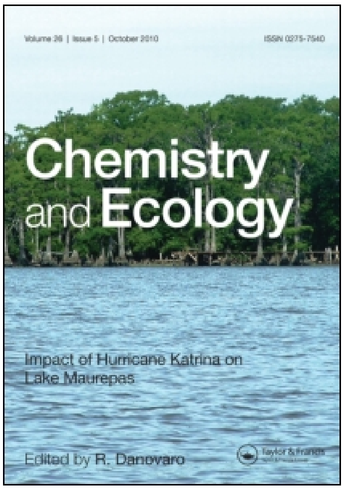


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# Nutrient-flux evaluation by the LOICZ Biogeochemical Model in Mediterranean lagoons: the case of Cabras Lagoon (Central-Western Sardinia)

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In this study, the Land-Ocean Interactions in the Coastal Zone (LOICZ) budgeting procedure was used to evaluate the main nutrient pathways and ecosystem functions within Cabras Lagoon (Central-Western Sardinia, Italy) in 2004. The results of a simple one-box and one-layer model showed that nutrient accumulation prevailed over mobilisation for both dissolved inorganic phosphorus (annual mean of 675.69 mol $d^{-1}$) and dissolved inorganic nitrogen (mean of 6120.05 mol $d^{-1}$). Net ecosystem metabolism (NEM) was always positive, implying that production predominated over respiration throughout the year (mean of 3.3 mmol C $m^{-2}d^{-1}$). Estimates obtained from the model also highlighted the fact that nitrogen fixation prevailed over denitrification (mean of 0.14 mmol $m^{-2}d^{-1}$). Finally, extended water-residence times (mean of 192 days) were observed in the lagoon, particularly in the summer. An approach based on the improvement of water exchange with the sea would provide a relatively simple and short-term interim strategy, until more comprehensive actions aimed at reducing the anthropogenic nutrient loads in the watershed can be implemented.

**Keywords:** coastal lagoon; nutrient balance; net ecosystem metabolism; eutrophication; Mediterranean lagoon; Cabras Lagoon

## 1. Introduction

Lagoons and estuaries are part of the continuum between the watershed and the coastal zone, acting as important filters and transformers of the inorganic and organic nutrients contained in river discharges [1–3]. However, as such they are highly vulnerable to the adverse effects of anthropogenic impacts, especially those of pollution, eutrophication, and physical disturbances [2,4]. This vulnerability has highlighted the need for local management policies that integrate scientific and socio-economic considerations, in agreement with the directives laid out by the European Union [5], while allowing for the sustainable use of coastal resources [6].

Assessment of nutrient fluxes, especially, water, salt, and nutrient balances [2,7] in lagoon systems is a crucial step in understanding their ecology. While lagoon metabolism has been

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extensively reviewed in a number of relatively recent papers [8], difficulties persist due to the limited amount of data available on nutrient concentration and to seasonal variability, especially with respect to land run-off and the atmospheric compartment. These difficulties can be overcome by the use of models that budget biogeochemical processes, as they not only allow integral estimates over large areas but also can be applied locally, including those sites where direct measurements are not available [4].

The guidelines proposed by the Land-Ocean Interactions in the Coastal Zone (LOICZ) [9] biogeochemical model offer a simple general approach to construct C, N, and P biogeochemical budgets in coastal environments, with the broader aim of assessing their roles in the cycling of carbon and nutrients at local and global scales. The LOICZ model estimates water flows and the water/nutrient flow within that system elucidating features such as: (i) net ecosystem metabolism (NEM); (ii) whether the system acts as a sink or a source for nutrients; and (iii) the prevalence of denitrification vs. N-fixation. In addition, application of the model allows water-residence times to be estimated, yielding a broadly useful indication of the hydrological dynamism of the system under study. Based on the information obtained, ecosystems can be grouped according to their typology and thus compared and analysed on regional and global scales [5]. Indeed, the LOICZ biogeochemical model has been applied on a worldwide scale to a very wide range of environments, including transitional areas in general (see the LOICZ Reports and Studies series) [2,4,10], river basins, and coastal zones, and have confirmed that coastal eutrophication is a consequence of elevated levels of waterborne nutrients [11–13].



At a global scale, heterotrophism has been correlated with hypersaline systems [14–21], especially for leaky lagoons. In lagoons in which long water-residence times lead to the retention of large quantities of anthropogenic phosphorus in the sediments, hypersalinity limits, albeit only indirectly, both the growth of biomass and net primary production. In these cases, lagoons act as true sinks for terrestrial and marine phosphorus. Nonetheless, despite their retention of large amounts of terrestrial (mainly anthropogenic) inputs, lagoons may also act as a source of dissolved inorganic nitrogen (DIN) input to coastal waters [10]. In other cases, systems mainly controlled by freshwater (river) discharge (particularly those with a relevant level of enclosure) are important sources of nutrients and are thus characterised by a net autotrophism [22,23].

Since 2002, the LaguNet research group has applied the LOICZ model to study 22 ecosystems of the Mediterranean basin. The purpose was to integrate regional expertise with information obtained from studies on lagoons and coastal transitional ecosystems in order to evaluate nutrient fluxes and related ecosystem functions [5]. About 50% of the systems studied so far have been shown to receive high loads of dissolved inorganic phosphorus (DIP) and nitrogen (DIN), more than 0.05 and 0.8 $\text{mol m}^{-2}\text{ y}^{-1}$, respectively, reflecting intense human pressure on the respective watersheds, the majority of which are subjected to intense agricultural exploitation. At the study sites, a strong relationship between DIP loads and variations in DIP in the lagoons has been determined. Specifically, at low loads these systems act as sources of DIP (positive $\Delta$DIP), whereas at high loads they function as DIP sinks [5]. Other trends, such as the dominance of autotrophic systems and net denitrifying systems in the global coastal zone, have also been assessed by LaguNet researchers [5]. For example, NEM values, which indicate whether a system is highly heterotrophic or autotrophic, were estimated for systems dominated by floating macroalgae and found to be very high (both positive and negative). The difference between N-fixation and denitrification (*nfix-denit*) within such systems reflects the fact that microbial processes are linked to the availability of inorganic nitrogen, the abundance of organic matter, as well as on oxygen availability. In general, LaguNet studies have shown that, at high nitrogen loads, denitrification dominates over N-fixation [5].

