An Admissible Annual Load framework for nutrients in hypertrophic coastal Mediterranean lagoons: a case study

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Abstract:

The GAMELag box-model tool is used in a collaborative approach between scientists and ecosystem managers to determine admissible nutrient load in lagoon environments. This case study of its application in a hypereutrophic French Mediterranean lagoon demonstrated its ability to determine exogenous nutrient flows compatible with good ecological status. A new method, based on the exploratory analysis of simulated scenarios of flow reduction (exogenous and endogenous), revealed the predominant role of sediment stocks and exchanges in the ecological status of this lagoon. Reducing inflows from the catchment area allowed sediment release and initiated the restoration of this compartment. A reduction in exogenous nitrogen inputs by a factor of 0.24 and phosphorus by 0.1 was found to be necessary to achieve EU Water Framework Directive objectives. These results are helping lagoon managers to raise the awareness of local stakeholders and co-construct management measures to encourage a dynamic of restoration.

1. Introduction

1.1 Context

An increase in nitrogen and phosphorus inflows from catchment areas with growing populations and expanding anthropogenic activities, particularly since the 1960s, is recognised as a major cause of the environmental degradation of coastal ecosystems (Cloern, 2001). On a global scale, coastal lagoons are especially affected by the resulting eutrophication, which leads to profound changes in the structure and functioning of these ecosystems and the services they provide (Zaldívar et al., 2008; Pérez-Ruzafa et al., 2019). In Europe, since the mid-2000s, the EU Water Framework Directive has required member states to restore the ecological quality of degraded hydrosystems by implementing measures to reduce nutrient inputs and to monitor the effectiveness of these management measures (Voulvoulis et al., 2017; de Wit et al., 2020; Newton et al., 2022).

On the Mediterranean coast of France, following the application of the French Water Law (Law no. 92-3 of 3 January 1992), which reinforced the powers of municipalities in water management, the Rhône-Mediterranean-Corsica Water Agency (RMC Water Agency) proposed that a network be set up to measure and monitor the quality of the basin's lagoons (in the regions of Occitanie, Provence-Alpes-Côte d'Azur and Corsica) at the beginning of the 2000s. In parallel, the fishing and marine farming sectors expressed the need to develop environmental management actions, as well as to receive regular information about the environmental quality of waters on which their activities depend.

To this end, a partnership between public agencies and scientists led to the creation of the Regional Lagoon Monitoring Network in 2002 with the twofold objective of (i) acquiring data to diagnose the state of lagoons with regard to eutrophication, and (ii) developing tools to assess the impact of nutrient inputs on the functioning of lagoon ecosystems and to assist in the management of these environments. Since 2006, the monitoring programme required by the EU Water Framework Directive (WFD) has been implemented in Mediterranean lagoons. The Regional Lagoon Monitoring Network proved a solid base for WFD monitoring, since the eutrophication indicators specific to lagoons measured by the network's protocol (Zaldívar et al., 2008) were adopted and progressively consolidated to become WFD ecological status indicators for these transitional water bodies. The resulting information about the degraded state of almost all aquatic ecosystems in the region of Occitanie in France (Ifremer, 2003) has been disseminated to the managers of lagoon environments, raising awareness and triggering, in line with the WFD, the implementation of structural measures aimed at reducing urban waste (Derolez et al., 2019).

Since 2009, in lagoons where efforts have been made to reduce pollutant loads, the restoration process has raised questions about (i) the time required to restore all the ecosystem compartments in a lagoon, and (ii) the maximum nitrogen and phosphorus loads compatible with achieving and/or maintaining good ecological status.

The restoration of coastal environments involves either a direct return to a 'pre-degradation' state if disturbance levels are low (Greening et al., 2014), or more usually through a phenomenon of hysteresis, i.e. a partial restoration with different and generally longer processes than those occurring during degradation (Elliott et al., 2007; Duarte et al., 2009; Cloern et al., 2020). This hysteresis is due to the complex functioning of the ecosystem, the presence of threshold effects, and interconnected processes involving all the physical, chemical and biological compartments that play a role in cycles of matter.

The time required to restore the most integrative compartments of the ecosystem is medium to long (several years) (Borja et al., 2010), with the recolonisation of the environment by seagrass beds taking up to ten years, as has been observed in Tampa Bay, Florida (USA) (Greening et al., 2014). In lagoon environments, restoration time depends on: (i) the nutrient load from the catchment area; (ii) the structure and functioning of the biological community (e.g. its role in the matter cycle and storage of nutrients); (iii) exchanges between the benthic compartment and the water column (particularly sediment release); and (iv) the capacity to export excess nitrogen and phosphorus to the open environment (Ouisse et al., 2013; 2014).

1.2. 'Admissible load' approach

Maximum nutrient load is determined by the water planning and management regulations for the Rhône-Mediterranean-Corsica basin, which defines the 'admissible load' for a lagoon as "*the maximum pollutant load in a catchment area that does not compromise its quality standards. This corresponds to the maximum accumulation of a substance from discharge and emissions of discrete or diffuse pollutants in a catchment area while maintaining compliance with environmental quality criteria (ecological status, chemical status, specific objectives for drinking water, shellfish farming, swimming, etc.)*" (SDAGE, 2022).

More broadly, the 'admissible load' approach, which was developed to help managers tackle the eutrophication of aquatic environments (SDAGE, 2018), aims to: (i) better identify and quantify the various nutrient loads that reach a lagoon; (ii) estimate the admissible load of a lagoon with regard to its capacity to receive this without permanently jeopardising its ecological functioning; (iii) set an overall objective for reducing pollutant loads that is consistent with a lagoon's admissible load; (iv) define a restoration programme to implement relevant actions in collaboration with all local stakeholders to reduce nutrient inputs to a targeted lagoon.

1.3 A modelling approach to support lagoon management

In this context, we aimed to build a robust and reliable tool to acquire knowledge on the ecological functioning of eutrophicated lagoon ecosystems or those undergoing restoration (Pete et al., 2020a). The resulting management tool, GAMELag (*Gestion et Aménagement des Milieux Eutrophisés Lagunaires*: Management of Eutrophic Lagoon Environments), was developed within the framework of the Regional Lagoon Monitoring Network and was guided by the needs of managers responsible for restoring these ecosystems.

Modelling tools are relevant for addressing the issue of admissible load (Chapra et al., 2003). Based on a review of more than 300 Total Maximum Daily Load (TMDL) approaches carried out between 2015 and 2020 in the United States, Sridharan et al. (2021) found that those based on process models that link cause and effect (1D or 2D) are preferable, yet are only used in 25% of cases, with the large datasets required to implement these being their main limitation.

These authors also point out that the use of complex, high-resolution (3D) numerical models cannot yet be envisaged for management applications because of the long calculation times required. In this context, an alternative approach consists of using the results from high-resolution models to produce data that cannot be measured in situ and/or new knowledge to populate simpler management tools. In this way, the processes calculated in detail by powerful but complex tools can be integrated into support tools in a relevant way. Such methods have been used to develop tools to help assess the sanitary status of shellfish production areas (Mongruel et al., 2013), as well as tools aimed at shellfish farmers so they can adapt their farming practices and optimise their production in contexts of high interannual variability in environmental quality or mortality (Cugier et al., 2022).

1.4. A practical tool guided by management needs

The GAMELag tool was developed following this same approach. This model is based on a simplified representation of the ecosystem in 'physical units' (Gordon et al., 1996; Vijay et al., 2021; Ferrarin et al., 2010) and 'biological compartments'. A method based on the use of a high-resolution hydrodynamic model makes it possible to define the necessary number of physical units to account for the hydrodynamic functioning of a lagoon. The identification of hydrodynamic boundaries and heterogeneous water masses within a lagoon conditions the number of physical units to be considered (Fiandrino et al., 2017; Pete et al., 2017; 2020a). Within each unit, the model simulates the temporal change in the quantities of nitrogen and phosphorus stored in the main ecological compartments (water column, phytoplankton, zooplankton, macrophytes, sediment) as a result of nutrient loads from the catchment area and the atmosphere and exchanged (exported and imported) with the external marine environment (Figure 1). In this way, the model makes the link between the biological status of a lagoon and the pressures to which it is subjected.

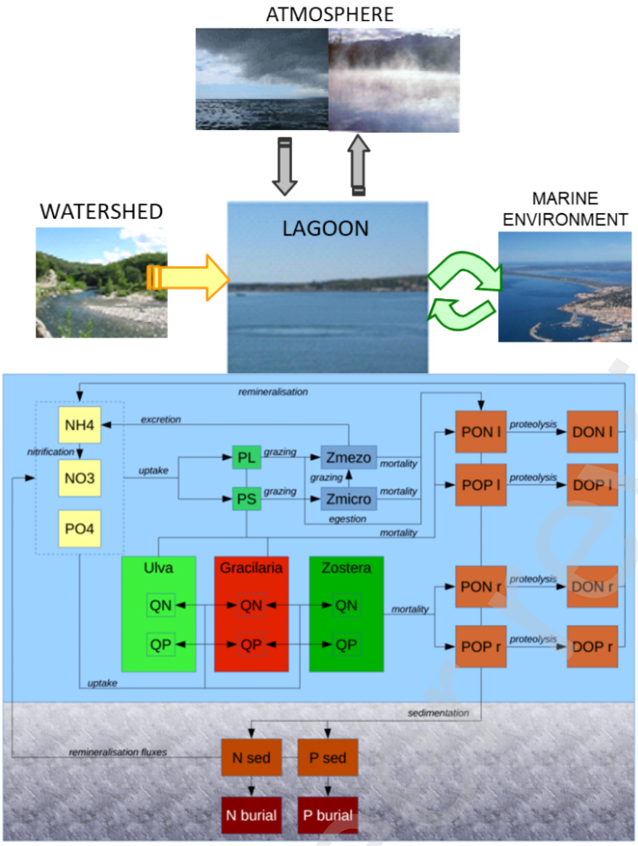

Figure 1: Conceptual diagram of the GAMELag model showing the compartments of the biogeochemical module and their interactions (adapted from figures 1 and 2 in Pete et al., 2020b).