An important aspect that has emerged from these initial efforts is the need to increase the number of cases in order to adequately apply the LOICZ model. In this study, the LOICZ biogeochemical model was used to evaluate nutrient fluxes and ecosystem functions in Cabras Lagoon

(Sardinia, Italy), a large and brackish water basin of the Mediterranean region. Cabras Lagoon is one of the widest in the Mediterranean and periodically undergoes dystrophic crises, with significant impact not only on related ecosystems but also on the socio-economics of the surrounding region. These effects have highlighted the need to develop scientifically supported management policies for both the lagoon and its coastal zone. In this context, the present study assumes a wide relevance since improved knowledge of the functioning of the Cabras Lagoon ecosystem and its relationship with neighbouring ecosystems, both marine and terrestrial, will facilitate the restoration of water quality within the lagoon as well as the design of an effective management protocol for this region.

## 2. Materials and methods

### 2.1. *Study area*

Cabras Lagoon is a shallow water body located on the west coast of Sardinia, in the Gulf of Oristano (western Mediterranean Sea; 39° 56′ 37″ N, 08° 28′ 43″ E; Figure 1 and Table 1).



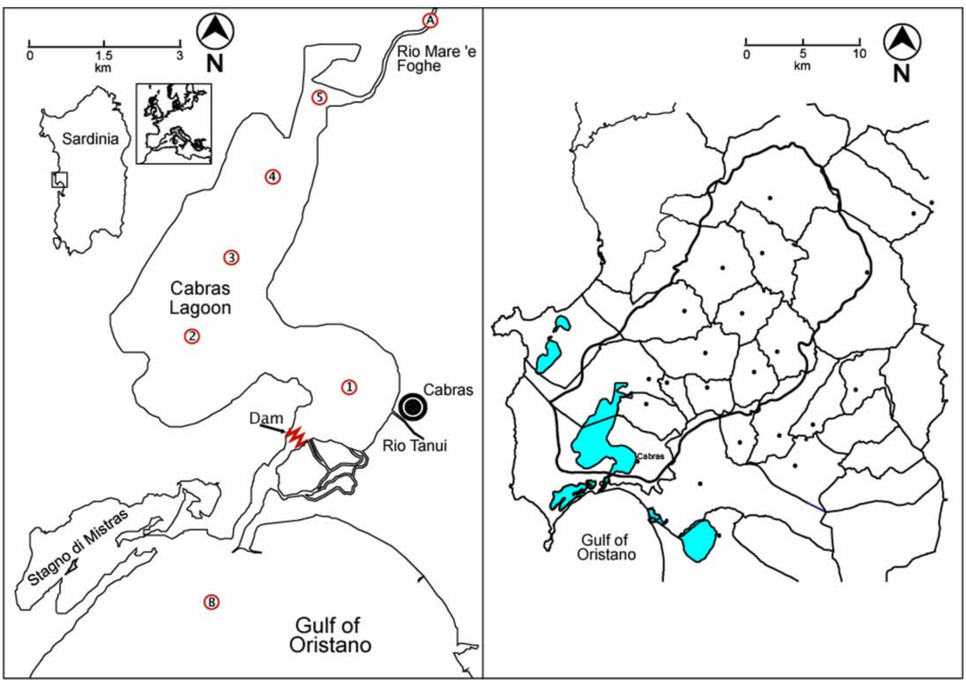


Figure 1. Localisation of the Cabras Lagoon and of the sampling stations is shown in the left panel; the bold line in the right panel delimits the Cabras Lagoon watershed and adjacent urban areas.

Table 1. Characteristics of Cabras Lagoon.

| | |
|---|---|
| Surface area | 23.8 $km^2$ |
| Mean depth | 1.6 m |
| Maximum depth | 3 m |
| Volume | $3.8 \times 10^7$ $m^3$ |
| Watershed area | 459 $km^2$ |
| Mean river discharge (main tributary) | $7.2 \times 10^7$ $m^3$ $a^{-1}$ |

With an area of about 23.8 km$^2$ and a mean depth of 1.6 m (maximum of about 3 m), the Cabras Lagoon is the largest in Sardinia and one of the largest in the Mediterranean Sea [25]. Due to its environmental importance, it is protected by international agreements, including the Ramsar Convention (EU Directive Special Protection Area, Site of Community Importance, Natural Protected Area), and is part of the Sinis-Montiferru Natural Reserve (Sardinia).

The watershed of Cabras Lagoon extends over an area of approximately 430 km$^2$. Water flowing within the system is derived from natural rivers as well as from canals that drain the surrounding lowlands. Most of the freshwater input in the lagoon originates from the Rio Mare ‘e Foghe, which drains an area of 313 km$^2$. River discharge, however, is rather limited due to the low rainfall regime characteristic of the region (ca. 10–100 mm, from July to December) and to the increasing demand for water, especially for agricultural purposes [26]. A minor tributary with no significant freshwater discharge is located in the eastern part of the lagoon, near the town of Cabras.

In general, the basin consists of both a flat zone, with a surface area of about 215 km$^2$ and an elevation not exceeding 60 m a.s.l., and a submountainous/mountainous zone, with heights up to 1050 m a.s.l. The flat zone, located in the southern part of the watershed, is the site of intensive agricultural activity, resulting in the release of high nutrient loads. The fertile soils of the submountainous/mountainous zone (from 200 m a.s.l.) in the northern part of the watershed are occupied by vineyards, olive groves, pastures, and forests. This region is frequently plagued by large-scale fires, which threaten soil conservation. Inside the watershed area, the total resident population is about 38,000 inhabitants, grouped in 19 urban centres. The largest of these is the town of Cabras (about 8,800 inhabitants), situated on the southeastern coast of the lagoon. Urban wastes of Cabras are collected separately and do not flow into the lagoon; elsewhere, however, the lack of infrastructure to treat sewage for nitrogen and phosphorus removal has led to the discharge of substantial amounts of inadequately depurated urban waste into the watershed. Accordingly, based on estimates of agricultural and non-agricultural nutrient loads from the watershed area, inputs of 29 t total phosphorus year$^{-1}$ [25] and 240 t total nitrogen year$^{-1}$ have been calculated [27].



The connection between the lagoon and the adjacent Gulf of Oristano mainly consists of four narrow creeks that flow into a large southernmost canal, the *Scolmatore* (=spillway), which was dredged in the late 1970s. The canal was constructed to allow the flushing of excess water during the heavy rainfalls in winter which regularly submerged a district the near town of Cabras, called, appropriately, ‘Little Venice’. The *Scolmatore* was subsequently closed by a 30 cm-high dam built to prevent further increases in the salinity of the lagoon by stopping the outflow of river-derived freshwater, which over time has strongly decreased due to agricultural demands. In addition, artificial barriers have been constructed to control the fish catch. Although the tidal amplitude in the Gulf of Oristano is $<$40 cm, the dam and barrier system limit the exchange of water between the lagoon and the Gulf. Consequently, the hydrodynamism of Cabras Lagoon is mainly governed by wind forcing, particularly with respect to water circulation, whereas the tide determines discharges through the lagoon’s inlets and modulates the circulation pattern established by the wind [28]. The results of simulations have shown that the wind tends to create a circular current in the larger expanse of the lagoon, with velocities along the shore that are higher than those in the centre of the basin [28].