Assessments at the watershed/lagoon interface revealed a lack of quantitative data on water and nutrient loads to the lagoons from surface catchments and groundwater. This observation led the RMC Water Agency to set up a monitoring network in 2015 to measure pollutant flows to lagoons with the aim of better quantifying nutrient and chemical contaminant inputs, particularly during flooding events (AERMC, 2022). This network made it possible to develop methods to calculate annual water and nutrient loads to the lagoons – methods adapted to intermittent watercourses subject to flooding phenomena, a major input in Mediterranean lagoons (Hydriad, 2022). This reinforcement of the monitoring of nutrient flows allowed the improvement of the GAMELag model's description of forcing factors at the watershed/lagoon interface (Figure 1).

The results obtained at the first sites where the tool was applied revealed its limitations (Fiandrino et al., 2022a) and reoriented subsequent studies on the processes involved in the variation of internal nitrogen and phosphorus loads (Figure 1), in particular: (i) the transfer kinetics of nitrogen and phosphorus between the benthic compartment and the water column as a result of sediment stocks and the seasonal variability in this flux (Ouisse et al, 2013); (ii) the dynamic of macrophytes during restoration (Le Fur et al., 2018; 2019) and their capacity to regulate fluxes of matter (Eyre et al., 2011; Le Fur, 2018) and thus reduce sediment release (the concept of storage sustainability).

Lastly, a method that estimates the biogeochemical parameters with the most influence in the model, based on global sensitivity analyses, allows optimal combinations of parameter values to be determined (Saguet et al., 2019). Simulations carried out systematically with these different sets of parameters make it possible to associate the water column and phytoplankton metrics with the uncertainties linked to the conceptualisation of the simulated processes. The resulting knowledge has been integrated into the tool (Pete et al., 2017; 2020a) and its use has been tested to establish its efficacy and limitations.

1.5 The tool and its application in the case study of the Or Lagoon

The GAMELag model was developed to evaluate admissible load in French Mediterranean lagoons, serving both as a tool to integrate knowledge acquired in lagoon ecosystems and to support lagoon management agencies that want to adopt an admissible load approach. This article presents a case study of how the GAMELag tool is being used in the specific example of the Or Lagoon, which is the first site where this collaborative approach between managers and scientists has been implemented.

For several decades, the Or Lagoon has been one of the most degraded lagoons on the French Mediterranean coast (Derolez et al., 2021; AERMC, 2021). Numerous projects, particularly in terms of wastewater treatment, have been carried out since the early 2000s to reduce nutrient inputs to this lagoon. In 2017, the lack of ecological restoration in this lagoon prompted public authorities (Syndicat Mixte du Bassin de l'Or, SYMBO) to launch a study to better understand the hydrodynamics and ecological functioning of the lagoon and to estimate the admissible nutrient load in this ecosystem.

2. Materials and methods

2.1. Study site: Or Lagoon

The Or Lagoon is located southeast of the city of Montpellier in the south of France near the Mediterranean coastline. It is the third largest lagoon in the region of Occitanie, with a surface area of 3190 ha, an average volume of 50.10^6 m^3 and an average depth of 1.3 m (Castaings, 2012). The brackish, continental water inputs it receives make it a mesohaline lagoon (average annual salinity $S_{mean} = 17.3 \pm 6.9$ PSU; SYMBO, pers. comm.). To the south, the Or Lagoon is connected to the Rhône to Sète Canal (CRAS) via the Carnon channel at the southwestern end of the lagoon and three other main channels distributed from west to east along the canal (Figure 2). The connection to the sea is indirect via the Carnon inlet, which in turn is connected to the Carnon channel where it intersects the CRAS.

To the north and east, the 410 km^2 catchment area is highly anthropized, with only 6% of natural areas remaining. Most of the land is used for agriculture (around two-thirds of the surface area) and to a lesser extent for urban purposes (~20%). The catchment area is experiencing strong demographic growth (+8% between 2011 and 2020, SYMBO and Acteon, 2021) due to the proximity of the cities of Montpellier and Nîmes and the high level of tourist activities (+50% of the permanent population in the summer period). The tributaries of the Or Lagoon subdivide the area into two parts. The northern watershed (N WS) is drained by four main streams: the Salaison, the Cadoule, the Bérange, and the Viredonne (Figure 2). The eastern watershed is drained by the Lunel Canal, which receives the waters of the Dardaillon, and feeds the lagoon via the Canalette (Figure 2) before flowing, further south, into the CRAS, upstream from the Or Lagoon. Parallel to the lagoon, the CRAS is under the dual influence of marine waters via the Carnon channel to the west and continental waters via the Lunel Canal to the east and the upstream part of the CRAS itself (which is outside the Or Lagoon watershed). The waters of the CRAS resulting from this mixture are brackish, and their ecological quality is strongly influenced by the degraded quality of the numerous tributaries that feed it more or less directly, in particular the Rhône River and the Lunel Canal.

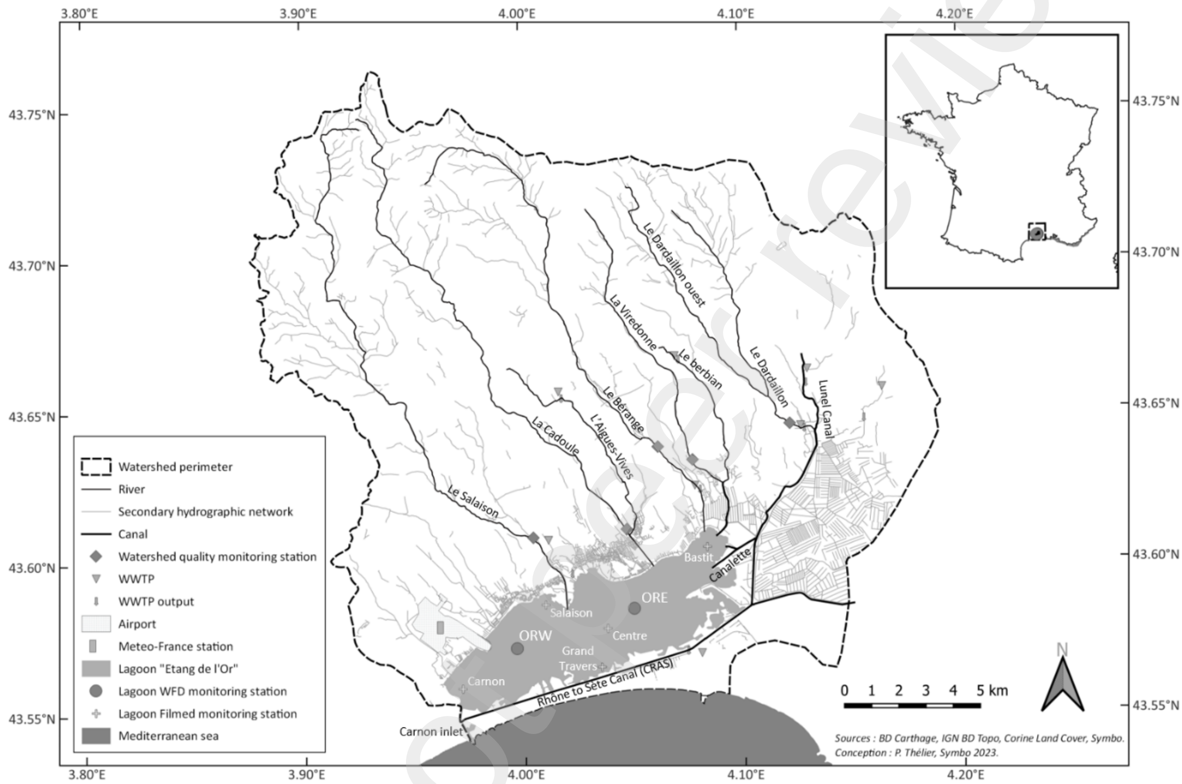

Figure 2: Main streams and measuring points in the catchment area and in the Or lagoon.

2.2. Application of the GAMELag model to the Or Lagoon

We applied the MARS-3D hydrodynamic model to the Or Lagoon (SYMBO, 2019) to define the number of 'physical units' to be considered in the model as suggested by Fiandrino et al. (2017). We found that a single unit was sufficient to represent the lagoon's hydrodynamics and exchanges with the CRAS (results not shown). Moreover, with a turnover time of 87 days and an average residence time of 117 days (results not shown), the mixing efficiency of this lagoon (~ 0.74, for a theoretical maximum value equal to 1) is among the highest in Mediterranean lagoons (Umgiesser et al., 2014), confirming that it can be considered a hydrodynamically homogeneous environment.

An analysis of monthly salinity measured by SYMBO between 2002 and 2018 at five sites in the Or Lagoon (grey crosses in Figure 2) made it possible to quantify the impact of freshwater inputs via the streams and the Canalette on the lagoon's salinity. Significant differences in salinity were observed between the Bastit site, located at the eastern end of the lagoon, and the other four sites. The largest gradient of salinity (7.7 ± 4.0) was observed between Bastit (S_{mean} = 12.6 ± 6.9) and Carnon, which is located in the extreme west and is influenced by marine water (S_{mean} = 20.1 ± 6.6). The differences in salinity between the other pairs of sites did not show any marked, stable gradients within the lagoon. Thus, given that the highest desalination is restricted to the zone at the extreme east of the lagoon, we postulated that the Or Lagoon is a single physical unit.

This unit receives fresh and brackish water and nitrogen and phosphorus inflows from the N WS and the Canalette (outlet from the eastern watershed into the Or Lagoon) and exchanges water and matter with the CRAS which, in the absence of a direct connection between the lagoon and the sea, represents the 'external marine environment' in the GAMELag tool.