The lagoon’s sediments are dominated by silt in the southern area, whereas the clay content increases towards the central-northern section. The surface sediments contain large amounts of organic matter (10%) and total organic carbon (33 mg g$^{-1}$) [29]. The benthic environment in the lagoon is very poor in macrofaunal component, with a few predominating taxa typically occurring in degraded and heavily disturbed sites [30].

Salinity in the lagoon follows a net temporal and spatial gradient, increasing from about 8–10‰ during the winter up to 30‰ in summer, with the difference ($\Delta$) between the northern (near the main tributary) and southern (near the mouth of the lagoon) sectors normally being about 4‰

[25]. The pluriannual mean values for the lagoon are about 77 mg N $m^{-3}$ for DIN and 42 mg P $m^{-3}$ for DIP. Dissolved oxygen fluctuates greatly over time, ranging from under- to over-saturation and having a mean value of 107% [25].

The lagoon has a high economic rating due to its numerous fisheries (e.g. *Liza ramada, Mugil cephalus*), which employ about 300 people and their families, and to fishing-related activities. In 1998, fish productivity reached 40,000 kg $km^{-2}$, corresponding to a profit of about 3.5 million Euros [26]. However, dystrophic events often cause massive fish mortality (the last such event occurred in the summer of 1999). In fact, the brackish ecosystem of Cabras Lagoon is eutrophic, such that water quality has steadily deteriorated, with a consequent decrease in the lagoon's fish productivity [25] (actually around 20,000 kg $km^{-2}$).

### 2.2. *LOICZ biogeochemical modelling*

The LOICZ biogeochemical modelling procedure was described in detail by Gordon et al. [9]. In short, it is an ecological model based on mass-balance budgets, i.e. the rates at which materials are imported, exported, or transformed within a system. For example, the transformation of an element within a particular system can lead to its net release (source) or accumulation (sink). Materials, such as water and certain salts that do not undergo these transformations are defined as being 'conservative'. Conversely, materials that undergo complex transformations in the ecosystem, such as carbon, nitrogen, and phosphorus, are defined as being 'non-conservative'.

The relationship between the different budget components in the LOICZ approach is expressed by the following equation:

$$dM/dt = \Sigma \text{ inputs} - \Sigma \text{ outputs} + \Sigma \text{ [sources–sinks]}, \tag{1}$$

where $dM/dt$ represents the change in mass of any material in the system with respect to time. For this study, it was assumed that $dM/dt = 0$, i.e. that the lagoon system at large is at steady state. The LOICZ approach sequentially establishes budgets for water, salt, and non-conservative materials, as well as the stoichiometric relationships among non-conservative budgets.

Equation (1) can be simplified as follows because water and salt have no internal variations and the system is considered to be at steady-state:

$$0 = \Sigma \text{ inputs–}\Sigma \text{ outputs}. \tag{2}$$

The water budget is then equal to:

$$V_R = -(V_Q + V_P + V_E + V_G), \tag{3}$$

where $V_Q$ is the river discharge, $V_P$ is the direct precipitation in the system, $V_E$ is the evaporation, and $V_G$ is the groundwater inflow. In this equation, positive values indicate that water flows into the lagoon, while negative values imply that water leaves the lagoon. Residual flow ($V_R$) results from the balance between the two processes: if $V_R$ is positive, there is a net inflow of seawater into the lagoon, whereas if $V_R$ is negative there is net outflow from the lagoon.

The salt budget is important in deriving the mixing flow $V_X$, which in turn is critical in calculating nutrient budgets. In fact, if residual flow ($V_R$) is balanced by a volume of water entering the lagoon, then the nutrient-rich lagoon water is constantly exchanged with nutrient-poor seawater. This budget is equal to zero, as expressed by the following equation:

$$0 = V_R S_R + V_X S_{sea} - V_X S_{sys}. \tag{4}$$

$S_R$ is the mean of the salinity value of the adjacent sea ($S_{sea}$) and that of the lagoon ($S_{sys}$). The mixing flow ($V_x$) is then equal to

$$V_x = V_R S_R / (S_{sys} - S_{sea}). \tag{5}$$

For the nutrient budget, variations that may occur in the system as a consequence of biogeochemical processes cannot be ignored. These are taken into account by the following equation:

$$\Sigma\,[\text{sources} - \text{sinks}] = \Delta F = \Sigma\ \text{inputs} - \Sigma\ \text{outputs}. \qquad (6)$$

Nutrient fluxes are calculated as the products of the volumes (V) of water input/output and the concentrations of the investigated nutrient (Y), as measured analytically:

$$\Delta F = V_Q Y_Q + V_P Y_P + V_G Y_G + V_E Y_E + V_X Y_{sea} - V_X Y_{sys} + V_R (Y_{sys} + Y_{sea})/2. \qquad (7)$$

A positive $\Delta F$ implies that, within the lagoon, uptake of the nutrient prevails over its release.

At this point, if the nutrient budget of phosphorus is taken into account, $\Delta$DIP can be correlated with NEM by considering the simple stoichiometric ratio C:N:P. Although direct estimation of this ratio is frequently advised, the Redfield ratio [31], 106:16:1, can be used in the case of systems dominated by phytoplankton. Negative $\Delta$DIP indicates a net loss of DIP due to its uptake by plants and the subsequent prevalence of production (p) over respiration (r). This concept is summarised by the following equation:

$$(p - r) = \Delta DIP(C{:}P). \qquad (8)$$

This approach is possible only for phosphorus, as its biogeochemical cycle does not include a gaseous phase. By contrast, both nitrogen and carbon have other major flux pathways, such as denitrification, nitrogen fixation, and gas exchange across the air–sea interface [32].