2.3. Forcing dataset for the model

2.3.1 Atmosphere

The daily time series of air temperature (in °C), relative humidity (in %), wind speed (in $m.s^{-1}$) and solar radiation (in $10^6\,J.m^{-2}.d^{-1}$) necessary to calculate evaporation and the daily precipitation time series (in $mm.d^{-1}$) were acquired from the nearby Montpellier-Fréjorgues meteorological station (Météo-France 43,58°N|; 3,96°E; Figure 2) for the period 2013–2018.

2.3.2. Watershed

In the N WS, the Salaison is the only stream in the catchment area equipped with a gauging station for high-frequency flow monitoring (since 1986) (David et al., 2019). The flows of the other streams in this catchment area (Figure 2) were estimated from the daily flow series of the Salaison according to the percentages calculated by Colin et al. (2017): Cadoule (37%), Viredonne (20%), Bérange (18%) and Jasse (4.8%). Nitrogen and phosphorus concentrations in these streams are measured every 15 days (Naïades portal, Watershed quality monitoring stations in Figure 2). Emissions from wastewater treatment plants (WWTPs), which are discharged either directly into the lagoon or into the watercourses downstream of the monitoring points (WWTP in Figure 2), were also taken into account: daily flow data and nitrogen and phosphorus concentrations measured at two-week intervals were provided by the facility managers. In the eastern watershed, the flows and salinity of the Canalette were measured at high frequency (every 10 min) and bimonthly measurements of nitrogen and phosphorus concentrations were acquired over the period from 1 March 2017 to 31 March 2018 (SYMBO, 2019).

2.3.3. The Rhône to Sète Canal (CRAS)

The hydrological module of the GAMELag tool, based on the hypothesis that the volume of the lagoon remains constant, simulates the daily net residual volumes (V_R) exchanged with the external environment ($V_R = |V_{In}| - |V_{Out}|$), but does not account for the volume of water that oscillates daily between the lagoon and the external environment (V_{in} and V_{Out}). Yet these inflows/outflows, which partly compensate each other diurnally (particularly through tidal action), strongly contribute to the mixing of lagoon and marine waters. To take the impact of this oscillating volume into account, the GAMELag model includes the conceptual mixing volume variable (V_x) defined by Gordon et al. (1996) as a forcing variable. The MARS-3D hydrodynamic model provides the mixing volume time series, defined as the average daily volume exchanged between the lagoon and the CRAS [$V_x = 0.5.(|V_{In}| + |V_{Out}|)$].

High-frequency salinity measurements were taken in the CRAS (every 10 min) over the period from 1 March 2017 to 31 March 2018, and the daily averages were used as a forcing condition for the hydrological module (Picard, 2021). Discrete data of concentrations of dissolved inorganic nitrogen, total organic nitrogen, phosphate and total organic phosphorus acquired in the CRAS over the same period were used as forcing conditions for the biogeochemical module (SYMBO, 2019).

2.4. Validation of the tool for the Or Lagoon

2.4.1. Validation of the hydrological module: comparing the salinity measurements to the model

The model's ability to reproduce the mixing phenomena between the brackish waters of the lagoon, the marine-influenced waters of the CRAS, and freshwater inputs from the catchment area was evaluated via the temporal changes in salinity simulated in the lagoon on a daily time step between 1 March 2017 and 31 March 2018, the period of the in-situ monitoring. The daily averages of the high-frequency salinity data (acquired every 10 min) from the ORE and ORW sites (Figure 2) were compared to the simulated daily salinity in the physical unit (the lagoon). The performance of the model was analysed using several indices: Root Mean Square Error (RMSE), percent bias (PBias), regression coefficient (R^2) and (dr) index of agreement (Willmott et al., 2012). These statistical indicators were calculated with the hydroGOF package version 0.4-0 in R software.

2.4.2. Parameterisation of the biogeochemical module

The method developed for the GAMELag model to estimate biogeochemical parameters (Saguet et al., 2019) exploits the large number of simulations (several tens of thousands) generated by global model sensitivity analysis methods (Morris, 1991; Saltelli et al., 2000). The state variable values of the biogeochemical module, calculated at a time step of 10 minutes and averaged over the day, were compared with the in-situ data; then the values of the statistical performance indices (identical to those defined for salinity) resulting from these comparisons allowed us to order the simulations and retain the parameterisations (i.e. the combinations of values of the model's 120 parameters), reducing discrepancies between the model's results and the in-situ measurements.

The data available for the Or Lagoon are the spot concentrations of dissolved inorganic nitrogen (DIN), total organic nitrogen (TON), total nitrogen (TN), phosphate (PO_4), total organic phosphorus (TOP), total phosphorus (TP) and chlorophyll *a* (chl.a) measured annually in the months of June, July and August in 2017 and 2018 at the ORE and ORW sites. These summer data were supplemented by discrete DIN, TON, TN, PO4, TOP and TP data acquired in the lagoon in January and May 2017 at the same sites (David, 2019). Applying this method for estimating biological parameters in the Or Lagoon resulted in eight different parameterisations, for which 35 parameters differed from their reference values in the literature (results not shown, for more details see Fiandrino et al., 2022a).

No in-situ measurements were available for the 'Sediment' and 'Macrophyte' compartments during the validation period. The ability of the model to describe changes in the 'Sediment' compartment was based on total nitrogen and total phosphorus concentration data acquired at 15 sites in the Or Lagoon in 2010 (Ifremer, 2011) and 2019. The simulated biomass of opportunistic algae was compared with the biomass value corresponding to the overall eutrophication of the lagoon defined on the basis of the most degraded state simulated for the water column and phytoplankton. The relationship between the ranges of biomass values for opportunistic algae and the global ecological status of a lagoon was provided by the analysis of macrophyte biomass data acquired in 13 lagoons between 2001 and 2006 within the framework of the Regional Lagoon Monitoring Network (Fiandrino et al., 2022b).

2.5. Assessment of admissible load with the GAMELag tool

The method of estimating admissible load is based on exploratory scenario analysis and aims to find the 'balanced ecological functioning of the ecosystem'. This is considered to be the case when (i) the physico-chemical indicators of the water column ([DIN], [DIP], [TN] and [TP]) and the metric associated with phytoplankton biomass meet the 'good' status thresholds set by the WFD (MTES, 2018); (ii) the biomass of opportunistic algae is compatible with the values observed in lagoons in 'good' ecological status (Fiandrino et al., 2022b); (iii) on a yearly scale, the ecosystem does not store nitrogen and phosphorus in the sediment.

Different scenarios of exogenous and possibly endogenous matter inputs via the sediment compartment were simulated based on forcing conditions characteristic of the current situation. An exploratory analysis of the results of the simulations revealed the typologies of the functions characteristic of the ecosystem. Combining the clusters obtained and the constraints of the 'balanced ecological functioning of the ecosystem' defined above resulted in a pressure–state chart that makes it possible to quantify the ecosystem's admissible load.

2.5.1. Descriptors for ecosystem functioning

The descriptors selected to characterise the ecological functioning of the lagoon are listed in Table 1. Descriptors of the exogenous nitrogen and phosphorus loads that feed the lagoon via various sources and of the stocks of nitrogen and phosphorus in sediment were also defined to account for pressures on the ecosystem (Table 2).

Table 1: Descriptors of the ecological functioning of the lagoon

Descriptor	***Meaning***	***Unit***
$[DIN]_{Lag}$	average summer concentration of dissolved inorganic nitrogen	$mmolN.m^{-3}$
$[DIP]_{Lag}$	average summer concentration of dissolved inorganic phosphorus	$mmolP.m^{-3}$
$[TN]_{Lag}$	average summer concentration of total nitrogen	$mmolN.m^{-3}$
$[TP]_{Lag}$	average summer concentration of total phosphorus	$mmolP.m^{-3}$
$[chl.a]_{Lag}$	average summer concentration of chl.a	$mg\ chl\ a.m^{-3}$
$[Opport]_{Lag}$	average spring biomass of opportunistic species	$gdW.m^{-3}$
$[\Delta TN]_{Sed}$	annual change in nitrogen concentration in the sediment	$mmolN.m^{-2}.y^{-1}$
$[\Delta TP]_{Sed}$	annual change in phosphorus concentration in the sediment	$mmolP.m^{-2}.y^{-1}$
$TN_{Out\ CRAS}$	annual amount of nitrogen exported to CRAS	$Tonnes\ N.y^{-1}$
$TP_{Out\ CRAS}$	annual amount of phosphorus exported to CRAS	$Tonnes\ P.y^{-1}$

Table 2: Descriptors of pressures on the ecosystem

Descriptor	***Meaning***	***Unit***
N Load	total annual amount of nitrogen imported into the lagoon via the catchment area and the CRAS	Tonnes $N.y^{-1}$
P Load	total annual amount of phosphorus imported into the lagoon via the catchment area and the CRAS	Tonnes $P.y^{-1}$
$[TN_{Sed}]$	initial concentration of nitrogen levels in the sediment	mmol $N.m^{-2}$
$[TP_{Sed}]$	initial concentration of phosphorus levels in the sediment	mmol $P.m^{-2}$

2.5.2. Simulation of scenarios (sediment supply/stock) to find optimal functioning

The forcing data defined over a four-year period from 2015 to 2018 and the sediment stock assessed in 2010 (TN_{Sed} = 12 000 $mmol.m^{-2}$ and TP_{Sed} = 724.6 $mmol.m^{-2}$, Ouisse et al., 2013) were used to define the 'Current' situation (Table 3). From this initial condition, an experimental design was constructed in order to test different scenarios in terms of reducing exogenous inputs from the three sources (the Canalette, the N WS, and the CRAS, Figure 2) and from the sediment compartment. Decreases in nitrogen and phosphorus inputs from exogenous sources were made (compared to the 'Current' situation) through either a proportional decrease in nitrogen and phosphorus, or a greater decrease in phosphorus, modifying the N/P ratio of inputs. The 'Zero inputs' scenario (scenario 38: Table 3) corresponded to an 'extreme' situation in which the exogenous inputs from the catchment area and the CRAS were considered to be nil. Between these two contrasting situations, 37 intermediate scenarios were simulated (scenarios 1 to 37: Table 3). A further 13 scenarios were simulated by reducing sediment stock in conjunction with reductions in exogenous flows (scenarios 39 to 51: Table 3). The most restrictive situation for the sediment compartment was 'very good' status (TN_{Sed} = 2721 $mmol.m^{-2}$ and TP_{Sed} = 484 $mmol.m^{-2}$ as defined by Ouisse et al., 2020), i.e. Sed_{init} reduction factors of 0.23 for nitrogen and 0.67 for phosphorus. A total of 52 scenarios (including the 'Current' situation) were simulated.

2.5.3. Analysis of the scenarios to create a pressure–state chart of the ecosystem

A Principal Component Analysis (PCA) and an Ascending Hierarchical Classification (AHC), carried out with the FactoMineR package in R, allowed an exploration of the values of the descriptors for the 52 simulated scenarios, the four years (2015–2018) and the eight sets of selected parameters (i.e. 1664 independent statistical elements), revealing the typologies of characteristic ecosystem functioning (grouped in clusters).

Subsequently, in order to determine a pressure–state chart that links exogenous and endogenous nutrient inputs to the ecological functioning of the ecosystem, ecological criteria were taken into account and a second sub-categorisation was made by considering within each cluster the elements for which: (i) the values of the physicochemical indicators of the water column [DIN], [DIP], [TN], [TP] and the metric associated with phytoplankton biomass [chl.a] were compatible with 'good' status (indicated by 'A' after the cluster number) and, in contrast; (ii) the values of indicators [TN], [TP] and [chl.a] were representative of 'poor' to 'bad' status (indicated by 'D' after the cluster number); (iii) the ecosystem did not store nitrogen and phosphorus in the sediment (indicated by 'B' after the cluster number) and, in contrast; (iv) the ecosystem stored nitrogen or phosphorus in the sediment compartment (indicated by 'C' after the cluster number). This allowed the quantification in the pressure–state chart of the ecosystem's admissible load, i.e. the exogenous inflows admissible for the functioning of the ecosystem compatible with 'good' ecological status.

Table 3: Scenarios for reducing the concentration of exogenous nitrogen and phosphorus inputs in initial sediment conditions. The values correspond to the reduction coefficients applied to concentrations in the 'Current' situation (1.00 corresponds to maintaining the initial values and 0.00 to reducing these to a concentration of zero).

	NITROGEN				PHOSPHORUS			
Scenario	**Canalette**	***Watershed***	***CRAS***	***Sed $_{Init}$***	***Canalette***	***Watershed***	***CRAS***	***Sed $_{Init}$***
Current	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	1.00	1.00	0.93	1.00	1.00	1.00	0.58	1.00
2	1.00	1.00	0.93	1.00	1.00	1.00	0.30	1.00
3	1.00	1.00	0.47	1.00	1.00	1.00	0.29	1.00
4	1.00	1.00	0.47	1.00	1.00	1.00	0.13	1.00
5	1.00	1.00	0.23	1.00	1.00	1.00	0.15	1.00
6	1.00	1.00	0.23	1.00	1.00	1.00	0.07	1.00
7	1.00	1.00	0.12	1.00	1.00	1.00	0.07	1.00
8	1.00	1.00	0.12	1.00	1.00	1.00	0.03	1.00
9	1.00	1.00	0.06	1.00	1.00	1.00	0.01	1.00
10	0.59	1.00	1.00	1.00	0.27	1.00	1.00	1.00
11	0.59	1.00	1.00	1.00	0.20	1.00	1.00	1.00
12	0.59	1.00	0.93	1.00	0.27	1.00	0.58	1.00
13	0.59	1.00	0.93	1.00	0.20	1.00	0.30	1.00
14	0.59	0.75	0.93	1.00	0.27	0.75	0.58	1.00
15	0.59	0.75	0.93	1.00	0.20	0.55	0.30	1.00
16	0.29	1.00	1.00	1.00	0.14	1.00	1.00	1.00
17	0.29	1.00	1.00	1.00	0.08	1.00	1.00	1.00
18	0.29	1.00	0.47	1.00	0.14	1.00	0.29	1.00
19	0.29	1.00	0.47	1.00	0.08	1.00	0.13	1.00
20	0.29	0.50	0.47	1.00	0.14	0.50	0.29	1.00
21	0.29	0.50	0.47	1.00	0.08	0.35	0.13	1.00
22	0.15	1.00	1.00	1.00	0.07	1.00	1.00	1.00
23	0.15	1.00	1.00	1.00	0.04	1.00	1.00	1.00
24	0.15	1.00	0.23	1.00	0.07	1.00	0.15	1.00
25	0.15	1.00	0.23	1.00	0.04	1.00	0.07	1.00
26	0.15	0.75	0.23	1.00	0.07	0.75	0.15	1.00
27	0.15	0.75	0.23	1.00	0.04	0.55	0.07	1.00
28	0.07	1.00	1.00	1.00	0.03	1.00	1.00	1.00
29	0.07	1.00	1.00	1.00	0.02	1.00	1.00	1.00
30	0.07	1.00	0.12	1.00	0.03	1.00	0.07	1.00
31	0.07	1.00	0.12	1.00	0.02	1.00	0.03	1.00
32	0.07	0.50	0.12	1.00	0.02	0.35	0.03	1.00
33	0.07	0.25	0.12	1.00	0.02	0.17	0.03	1.00
34	0.04	1.00	1.00	1.00	0.01	1.00	1.00	1.00
35	0.04	1.00	0.06	1.00	0.01	1.00	0.01	1.00
36	0.04	0.15	0.06	1.00	0.01	0.05	0.01	1.00
37	0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00
38	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00
39	1.00	1.00	1.00	0.84	1.00	1.00	1.00	0.95
40	0.00	0.00	0.00	0.84	0.00	0.00	0.00	0.95
41	1.00	1.00	1.00	0.50	1.00	1.00	1.00	0.50
42	0.04	0.15	0.06	0.50	0.01	0.05	0.01	0.50
43	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.50
44	0.59	1.00	1.00	0.23	0.20	1.00	1.00	0.67
45	1.00	1.00	1.00	0.23	1.00	1.00	1.00	0.67
46	1.00	1.00	0.47	0.23	1.00	1.00	0.13	0.67
47	0.29	1.00	1.00	0.23	0.08	1.00	1.00	0.67
48	0.29	1.00	0.47	0.23	0.08	1.00	0.13	0.67
49	0.29	0.50	0.47	0.23	0.08	0.35	0.13	0.67
50	0.00	1.00	0.00	0.23	0.00	1.00	0.00	0.67
51	0.00	0.00	0.00	0.23	0.00	0.00	0.00	0.67

3. Results

3.1. Model's ability to reproduce mixing phenomena

A comparison between measured and simulated salinity over the period from 1 March 2017 to 31 March 2018 showed that the model correctly reproduced the general trend (Figure 3). The increase in salinity between early April and mid-October 2017 was replicated well by the model (r^2 = 0.96; d = 0.99, bias = -1.2%). The very low inflow of fresh water from the catchment area (26.4 10^6 m^3) and very low direct precipitation falling on the lagoon (7.5 10^6 m^3), as well as the significant evaporation (-26.5 10^6 m^3) over this 7-month period, explain the particularly high salinity values reached in autumn 2017 (>30).

The significant drop in salinity (ΔS = -20 between the beginning of December 2017 and the end of March 2018) was also well reproduced by the model, although in advance (r^2 = 0.89; d = 0.84, bias = -24.4%). The rainfall that occurred between the beginning of December 2017 and the beginning of January 2018 resulted, in the model forcing, in significant freshwater inputs (26.4 10^6 m^3 from the catchment area and 2.4 10^6 m^3 from direct rainfall on the lagoon), which led to a decrease in the simulated salinity. This first rainfall after a long dry period had little impact on measured salinity in the lagoon. The drop in salinity was only observed from mid-January 2018 after heavy rainfall followed by a very wet end of winter. Over the period from mid-January to the end of March 2018, freshwater inflows from the catchment area were estimated at 48.8 10^6 m^3 and from direct rainfall on the lagoon at 12.0 10^6 m^3.

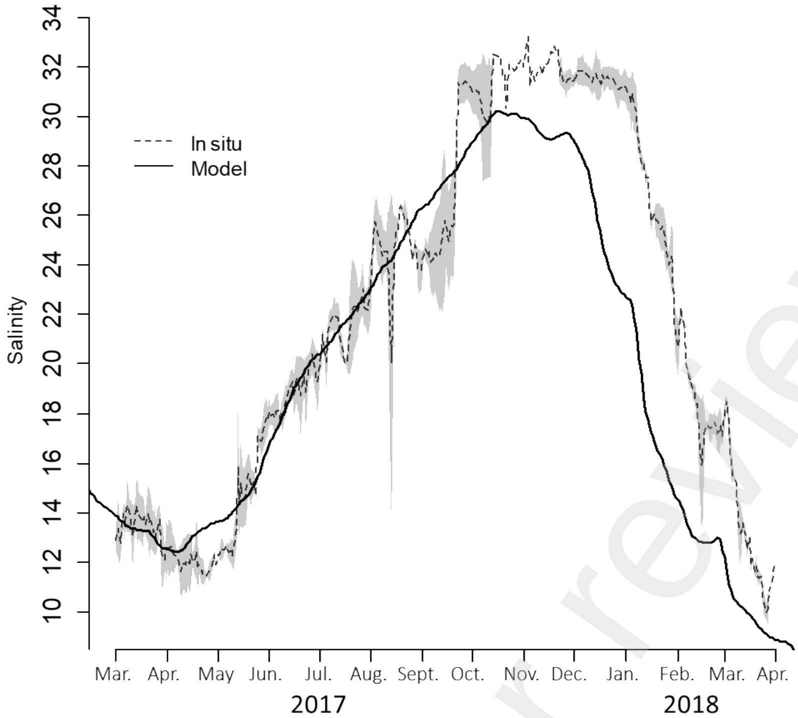

Figure 3: Change in salinity over the period from 1 March 2017 to 31 March 2018: model simulation shown by the black solid line and high-frequency in-situ measurements taken at the ORW and ORE sites shown in grey (grey dashes = mean value).