For DIN, an *observed* value of $\Delta$DIN, which is the direct outcome of the nitrogen budget ($\Delta DIN_{obs}$), can be compared with an *expected* $\Delta$DIN ($\Delta DIN_{exp}$), which is related to the N:P ratio of organic matter. The latter is, in turn, linked to the uptake or release of organic P. Accordingly, the prevalence of N-fixation (nfix) over denitrification (denit) can be estimated by:

$$(\text{nfix} - \text{denit}) = \Delta DIN_{obs} - \Delta DIN_{exp} = \Delta DIN_{obs} - \Delta DIP(N{:}P). \qquad (9)$$



### 2.3. *Data sets*

To apply the LOICZ model to Cabras Lagoon, data collected during a monitoring program carried out in 2004 were considered. River discharge ($V_Q$) was evaluated using a hydrological model available for the watershed basin of the lagoon. The model was calibrated by calculating the deflux ratio on the basis of pluri-annual observations (from 1936–2000) of precipitation in the watershed and the corresponding downflow of water volumes in the closing section of the tributary. Monthly river discharge was calculated by the model on the basis of precipitation observed during the same period. Precipitation data were obtained from a meteorological station, situated in Milis, and were representative of the mean condition of the watershed basin. Direct precipitation input ($V_P$) was determined simply by considering the cumulative daily sum of rainfall during each month multiplied by the area of the system. Evaporation data ($V_E$) were calculated using the Hargreaves equation [33] and were based on the daily mean temperatures during the study period, as recorded at the meteorological station in Oristano-Arborea, the station nearest to the lagoon. Precipitation and temperature data were provided daily by the Dipartimento Idrometeoclimatico of Sardinian Regional Environmental Protection Agency [34]. Groundwater input ($V_G$) was estimated by the variation in the piezometric level, assuming that a plug effect was constant throughout the entire period; these studies in the basin were conducted by the Consorzio di Bonifica dell'Oristanese by means of model simulations.

To obtain data on nutrients (DIN and DIP) and salinity, a sampling program was carried out every 2 weeks in three compartments: tributary, lagoon, and the adjacent sea. DIN refers to the sum of ($N{-}NO_2 + N{-}NO_3 + N{-}NH_4$) and DIP to $P{-}PO_4$. DIN and DIP were analysed according to the method described by Strickland and Parsons [35]. Salinity was detected using a multi-parameter probe (Idromar model IM71, Genoa, Italy). Nutrients ($DIP_Q$ and $DIN_Q$) and salinity ($S_Q$) entering the lagoon were detected at a sampling station located at the terminal portion of the main tributary, the Rio Mare 'e Foghe (Figure 1, station A). The nutrient concentrations ($DIP_{syst}$ and $DIN_{syst}$) and the salinity ($S_{syst}$) of the lagoon were detected at five sampling stations (Figure 1, stations 1–5) and subsequently averaged. Nutrients and salinity in the sea ($DIP_{sea}$, $DIN_{sea}$, and $S_{sea}$, respectively) were detected in the Gulf of Oristano at a sampling station facing the lagoon (Figure 1, station B). The concentrations of DIN and DIP in the groundwater were assumed to be insignificant. For all three compartments, the obtained data were normalised using the average monthly level.

## 3. Results and discussion

### 3.1. *Water and salt balances*

A summary of the water fluxes throughout the year 2004 is shown in Table 2.

Consistent with the climate of the area, the highest values for precipitation ($V_P$) and related river discharge ($V_Q$) were recorded from autumn to spring (maximum in April: $295.7 \times 10^3$ $m^3$ $d^{-1}$) and the lowest values in summer (minimum in August, $81.3 \times 10^3$ $m^3$ $d^{-1}$). In fact, more than one-third of the total direct precipitation entered the lagoon between March and May.

The largest volume of evaporated water ($V_E$) was detected in July ($84.5 \times 10^3$ $m^3$ $d^{-1}$), and the lowest in December ($19.5 \times 10^3$ $m^3$ $d^{-1}$). Groundwater inputs ($V_G$) were assumed to be constant throughout the year, considering a plug effect of the watershed. Studies conducted in this area by means of model simulations indicated a mean ground water ingression of about $30 \times 10^3$ $m^3$ $d^{-1}$ (unpublished data).

With reference to the salt budget (Table 3), the salinity of water inputs ($S_Q$) ranged between 0.2‰ (March, November, and December) and 1.1‰ (September). The latter value may have reflected the rise in the level of the lagoon waters in the tributary compartment. Salinity in the lagoon ($S_{syst}$) was highly influenced by the large river inputs from March until June, varying from 8.4‰ in June to 16.1‰ in September. The salinity of seawater adjacent to the lagoon ($S_{sea}$) ranged between 35.6‰ in January and 37.9‰ in August.

Table 2. Water fluxes (in $10^3$ $m^3$ $d^{-1}$) in river discharge ($V_Q$), groundwater ($V_G$), precipitation ($V_P$), evaporation ($V_E$), residual flow ($V_R$), mixing flow ($V_X$) and water-residence time (in days).

| Month | $V_Q$ | $V_G$ | $V_P$ | $V_E$ | $V_R$ | $V_X$ | $\tau$ |
|---|---|---|---|---|---|---|---|
| January | 225.0 | 30.0 | 58.1 | 20.6 | −292.5 | 294 | 65 |
| February | 224.9 | 30.0 | 58.1 | 28.4 | −284.7 | 278.7 | 68 |
| March | 251.6 | 30.0 | 48.1 | 40.1 | −289.6 | 303.4 | 64 |
| April | 295.7 | 30.0 | 83.8 | 53.7 | −355.7 | 334.9 | 55 |
| May | 210.0 | 30.0 | 65.3 | 66.9 | −238.3 | 204.7 | 86 |
| June | 101.8 | 30.0 | 14.8 | 82.2 | −64.4 | 49.5 | 334 |
| July | 81.9 | 30.0 | 0.0 | 84.6 | −27.3 | 22.3 | 768 |
| August | 81.3 | 30.0 | 0.0 | 76.8 | −34.5 | 38.4 | 522 |
| September | 127.4 | 30.0 | 27.8 | 58.1 | −127.1 | 152.4 | 136 |
| October | 225.2 | 30.0 | 58.2 | 41.5 | −271.9 | 264.8 | 71 |
| November | 266.7 | 30.0 | 74.5 | 26.3 | −344.9 | 322.1 | 57 |
| December | 265.2 | 30.0 | 73.9 | 19.6 | −349.5 | 328.2 | 56 |
| *Mean** | *196.1* | *30.0* | *46.7* | *50.0* | *−222.9* | *215.6* | *191.7* |

Note: *Mean annual values were obtained from monthly weighted averages.