3.2. Model's ability to reproduce changes in the sediment stock of nitrogen and phosphorus

The model simulated an increase in nitrogen stock in the first 5 cm of sediment (Figure 4, left) of +334 mmol $N.m^{-2}.y^{-1}$ and a slow decrease in the sediment stock of phosphorus (Figure 4, right) of -6.8 mmol $P.m^{-2}.y^{-1}$.

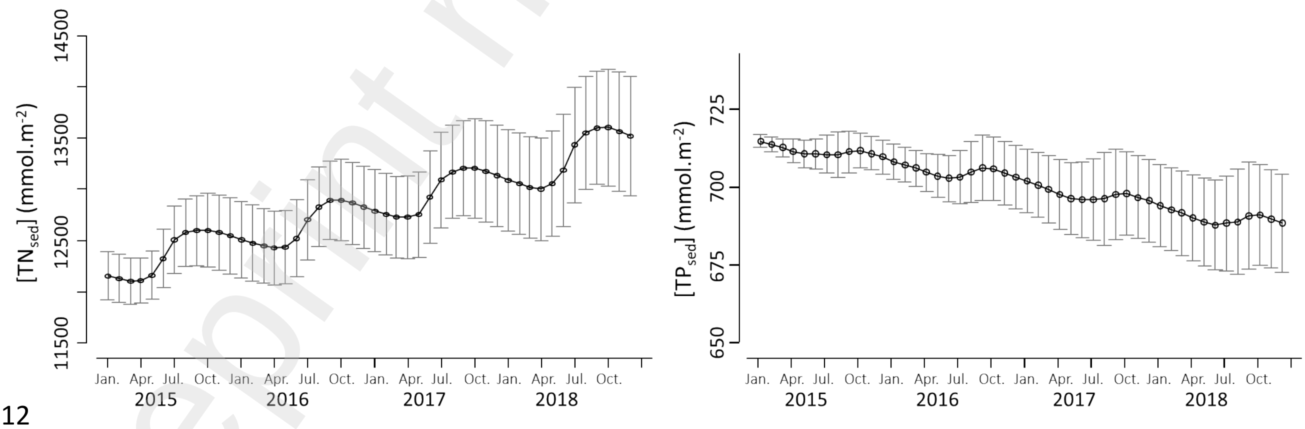

Figure 4: Simulated monthly change in nitrogen and phosphorus sediment stocks between 2015 and 2018. The dots represent the means and the error bars the standard deviations of the values obtained from the eight parameterisations used in the model.

The simulated increase in nitrogen stock was not in line with observations, which showed a significant decrease between 2010 and 2019 $[\Delta TN_{Sed}]_{2019\text{-}2010} = -1976.2 \pm 2112.1$ mmol N.m^{-2} (p-value < 0.1). However, the model correctly accounted for the change in the sediment stock of phosphorus. Over the period 2010 and 2019, the simulated difference in phosphorus stock (-61 mmolP.m^{-2} extrapolating the results obtained during 2015–2018) was in line with observations ($[\Delta TP_{Sed}]_{(2019\text{-}2010)} = -41.2 \pm 131.3$ mmol P.m^{-2}).

3.3. Model's ability to reproduce ecological functioning of the lagoon

The model's inability to simulate the change in the sediment stock of nitrogen over the medium to long term does not call into question its ability to account for changes in the water column, phytoplankton and macrophyte parameters. Indeed, the model satisfactorily reproduced the ecological functioning of the lagoon in the summer period, showing excessive primary production limited by the availability of dissolved inorganic forms of nitrogen and an excess of phosphate in the water column (Figure 5). The summer phosphate concentration was, on average, overestimated by a factor of two over the eight simulations (bias = 110%), and the summer organic phosphorus concentration was underestimated (bias = -26.4%), with a consequent overestimation of total phosphorus concentration (bias = 32.9%). The summer concentration of inorganic nitrogen was on average overestimated by the model over the eight simulations (bias = +87.7%), particularly in August, but this overestimation must be put into perspective due to the very low values below the 'very good'/'good' threshold (green line on Figure 5). Dissolved organic nitrogen concentration was underestimated (bias = -34.8%) with a direct impact on total nitrogen concentration (bias = -20%). However, taking into account the uncertainties of the model, it can be considered that it gave a reasonable representation of the measured values of these four parameters (Figure 5).

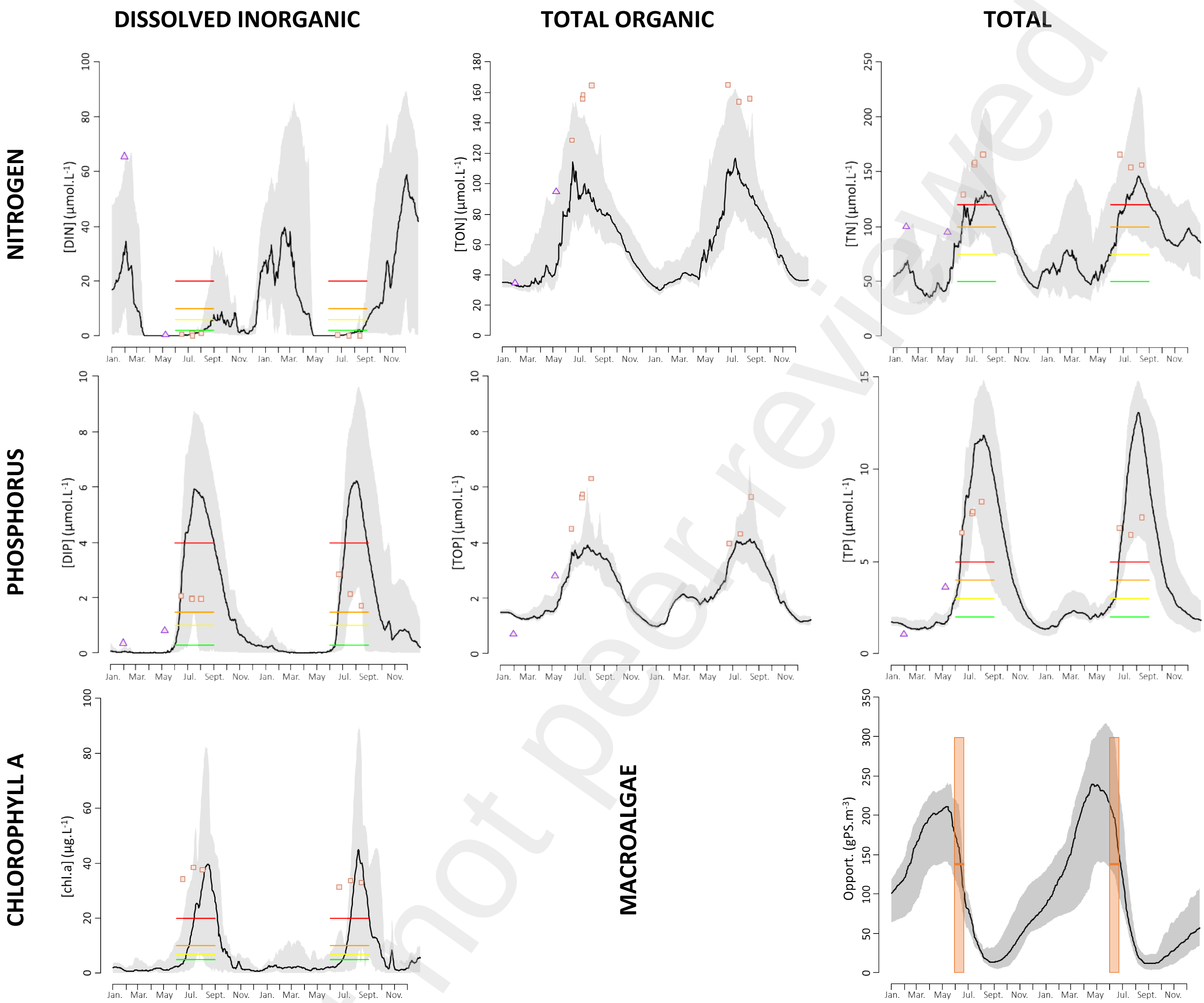

Figure 5: Temporal change in the parameters DIN, TON, TN, DIP, TOP, TP and chl.a simulated between 1 January 2016 and 31 December 2018. The solid line corresponds to the average of the results obtained with the eight parameter sets and the shaded area is defined by the minimum and maximum values. WFD monitoring data (squares), discrete data (triangles), and the lower thresholds of the WFD status classes are also represented ('Good': green line; 'Average/Fair': yellow line; 'Poor': orange line; 'Bad': red line). On the macroalgae graph, the orange bars show the mean values and standard deviations of the biomass characteristic of a poor state.

The model simulated a phytoplankton bloom between the months of June and October with a chlorophyll *a* peak in August, the average intensity of which over the eight simulations was comparable to observations (35 to 45 µg.L^{-1}). The underestimation of the simulated chlorophyll concentration in June suggests, however, that the estimated start of the bloom was somewhat late. The simulated biomass of opportunistic algae was minimal in early autumn, increased to its maximum value between March and May (~ 200 $gPS.m^{-3}$ in 2017 and 250 $gPS.m^{-3}$ in 2018) and then decreased rapidly in June. In 2017, the simulated biomass was in line with the biomass value corresponding to a lagoon in 'poor' to 'bad' status (orange bars defined based on Fiandrino et al., 2022b). In 2018, the simulated algal bloom was larger, and the biomass was in the high range of the descriptor.