Table 3. Salinity (in ‰) in the river ($S_Q$), groundwater ($S_G$), lagoon ($S_{sys}$), sea ($S_{sea}$), and mean salinity of net flux to the sea ($S_R$).

| Month | $S_Q$ | $S_G$ | $S_{sys}$ | $S_{sea}$ | $S_R$ |
|---|---|---|---|---|---|
| January | 0.3 | 0.0 | 12.1 | 35.6 | 23.9 |
| February | 0.3 | 0.0 | 12.1 | 36.8 | 24.4 |
| March | 0.4 | 0.0 | 13.2 | 36.7 | 24.9 |
| April | 0.3 | 0.0 | 11.2 | 36.0 | 23.6 |
| May | 0.2 | 0.0 | 9.79 | 36.5 | 23.1 |
| June | 0.4 | 0.0 | 8.4 | 37.4 | 22.9 |
| July | 0.4 | 0.0 | 10.0 | 37.3 | 23.6 |
| August | 0.5 | 0.0 | 15.1 | 37.9 | 26.5 |
| September | 1.1 | 0.0 | 16.1 | 37.4 | 26.7 |
| October | 0.3 | 0.0 | 12.1 | 37.1 | 24.6 |
| November | 0.2 | 0.0 | 11.0 | 36.0 | 23.5 |
| December | 0.2 | 0.0 | 11.0 | 35.8 | 23.4 |
| *Mean** | *0.4* | *0.0* | *11.8* | *36.7* | *24.3* |

Note: *Mean annual values were obtained from monthly weighted averages.



As seen in Table 2, water-balance calculations, always yielded negative results for residual flows ($V_R$), clearly indicating a net loss of water from the system. The largest $V_R$ value ($355.7 \times 10^3\ m^3\ d^{-1}$) was obtained in April and was related to the lowest water-residence time (about 55 days) determined during the study period. By contrast, the lowest $V_R$ ($27.3 \times 10^3\ m^3\ d^{-1}$) was recorded in July, when the water-residence time reached 768 days, the highest calculated value. Since a negative $V_R$ indicates water output from the lagoon, there was a compensating water input into the lagoon in the form of mixing flow, $V_X$ (Table 2).

Long water-residence times play a major role in nutrient metabolism, as they allow the retention of anthropogenic phosphorus and nitrogen loadings in the sediment [10]. From an ecological point of view, the increased enclosure rate of a lagoon has important consequences for productivity, as shown by Knoppers [36] in several coastal lagoons in Mexico. In these cases, increased productivity was positively related to the degree of enclosure of the systems. In Cabras Lagoon, the water-residence times were very long and mainly linked to river inflows (Figure 2). This was particularly the case in summer, when the durations were longest due to reductions in freshwater inputs.

The principal cause of the prolonged water-residence times is the present connection between the lagoon and the sea. The presence of the dam at the mouth of the lagoon facilitates the removal of flood waters but obstructs the input of seawater. Simulations carried out by Ferrarin and Umgiesser [28] have corroborated this conclusion. This agrees also with Magni et al. [38], who observed that

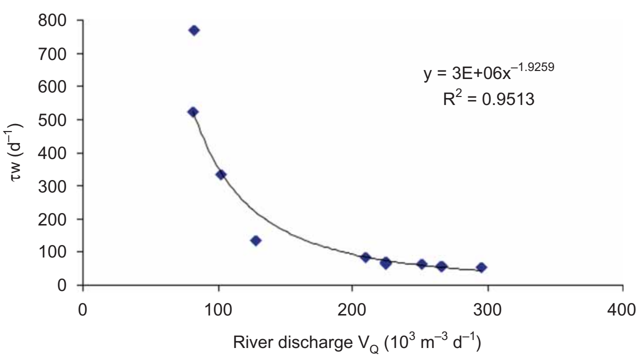


Figure 2. Relationship between water fluxes ($V_Q$) and water-residence time ($\tau w$) in Cabras Lagoon during 2004.

both the freshwater inflow and the connection with the sea are low and that the former is more important in controlling water residence time. It was also determined that, in the absence of the dam within the canal, the tide would strongly affect the circulation of water in the southern area of the lagoon, ensuring greater mixing than is presently the case for the closed canal. In addition, creeks that connect the lagoon to the sea and which bypass the dam are too narrow to guarantee regular water flux. The situation is worsened by the presence of fish-capture structures in the channels. Therefore, recalibration of the lagoon–sea exchange would ensure adequate water circulation in Cabras Lagoon, accelerating the removal and dilution of water masses responsible for the lagoon's eutrophication, thus avoiding highly undesirable nutrient-accumulation conditions.

### 3.2. *Non-conservative material budget*

An assessment of nutrient concentrations in the different water sources (Table 4) showed that DIP ($DIP_Q$) in the river discharge reached a maximum in June (13.30 mmol m$^{-3}$) and a minimum in November (3.46 mmol m$^{-3}$). For DIN ($DIN_Q$), a maximum (64.54 mmol m$^{-3}$) was recorded in April and a minimum (9.10 mmol m$^{-3}$) in June.

Within the system (Table 4), the DIP ($DIP_{sys}$) concentrations ranged between 0.03 mmol m$^{-3}$ (March) and 6.08 mmol m$^{-3}$ (June) whereas for DIN ($DIN_{sys}$) the range was between 2.58 mmol m$^{-3}$ (July) and 29.99 mmol m$^{-3}$ (June).

In the sea compartment, DIP ($DIP_{sea}$) levels were not detectable in February, August, and October but reached a maximum of 1.64 mmol m$^{-3}$ in December. DIN variations were wider, from 0.52 mmol m$^{-3}$ in August to 26.10 mmol m$^{-3}$ in December, and were most likely a direct consequence of discharge from the most important river in Sardinia, the Tirso, into the Gulf of Oristano, as the mouth of the river is in close proximity to the study area.

Table 5 presents the data for net nutrient balance, expressed as the difference between mean daily nutrient import ($V_Q\, Y_Q + V_P\, Y_P + V_G\, Y_G + V_X\, Y_{sea}$) and mean daily nutrient export ($V_X\, Y_{sys} + V_R\, (Y_{sys} + Y_{sea})/2$), for each month. The daily import of material into the lagoon ranged between 644 mol d$^{-1}$ in August and 1354 mol d$^{-1}$ in June for DIP and from 1503 mol d$^{-1}$ in August to 22938 mol d$^{-1}$ in April for DIN. Monthly DIP loads were not related to their internal fluxes (Figure 3(a)), in contrast to monthly DIN loads, for which a significant relationship with internal fluxes of the nutrient was determined (Figure 3(b)) ($R^2 = 0.968$, $n = 12$, $p < 0.05\%$). This finding is related to major freshwater inputs of nitrogen into the lagoon during months

Table 4. Monthly DIP and DIN concentrations measured in the different water sources (in mmol m$^{-3}$).

| Month | $DIP_Q$ | $DIP_{sys}$ | $DIP_{sea}$ | $DIN_Q$ | $DIN_P$ | $DIN_{sys}$ | $DIN_{sea}$ |
|---|---|---|---|---|---|---|---|
| January | 4.77 | 0.17 | 0.19 | 41.49 | 46.00 | 7.40 | 18.46 |
| February | 4.77 | 0.17 | 0.00 | 41.48 | 46.00 | 7.40 | 10.77 |
| March | 4.10 | 0.03 | 0.10 | 15.21 | 46.00 | 4.68 | 10.96 |
| April | 3.58 | 0.66 | 0.17 | 64.54 | 46.00 | 7.75 | 8.61 |
| May | 3.36 | 1.10 | 0.48 | 48.62 | 46.00 | 12.92 | 21.34 |
| June | 13.30 | 6.08 | 0.32 | 9.10 | 46.00 | 29.99 | 1.62 |
| July | 8.14 | 1.16 | 0.02 | 37.34 | 46.00 | 2.58 | 0.82 |
| August | 7.93 | 1.04 | 0.00 | 18.49 | 46.00 | 4.42 | 0.52 |
| September | 6.39 | 1.55 | 0.02 | 27.84 | 46.00 | 10.18 | 0.76 |
| October | 4.77 | 0.17 | 0.00 | 41.52 | 46.00 | 7.40 | 1.00 |
| November | 3.46 | 1.03 | 0.48 | 48.28 | 46.00 | 8.85 | 4.70 |
| December | 3.51 | 1.01 | 1.64 | 48.04 | 46.00 | 8.81 | 26.10 |
| *Mean** | *6.67* | *1.64* | *0.16* | *31.56* | *46.00* | *10.28* | *6.41* |

Note: *Mean annual values were obtained from monthly weighted averages.

Table 5. Calculated values (in mol $d^{-1}$) of daily import, daily export, and net balance for DIP and DIN.

| | DIP | | | DIN | | |
|---|---|---|---|---|---|---|
| Month | Daily import | Daily export | Balance | Daily import | Daily export | Balance |
| January | 1073.59 | 49.00 | 1025.00 | 12011.00 | 532.00 | 11479.00 |
| February | 1073.77 | 70.00 | 1004.00 | 12002.00 | 1646.00 | 10356.00 |
| March | 1031.50 | −6.00 | 1037.00 | 6037.00 | 361.00 | 5676.00 |
| April | 1059.69 | 310.00 | 750.00 | 22938.00 | 2623.00 | 20315.00 |
| May | 705.11 | 315.00 | 390.00 | 13212.00 | 2359.00 | 10853.00 |
| June | 1354.09 | 491.00 | 863.00 | 1606.00 | 2422.00 | 816.00 |
| July | 666.33 | 41.00 | 625.00 | 3058.00 | 85.00 | 2973.00 |
| August | 644.38 | 58.00 | 586.00 | 1503.00 | 235.00 | 1268.00 |
| September | 814.40 | 333.00 | 481.00 | 4826.00 | 2131.00 | 2695.00 |
| October | 1073.18 | 70.00 | 1003.00 | 12027.00 | 2836.00 | 9191.00 |
| November | 922.14 | 440.00 | 482.00 | 16304.00 | 3675.00 | 12629.00 |
| December | 929.63 | 259.00 | 671.00 | 16137.00 | 424.00 | 15713.00 |
| *Mean** | *893.98* | *218.07* | *675.69* | *7566.40* | *1446.36* | *6120.05* |

Note: *Mean annual values were obtained from monthly weighted averages.



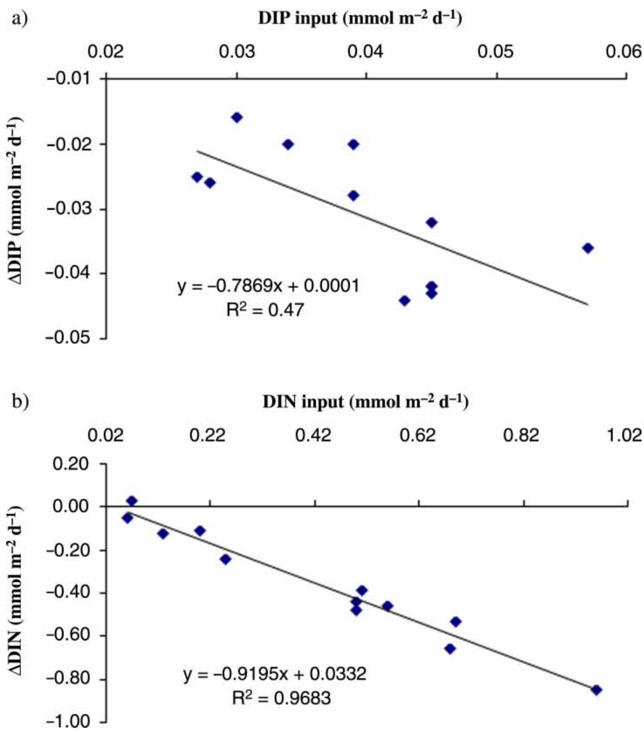


Figure 3. Relationship between DIP (a) and DIN (b) loads and internal fluxes (monthly estimations) in Cabras Lagoon during 2004.

of relatively higher rainfall and perhaps also to the intensive agricultural and zootechnical uses of the watershed [25]. The absence of a significant correlation for DIP may indicate a greater importance in the exchange of phosphorus with the sediment, because of the shallowness of the lagoon. However, it should be noted that nutrient concentrations in freshwaters vary greatly as a consequence of intensive exploitation and are especially sensitive to agriculture-rotation practices.

The daily export of DIP was highest in June (491 mol d$^{-1}$) and lowest in March, with a consequent value of 6 mol d$^{-1}$ caused by the prevalence of seawater inflow. The highest value of DIN export (3675 mol d$^{-1}$) was recorded in November, whereas the lowest value (85 mol d$^{-1}$) occurred in July. For both DIP and DIN, the daily export maximum coincided with very high loads ($V_Q DIP_Q$ and $V_Q DIN_Q$) and the minimum with the lowest concentrations of these nutrients in the system ($DIP_{sys}$ and $DIN_{sys}$).