3.4. Matter and water balance

The water balance and matter balance for 2015 to 2018 (Table 4) showed high interannual variability of inputs linked to variation in precipitation, which influences the flow of streams in the natural catchment area (northern watershed, Table 4) and, to a lesser extent, the flow of the Canalette. Freshwater inflow from the N WS was almost three times higher in a wet year (2018) than in a dry year (2017). For the Canalette, which is the main source of water in the catchment area, the factor between wet and dry years was 1.9: it accounted for 62% of inflow in wet years and 79% in dry years.

Nitrogen and phosphorus inputs from the catchment area (Watershed, Table 4) also showed high interannual variability (factor of 2.6 for nitrogen and 2.4 for phosphorus between dry and wet years). The N:P mass ratio of inputs from the N WS varied around 46.6 ± 15, with the highest values in dry years and the lowest in wet years. The N:P mass ratio from the Canalette was much more stable at around 10 ± 0.8. This stable, marked imbalance in phosphorus from the Canalette made it the lagoon's main source of phosphorus, with a contribution to the input from the catchment area that varied between 73% in wet years and 88% in dry years. However, while the Canalette was also the main source of nitrogen in the watershed in a dry year (79%), the N WS became the main source in a wet year, with 55% of the nitrogen input.

Nitrogen and phosphorus inputs from the CRAS (CRAS In, Table 4) showed low interannual variability (factor of 1.3 for nitrogen and 1.2 for phosphorus between dry and wet years). The contribution of CRAS to total annual nitrogen input (336 Tonnes $N.y^{-1}$) was predominant in dry years (66%) and represented more than one-third of total annual inputs in wet years (457 Tonnes $N.y^{-1}$). The CRAS's contribution to total annual phosphorus inputs (26 Tonnes $P.y^{-1}$) was even more marked and represented nearly 71% in a dry year and nearly 47% of the 33.5 Tonnes $P.y^{-1}$ that the lagoon received in a wet year.

The net balance of matter between the lagoon and the CRAS was in equilibrium in dry years (Inputs/Outputs: $I/O_N^{CRAS} = -6 \pm 39$ Tonnes $N.y^{-1}$; $I/O_P^{CRAS} = -7 \pm 6$ Tonnes $P.y^{-1}$) and strongly tipped to matter export in wet years ($I/O_N^{CRAS} = -161 \pm 47$ Tonnes $N.y^{-1}$; $I/O_P^{CRAS} = -16 \pm 6$ Tonnes $P.y^{-1}$). The annual matter balance on the scale of the lagoon was positive: i.e. nitrogen and, to a lesser extent, phosphorus tended to accumulate in the lagoon whatever the hydrological conditions ($I/O_N^{LAG} = +136 \pm 47$ Tonnes $N.y^{-1}$; $I/O_P^{LAG} = +4 \pm 7$ Tonnes $P.y^{-1}$).

Table 4: Annual balance of water, nitrogen and phosphorus inputs to the Or Lagoon from the atmosphere, the watershed (N WS = northern watershed) and the Rhône to Sète Canal (CRAS) from 2015–2018. The years in brackets are associated with the minimum and maximum values for each parameter. For the import/export of matter by CRAS, the values correspond to the average and the standard deviation of the eight sets of parameters.

WATER ($10^6 m^3.y^{-1}$)

ATMOSPHERE		**WATERSHED**				***CRAS***	
Rainfall	***Evaporation***	***Watershed***	***Canalette***	***N WS***	***WWTP***	***In***	***Out***
10.3 - 30.9	25.8 - 28.1	56.2 - 122.0	40.0 - 75.4	15.3 - 46.6	0.07 - 0.08	162.2 - 203.1	243.1 - 289.7
(2017) - (2018)	(2016) -(2017)	(2017) - (2018)	(2017) -(2018)	(2017) - (2018)	(2016) - (2017)	(2018) - (2017)	(2017) - (2018)

NITROGEN ($Tons.y^{-1}$)

ATMOSPHERE		**WATERSHED**				***CRAS***	
Rainfall	***Evaporation***	***Watershed***	***Canalette***	***N WS***	***WWTP***	***In***	***Out***
3.1 - 9.5	-	114.6 - 291.1	60.1 - 171.0	46.0 - 160.5	0.3 - 0.5	165.5 - 221.1	227.5 ± 39.8 / 326.5 ± 47.3
(2017) - (2018)	-	(2017) - (2018)	(2017) -(2016)	(2016) - (2018)	(2017) - (2015)	(2018) - (2017)	(2017) / (2018)

PHOSPHORUS ($Tons.y^{-1}$)

ATMOSPHERE		**WATERSHED**				***CRAS***	
Rainfall	***Evaporation***	***Watershed***	***Canalette***	***N WS***	***WWTP***	***In***	***Out***
0.2 - 0.7	-	7.5 - 17.8	6.6 - 16.4	0.8 - 4.3	0.05 - 0.09	15.7 - 18.4	25.8 ± 5.7 / 31.4 ± 5.6
(2017) - (2018)	-	(2017) - (2016)	(2017) -(2016)	(2017) - (2018)	(2018) - (2015)	(2018) - (2017)	(2017) / (2018)

3.5. Matter fluxes between the compartments of the ecosystem

The outcome of exogenous inputs in the ecosystem was analysed in terms of storage and matter fluxes exchanged between the different compartments of the ecosystem (Figure 6). The nitrogen and phosphorus stocks in the hydrobiological compartments (coloured circles) corresponded to annual averages. In the sediment, the values corresponded to the difference in nitrogen and phosphorus stocks between the end and the beginning of each year. The nitrogen and phosphorus fluxes between the compartments were cumulated over a year. The variation in stocks and annual fluxes was averaged over the four simulated years and the eight parameterisations.

3.5.1 'Current' situation

Internal sources (biological compartments and sediment) accounted for 73% of dissolved inorganic nitrogen inputs to the water column, with little interannual variability but seasonal variation (from 43% in winter to 96% in summer). From October to June, fluxes from sediment release were the main internal source of DIN (66%) and in summer, remineralisation of organic matter in the water column became predominant (48% from internal sources). Exogenous inputs accounted for an average of 23% of DIN inputs, more than two-thirds of which came from the catchment area (N WS and Canalette).

Internal sources also accounted for the majority of dissolved inorganic phosphorus. These endogenous sources represented more than 80% of inputs with seasonal variation (from 64% in winter to 91% in summer). Between May and July, the mortality of opportunistic algae was the main internal source of DIP (47%), and then in August–September the mineralisation of organic matter in the water column became predominant. For the rest of the year, sediment release was the main internal source of DIP (65%). Inputs from the catchment area and the CRAS represented at most 10% of the inputs (in wet years from the catchment area, and in dry years from the CRAS).

Opportunistic algae was primarily responsible for the assimilation of inorganic nitrogen: 57% was assimilated by algae compared to 38% for phytoplankton. The distribution was more balanced for phosphate, macrophytes and phytoplankton, which each assimilated around 48%. This assimilation of matter by macroalgae and phytoplankton was clearly staggered in time, with storage of matter (nitrogen and phosphorus) mainly in the 'Phytoplankton' compartment from July to September, and then storage in the 'Macroalgae' compartment from October to November, reaching a maximum in April before a decrease in June. Thus, the primary role of macroalgae and phytoplankton in the assimilation of inorganic nitrogen and phosphorus was reversed between June and July.

Exports of dissolved inorganic forms to the CRAS accounted for only 6% of DIN losses to the water column, compared to almost 11% for DIP. For DIN, exports were highest in winter (December to February), while DIP exports were highest in summer (June to September). This difference indirectly reflects the role of DIN as a limiting factor in primary production, particularly in the summer period.

Concerning detrital organic forms, internal sources accounted for nearly 80% of nitrogen inputs, 53% of which were derived from the degradation of opportunistic algae. The degradation of zooplankton and phytoplankton represented less than 14% and 9% of internal sources respectively. Exogenous inputs of nitrogen were mostly associated with CRAS (14%).

Internal sources accounted for almost 74% of detrital organic phosphorus inputs, of which 29%, 22% and 17% came from the degradation of opportunistic algae, zooplankton and phytoplankton respectively. As for nitrogen, exogenous inputs were primarily associated with CRAS (15%).

Exports of detrital organic forms to CRAS accounted for almost 29% of nitrogen losses and 40% of phosphorus losses.

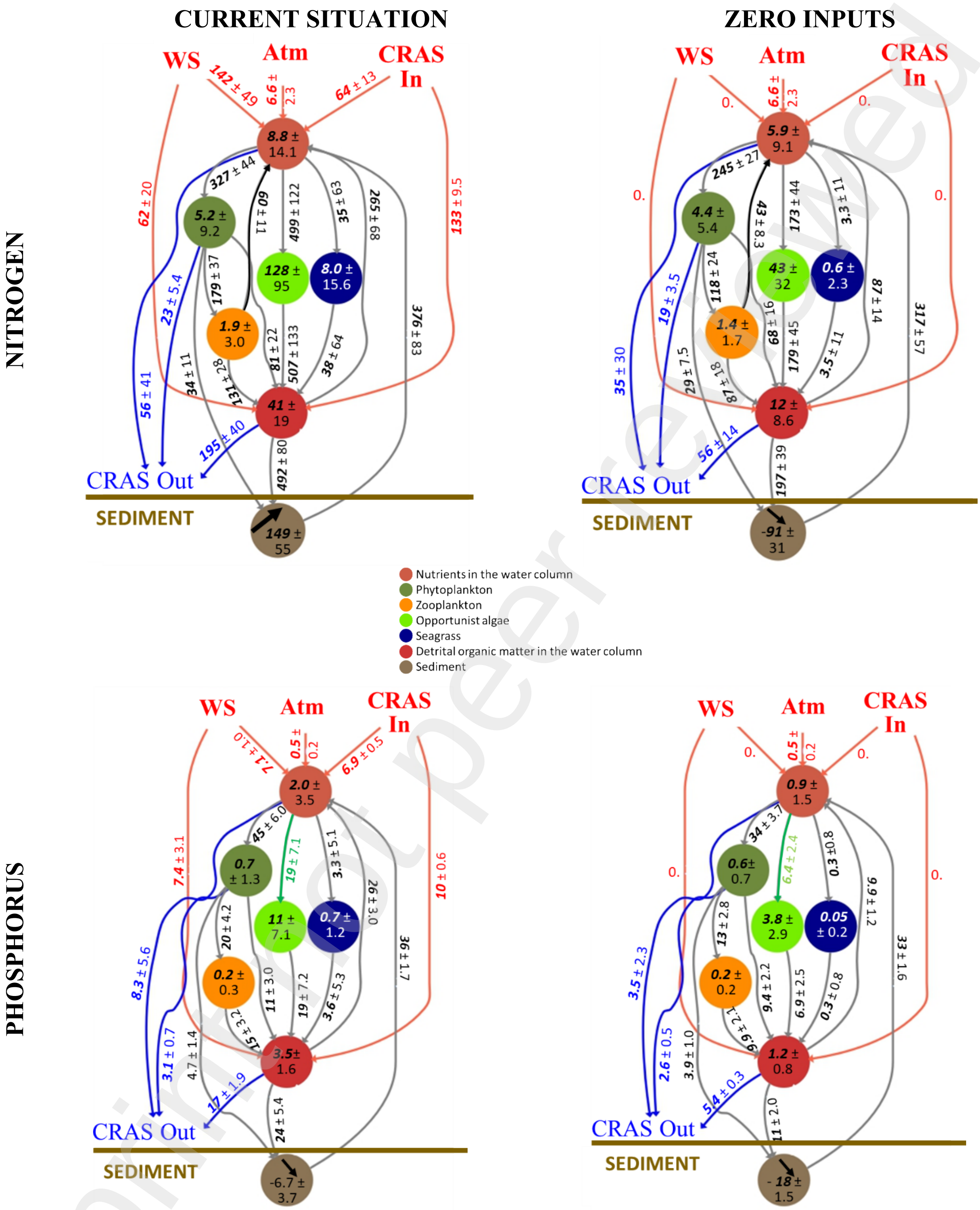

Figure 6: Representation of simulated stocks and fluxes of nitrogen (top) and phosphorus (bottom) for the 'Current' situation (left) and for a 'Zero inputs' from the watershed scenario (right). The arrows represent the cumulative annual fluxes (expressed in Tonnes.y^{-1}) between the different compartments. The green arrows correspond to a net balance of bilateral phosphate exchange between the 'DIP' and 'Macroalgae' compartments. The circles represent the average annual stocks (expressed in tonnes) in the compartments, except for the 'Macrophyte' compartment, in which the values represent the spring stocks (in tonnes), and the sediment compartment, in which the values correspond to the difference between the stock at the beginning and end of the year (in tonnes).

The degradation of organic matter accounted for almost 94% and 83% of the sources of sediment nitrogen and phosphorus respectively. This flux of nitrogen towards the sediment showed strong seasonal variability, with more than 48% of the annual flux generated in the summer period compared to less than 5% in winter. The magnitude of seasonal variation in the remineralisation fluxes of organic matter in the sediment (nitrogen losses in the sediment compartment) was lower, fluctuating between 35% in summer and 17% in winter. Thus, between October and March, there was a greater outflow of nitrogen leaving sediment than inflow, explaining the decrease in simulated stocks over this period; however, the marked differences in intensity in which inflow was greater from April to September were responsible for the overall tendency for nitrogen to be stored in the sediment compartment (Figure 6, left). Phosphorus fluxes exchanged between water and sediment showed the same seasonal changes as nitrogen fluxes, but the intensity of summer fluxes into and out of the sediment were of the same order of magnitude. Thus, the very low phosphorus storage simulated in the summer period did not compensate for the differences due to phosphorus release simulated in the periods from October to May (Figure 6, right).

3.5.2 'Zero inputs' scenario

In the scenario where inputs from the catchment area and CRAS were set to zero (scenario 38, Table 3), the functioning of the system was strongly modified. Compared to the 'Current' situation, the endogenous inputs of DIN and DIP decreased by a factor of 0.64 and 0.7 respectively, due to a marked reduction in the remineralisation processes of organic matter directly in the water column (factor of 0.34 for DIN and 0.39 for DIP). Summer stocks of DIP in the water column were greatly reduced (by a factor of 0.42), but remained characteristic of a 'poor' biological status with regard to the WFD indicators (Figure 7). As nitrogen remained the limiting factor in primary production, the summer stock of DIN in the water column was not significantly different between the two scenarios.

The assimilation of nutrients by opportunistic algae was also strongly impacted by removing exogenous inputs, reducing the quantities of nitrogen and phosphorus stored by these species in spring by a factor of 0.35. The maximum biomass of opportunistic algae was 75 g PS.m^{-3} compared to more than 200 g PS.m^{-3} in the 'Current' situation (Figure 7).

Nutrient uptake by phytoplankton was less impacted in the 'Zero inputs' scenario, reducing this by a factor of 0.75 compared to the 'Current' situation. Summer primary production remained excessive, with chlorophyll biomass still characteristic of 'bad' biological status (Figure 7).

This reduction in stocks of living matter resulted in a marked decrease in endogenous nitrogen and phosphorus fluxes to the organic compartment (by a factor of 0.45 for organic nitrogen and 0.54 for organic phosphorus), which was reflected in sedimentation fluxes (reduction by a factor of 0.43 for nitrogen and 0.54 for phosphorus). While the diffusion of nutrients from sediment to the water column was the process least impacted by the 'Zero inputs' scenario (reduction by a factor of 0.85 for DIN and 0.93 for DIP), the net balance of water–sediment exchanges was still strongly modified. The depletion of phosphorus, also simulated in the 'Current' situation, increased by a factor of 3.5 in the 'Zero inputs' scenario, and a major change in the functioning of the ecosystem was simulated with regard to the level of nitrogen, with a reversal of the trend and a depletion of nitrogen in sediment (Figure 6).

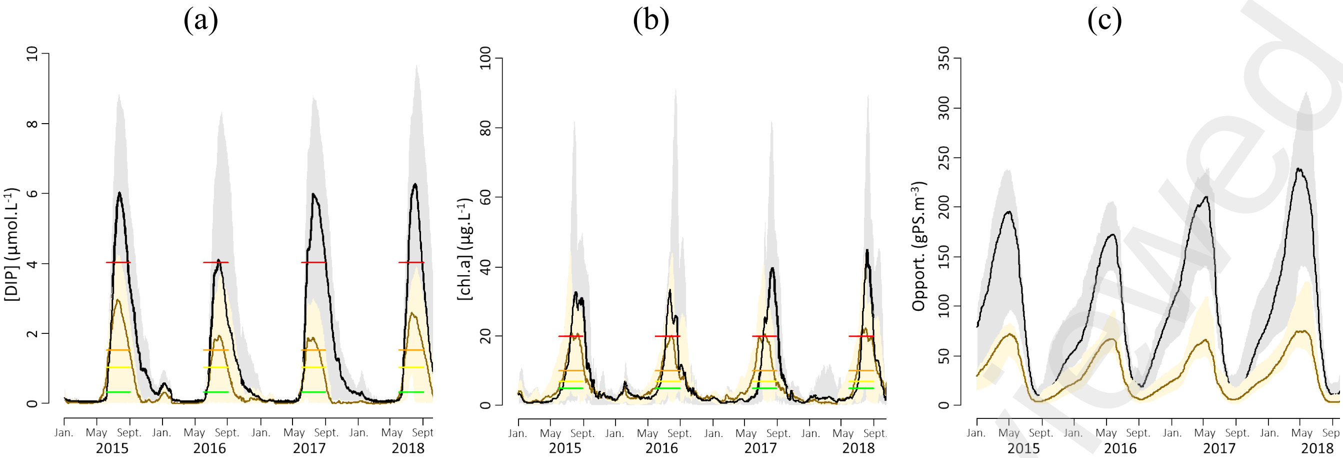

Figure 7: Temporal variations in DIP (a), chl.a (b) and opportunistic algal biomass (c) for the two scenarios 'Current' situation (black line and grey shading) and 'Zero inputs' (brown line and yellow shading). The lower thresholds of the WFD status classes ('Good': green line; 'Average/Fair': yellow line; 'Poor': orange line; 'Bad': red line) are also shown.

3.6. Typologies of ecosystem functioning: clustering results

The exploratory analysis of 52 scenarios (Table 3) and 1664 independent statistical elements was grouped into six clusters associated with types of ecological functioning (Figure 8). Four clusters (1, 3, 4, 6) were characteristic of ecosystem functioning in which nitrogen is the limiting parameter for biological production, with very low summer concentration of dissolved inorganic nitrogen (Figure 8a). Cluster 1 grouped elements (n=205) for which chlorophyll *a* concentrations (Figure 8e), biomass of opportunistic algae (Figure 8f) and summer stocks of total nitrogen and total phosphorus (Figure 8c, d) in the water column were among the lowest. Annual sediment stocks of nitrogen [ΔTN_{sed}] and phosphorus [ΔTP_{sed}] (Figure 8g, h) decreased.

Cluster 6 grouped the elements (n=410) in which the concentrations of dissolved inorganic phosphorus and total phosphorus in the water column (Figure 8b, d) were highest. This type of ecosystem was very productive, with concentrations of chlorophyll *a* and opportunistic algae biomass also among the highest (Figure 8e, f). The matter produced tended to be stored in the sediment, with large annual increases in sediment nitrogen stocks (Figure 8g).

Clusters 3 (n=531) and 4 (n=188) grouped elements that lay in between clusters 1 and 6 with respect to dissolved inorganic phosphorus and total phosphorus concentrations (Figure 8b, d).

The production of opportunistic algae remained moderate, with average biomass of less than 50 g PS.m^{-3} (Figure 8f). Chlorophyll biomass was high for cluster 3, with values that were on average in the middle of the poor category (Figure 8e). In cluster 4, predation by zooplankton limited phytoplankton production, but the organic matter produced was largely stored in the sediment (Figure 8g).