### 3.3. *Stoichiometric calculations*

In Cabras Lagoon, primary productivity can be predominantly ascribed to phytoplankton because of the scarce presence and growth of macroalgae [25]. This latter feature distinguishes Cabras Lagoon from other Sardinian lagoons and is probably related to its greater depth. Based on the lagoon's characteristics, the C:N:P ratio of 106:16:1, proposed by Redfield [31], was used for stoichiometric calculations. The C:N:P ratio allows estimation of the rate of assimilation and organic conversion of inorganic C−N−P, the rate of C−N−P release as organic compounds, and the consequent mineralisation of these compounds in the decomposition process. Accordingly, the calculations shown in Table 6 highlight that N-fixation generally prevailed over denitrification in Cabras Lagoon during 2004. The highest value of *nfix-denit* was obtained in June, 0.61 mmol m$^{-2}$ d$^{-1}$. Denitrification prevailed only from April to May and from November to December, with a maximum in April (−0.34 mmol m$^{-2}$ d$^{-1}$). The fact that these 4 months were characterised by a maximum DIN load ($V_Q DIN_Q$) suggests that at high loads the lagoon does not fix but instead loses nitrogen. This response was also observed in other LaguNet systems [5] and appears to be a general tendency. Actually, as highlighted in Section 3.2, nitrogen flux is more complex than the simple difference between measured nitrogen levels and those expected from the production and breakdown of organic matter. This leads to the consideration of at least two critical points of the model. The first is that, since phytoplankton prevails in Cabras Lagoon, the expected values are guided by the Redfield ratio of 16:1 whereas in systems in which macrophytes are the most important primary producer different ratios are applied. Nonetheless, the ratio can differ substantially at the local scale and thereby differentially affect the phytoplankton species composition [10]. This observation agrees with the low N:P ratios recorded over the major part of the

Table 6. Net ecosystem metabolism (NEM), expected DIN ($\Delta DIN_{exp}$), and difference between N-fixation and denitrification (nfix-denit) in the Cabras Lagoon (mmol m$^{-2}$d$^{-1}$).

| Month | NEM | $\Delta DIN_{exp}$ | ($N_{fix\text{-}denit}$) |
|---|---|---|---|
| January | 4.6 | −0.69 | 0.21 |
| February | 4.5 | −0.67 | 0.23 |
| March | 4.7 | −0.70 | 0.46 |
| April | 3.4 | −0.51 | −0.34 |
| May | 1.7 | −0.26 | −0.20 |
| June | 3.8 | −0.58 | 0.61 |
| July | 2.8 | −0.42 | 0.30 |
| August | 2.7 | −0.40 | 0.35 |
| September | 2.1 | −0.32 | 0.21 |
| October | 4.5 | −0.67 | 0.28 |
| November | 2.1 | −0.32 | −0.21 |
| December | 3.0 | −0.45 | −0.21 |
| *Mean** | *3.3* | *−0.5* | *0.14* |

Note: *Mean annual values were obtained from monthly weighted averages.

study year (<10 in 6 months and about 12 in the other 2 months) and the significant dominance of cyanobacteria in this lagoon. The second critical point is that differences between the measured nitrogen flux and that derived from calculations can be interpreted as reflecting the difference between the gaseous reactions of $N_2$ fixation and denitrification. Both reactions are carried out by bacteria and usually occur in anoxic sediment layers. Our results confirm that the two biological processes are linked to the availability of nitrogen rather than to production and respiration [5]. The dominance of cyanobacteria with species belonging to heterocystous and non-heterocystous genera within the phytoplankton of Cabras Lagoon [25] requires further study in order to evaluate their role in nitrogen flux.

Throughout the study period, positive values of NEM were obtained, implying a dominance of productivity processes within the system (Table 6). The highest values were recorded during the spring, with a maximum of 4.7 mmol $m^{-2}$ $d^{-1}$ in March. The prevalence of productivity over respiration in Cabras Lagoon identifies this ecosystem as 'autotrophic'. However, because of the low NEM values, it can be concluded only that the lagoon shows a tendency toward net autotrophism, particularly during the summer dry season. This condition is observed in several tropical and subtropical lagoons and is referred to as the 'choked' state, according to Kfjerve [37,39–41]. In choked lagoons, high rates of respiration are achieved only during the dry season, corresponding to the increased availability of organic material produced during the wet season. Furthermore, these dry periods potentially give rise to dystrophic events, which lead to the death of the entire lagoon community. The same tendency was reported by Wenzhi et al. [22]. In that study, a nutrient mass-balance model applied at the catchment scale and the LOICZ biogeochemical model were combined to evaluate agricultural N contributions from the Jiulong River catchment to the estuary. Phytoplankton was the dominant primary producer in this estuarine system, and the difference between the observed $\Delta$DIN and the value expected from the decomposition of organic matter designated this estuary as a net nitrifying system.

Stoichiometric calculations showed that the Jiulong River estuary is an autotrophic system. As in Cabras Lagoon, agricultural and anthropogenic activities in the catchment were determined to be the major N sources, with riverine N fluxes from these sources substantially influencing biogeochemical processes in the estuary. However, the net efflux of DIN from the system indicated that the Jiulong River estuary is a nitrogen source for the coastal sea whereas Cabras Lagoon acts as a filter that effectively reduces N loads from the catchment to the sea (Table 5).

The geographically closest comparison can be done with S'Ena Arrubia Lagoon, which is a small eutrophic system not far from Cabras Lagoon. The LOICZ model showed a prevalence of nutrient uptake over release in S'Ena Arrubia Lagoon as well as a consistent prevalence of N-fixation over denitrification and of production over respiration [42]. The results confirmed those obtained following application of the LOICZ model to data collected in 1994–1995 [24]. Both studies concluded that the S'Ena Arrubia Lagoon is an autotrophic system. NEM values are generally higher in S'Ena Arrubia Lagoon than in Cabras Lagoon and also show a wider range of variation. Among the many differences between these two Sardinian lagoons, three aspects can be highlighted: water-residence time (3 days in S'Ena Arrubia Lagoon vs. 192 in Cabras Lagoon), primary producers (prevalency of macrophytes over phytoplankton in S'Ena Arrubia Lagoon vs. almost exclusively phytoplankton in Cabras Lagoon), and morphological features (area of 1.2 $km^2$ and mean depth of 0.4 m in S'Ena Arrubia Lagoon vs. an area of about 23 $km^2$ and a mean depth of 1.5 m in Cabras Lagoon). No clear relation between dimension and ecosystem functions was observed in a comparison of the two lagoons. Obviously, the drastic agricultural exploitation of the lagoons' watershed areas plays an important role at both sites. However, nutrient release from the sediment and nutrient inputs result in significant accumulations in Cabras Lagoon whereas in S'Ena Arrubia Lagoon the effects of very high nutrient inputs are mitigated by the lower water-residence time.

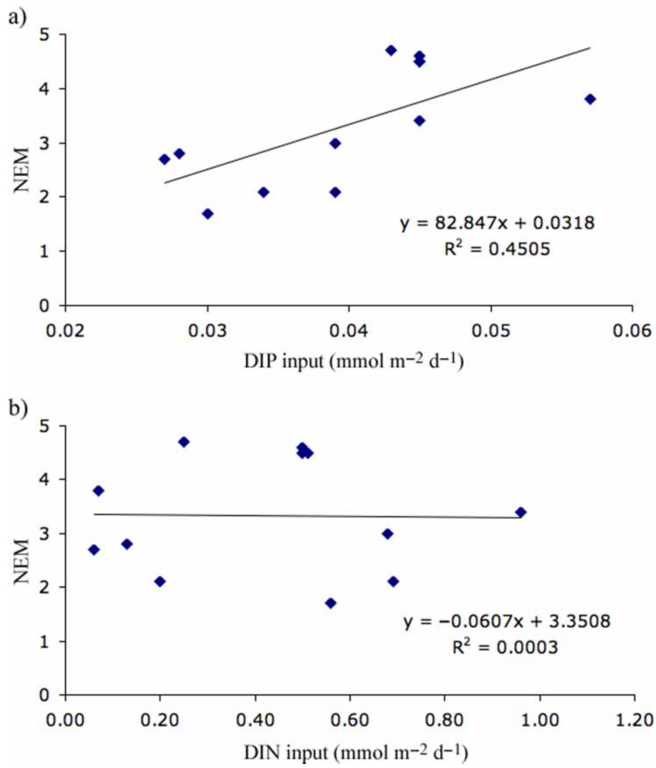


Figure 4. Relationship between DIP (a) and DIN (b) loads and NEM (monthly estimations) in Cabras Lagoon during 2004.



Finally, no significant correlations were detected between DIP and DIN loads and NEM (Figure 4) in Cabras Lagoon, confirming the hypothesis that productivity processes are controlled not only by external nutrient inputs but also by consistent contributions of nutrients released from the sediment.

## 4. Conclusions

Data collected for Cabras Lagoon were used to calculate nitrogen and phosphorus budgets by means of the LOICZ biogechemical model according to the one-box and one-layer approach. The results indicated that:

(1) For both DIP and DIN, nutrient accumulation prevailed over nutrient mobilisation (Table 5) in Cabras Lagoon during the study period.
(2) Monthly DIP loads were not related to internal fluxes, in contrast to monthly DIN loads, which were significantly related to internal fluxes of this nutrient.
(3) A significant power relationship between water fluxes ($V_Q$) and water-residence time ($\tau w$) was determined. Specifically, water-residence times were very long due to the inefficient exchange between the sea and the mouth of the lagoon and were mainly controlled by river inflows during winter.
(4) The positive NEM values obtained for the entire study period identified the Cabras Lagoon ecosystem as ‘autotrophic’. However, since the NEM values were low, a net prevalence of productivity over respiration cannot be concluded.

(5) There was, however, a tendency indicating that $N_2$ fixation prevailed over denitrification. This finding is in agreement with the low N:P ratios observed and the consequent significant dominance of cyanobacteria in the phytoplankton population of Cabras Lagoon.

Based on these considerations, improving the circulation of water in Cabras Lagoon by means of a recalibration of the lagoon–sea exchange could accelerate the removal and dilution of water masses responsible for the lagoon's eutrophication, by preventing the conditions that lead to extreme nutrient accumulation. This relatively simple strategy can be carried out relatively quickly and will lead to improvements in the environmental condition of the lagoon, until more long-term and potentially more difficult actions aimed at reducing the anthropogenic nutrient loads, especially phosphorus, in the watershed are implemented.

A comparison of the nutrient loads and internal fluxes of Cabras Lagoon with those in the LOICZ database is shown in Table 7. The considered data were those selected by Giordani et al. [43] for 94 shallow systems, with a mean depth $<10$ m and a water surface area $<2500$ km$^2$, as described in the LOICZ site database; a smaller group of 61 systems lacking large estuaries (this typology is not present along the Italian coasts); and a third group corresponding to 17 Italian sites of the LaguNet. The values obtained for nutrients loads and internal fluxes in Cabras Lagoon are within the range of those reported for selected systems included in the LOICZ worldwide database. The DIP load of Cabras Lagoon is very close to the LOICZ Italian mean value, whereas the DIN load is very low compared to the values obtained for Italian sites and to values reported in the worldwide database. The data describing internal fluxes confirmed these low and negative values, reflecting the tendency of the lagoon to retain nutrients and to accumulate them. Phosphorus availability is a crucial component of the lagoon's ecological status and is therefore one of the most important factors to be considered in establishing policies aimed at recovery of the lagoon's ecosystem.

As suggested by Wenzhi et al. [22], best management practices together with landscape management policies aimed at reducing diffuse nutrient losses through surface water can be efficiently applied to nutrient management in watersheds, lagoons, and coastal waters. In this context, the LOICZ model offers a simple and robust approach to assess nutrient status, even in those systems for which relatively few data are available [32]. As shown in the present study for Cabras Lagoon, the results of this approach provide important information useful to defining management strategies aimed at the control of primary productivity and thus at the prevention of dystrophic crises, both of which, in turn, influence local fishing activities and the socio-economics of the region.

Table 7. Comparison of nutrient loads and internal fluxes among Cabras Lagoon, shallow LOICZ sites, LOICZ sites without large estuaries, and shallow LaguNet sites (modified from Giordani et al. 2008 [43]).

| | No. of sites | | DIP load mol m$^{-2}$ y$^{-1}$ | DIN load mol m$^{-2}$ y$^{-1}$ | ΔDIP mmol m$^{-2}$ y$^{-1}$ | ΔDIN mmol m$^{-2}$ y$^{-1}$ |
|---|---|---|---|---|---|---|
| LOICZ | 94 | Median | 0.064 | 1.25 | −3.7 | −130 |
| (shallow systems) | | Min | 0.000 | 0.00 | −876.0 | −49640 |
| | | Max | 6.840 | 82.13 | 9125.0 | 242700 |
| | | Mean | 0.305 | 5.26 | 146.5 | 2423 |
| LOICZ | 61 | Median | 0.048 | 0.59 | −7.3 | −146 |
| (systems without large estuaries) | | Min | 0.000 | 0.00 | −525.0 | −49640 |
| | | Max | 1.169 | 57.03 | 3041.7 | 10220 |
| | | Mean | 0.108 | 2.38 | 35.3 | −813 |
| LOICZ | 17 | Median | 0.005 | 0.30 | −3.2 | −175 |
| (LaguNet systems) | | Min | 0.000 | 0.00 | −111.3 | −6435 |
| | | Max | 0.291 | 6.87 | 9.2 | 1239 |
| | | Mean | 0.036 | 1.18 | −13.7 | −761 |
| Cabras Lagoon | | | 0.0396 | 0.4248 | −0.0311 | −0.3576 |

Finally, this study contributes to the construction of a worldwide coastal budget aimed at schematising global trends in dissolved inorganic nutrient loading and in assessing the relevance of these trends to global environmental changes in the coastal zone one of the main targets of LOICZ research projects. Furthermore, the results of this study can be applied in simple budget comparisons among various sites and in grouping together ecosystems on the basis of similarities in their functional features.

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