Cluster 2 grouped elements (n=59) in which the summer concentration of dissolved inorganic nitrogen was highest (Figure 8a). Primary production was limited by the availability of phosphate in the water column (Figure 8b). Chlorophyll *a* concentration was among the lowest, and biomass of opportunistic algae was moderate (Figure 8e, f). Annual stocks of nitrogen and phosphorus in the sediment decreased (Figure 8g, h).

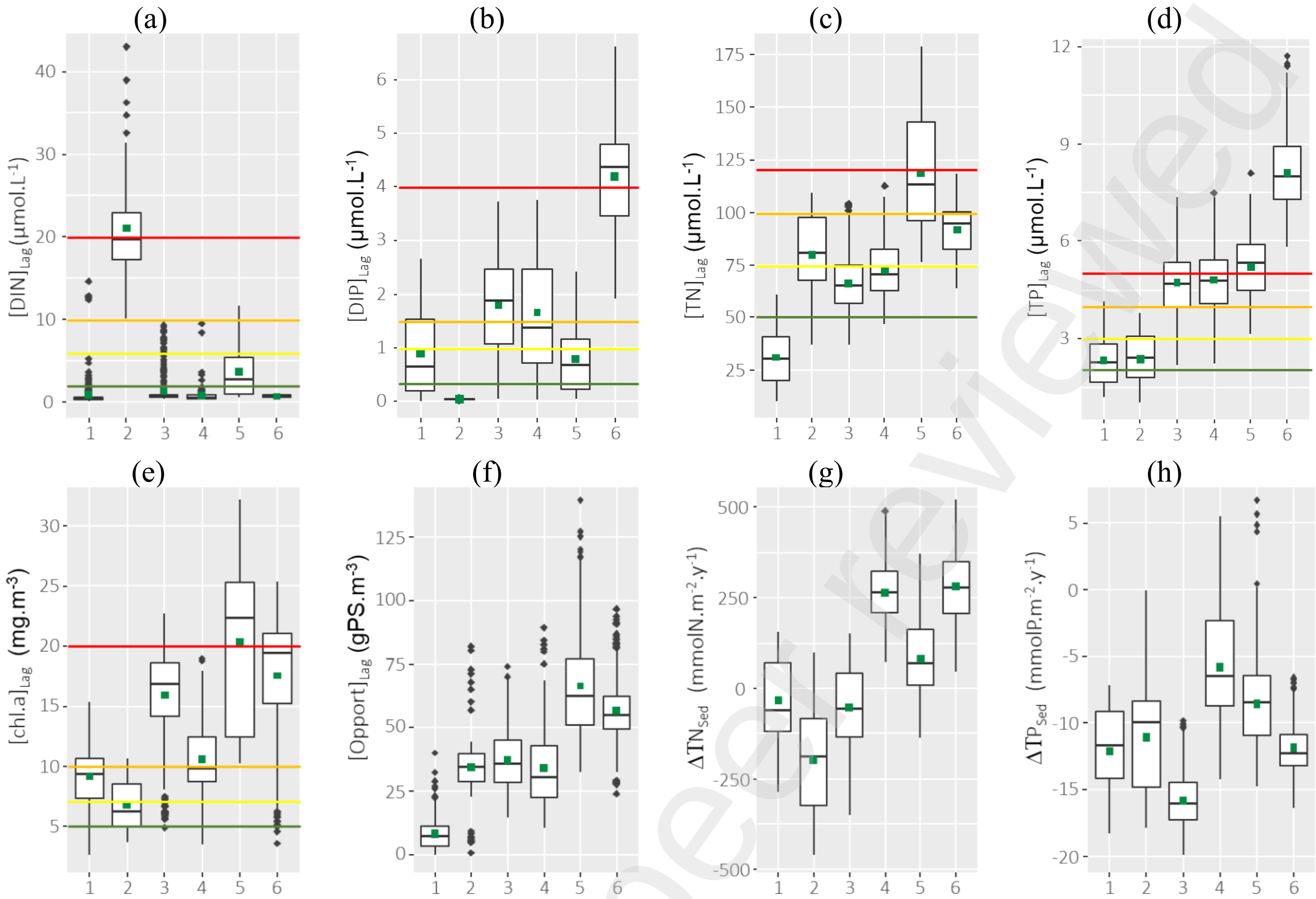

Figure 8: Distributions for the 1664 statistical elements of the values of 8 ecosystem descriptors (Table 1) within the 6 clusters identified by the AHC following the PCA: (a) DIN; (b) DIP; (c) TN; (d) TP; (e) chl.a; (f) opportunistic species; (g) annual change in sediment nitrogen stock; (h) annual change in sediment phosphorus stock. The horizontal lines represent the WFD thresholds when they exist (green: 'Very Good'/'Good' threshold; yellow: 'Good'/'Fair' threshold; orange: 'Fair'/'Poor' threshold; red: 'Poor'/'Bad' threshold).

Cluster 5 grouped elements (n=271) in which the chlorophyll *a* concentration (Figure 8e), biomass of opportunistic algae (Figure 8f) and the summer stock of total nitrogen in the water column were highest (Figure 8c). Annual nitrogen stock in the sediment tended to increase (Figure 8g).

3.7. Creation of a pressure–state chart to support lagoon management

The combination of the six clusters with the WFD thresholds of the water column and phytoplankton parameters and the change in the sediment stock resulted in the distribution of the 1664 elements in 16 sub-clusters (Table 5). The sub-clusters represented the ranges of variation in exogenous (northern and eastern watersheds and CRAS) and endogenous (sediment) pressures in relation to the response of hydrobiological parameters in the lagoon, providing a pressure–state chart that links the pressures experienced by the lagoon with its ecological state. For the sake of readability, Figure 9 shows the nine sub-clusters that were most contrasting (in terms of ecosystem functioning) and most representative (in terms of numbers of elements in the cluster).

Table 5: Distribution of the 1664 elements in the 16 sub-clusters resulting from the combination of the 6 clusters (in rows) and the 4 constraints (in columns) imposed on the water column/phytoplankton and sediment compartments (see §2.5.3. for the definition of conditions A,B,C,D). The 9 underlined/bold sub-clusters correspond to the sub-clusters retained to determine the pressure–state chart (Figure 9).

Cluster \ WFD Cond.	**Water / Phytoplankton status**			
	Good	*Intermediate*		*Bad*
	Sediment			
		No stock	*Stock*	
	A	**B**	**C**	**D**
1	**23**	**113**	**69**	
2		*55*	*4*	
3		**293**	**138**	*100*
4	*3*		**159**	*26*
5		**22**	*23*	**226**
6			*76*	**334**

Elements corresponding to the 'Current' situation were mainly grouped in sub-clusters 6D (63% of cases) and 5D (22% of cases). These two sub-clusters were characteristic of ecosystem functioning in which exogenous inputs (on the order of 316±72 Tonnes $N.y^{-1}$ and 19.5±6.4 Tonnes $P.y^{-1}$) and current sediment stock (poor state for nitrogen and average/fair state for phosphorus) (Figure 9, 'Pressures') supported excessive phytoplankton production and significant blooms of opportunistic algae (Figure 9, 'State'). The ecosystem stored nitrogen in the sediment compartment.

Assuming that 'current' exogenous inputs are associated with initial sediment stocks compatible with good status for phosphorus and average status for nitrogen (sub-cluster 4C, Figure 9), biological production of micro- and macroalgae would be lower, close to the average/fair threshold for phytoplankton. However, this functioning would result in significant annual storage of nitrogen in the sediment compartment. 'Current' inputs would therefore be likely to degrade a sediment compartment that was in good condition.

Even lower exogenous inputs (225±64 Tonnes N.y^{-1} and 12.5±6.6 Tonnes P.y^{-1}) combined with current sediment stocks (sub-clusters 3D and 5B) would still result in excessive biological production. Depending on the competition between micro- and macroalgae, these inputs would predominantly feed the 'Phytoplankton' (sub-cluster 3D) or 'Macrophyte' (sub-cluster 5B) compartments and leave excess dissolved inorganic phosphorus (sub-cluster 3D) or dissolved inorganic nitrogen (sub-clusters 5B) in the water column. Although such conditions of exogenous and endogenous pressure are not compatible with the ecosystem's good ecological status, they would make it possible to reverse the trend in terms of ecological trajectory by favouring the removal of phosphorus in sediment and limiting the storage of nitrogen (sub-cluster 3D) or even enabling its removal (sub-cluster 5B). An even more marked reduction in inputs (86±53 Tonnes N.y^{-1} and 3.5±2.3 Tonnes P.y^{-1}) associated with the current sediment stock (sub-cluster 3B) would accentuate this trend towards the restoration of the sediment compartment by favouring the massive destocking of nitrogen and phosphorous.

With exogenous inputs of the same order of magnitude (96±90 Tonnes N.y^{-1} and 3.3±2.7 Tonnes P.y^{-1}) and a sediment compartment in good condition as regards nitrogen and very good condition as regards phosphorus (sub-cluster 1A), the water column parameters and phytoplankton biomass showed values compatible with good ecological status. The primary production of micro- and macroalgae, jointly limited by nitrogen and phosphorus, did not leave excess nutrients in the water column, and the sediment compartment tended to release nitrogen and phosphorus. Such conditions reflect a balance between exogenous and endogenous fluxes.

Higher sediment stock associated with lower exogenous inflows (sub-cluster 1B) or, conversely, lower sediment stock associated with higher exogenous inflows resulted in phytoplankton production that was not compatible with good ecological status (chl.a close to the average/fair threshold: Figure 9, ‘State’). Thus, endogenous and exogenous conditions corresponding to sediment stock in “good” condition for nitrogen and in “very good” condition for phosphorus, and a reduction in exogenous inflows by a factor of 0.24 for nitrogen and 0.1 for phosphorus compared with current average annual inputs (402 Tonnes $N.y^{-1}$ and 31 Tonnes $P.y^{-1}$) would be compatible with the good ecological status of all the compartments in the ecosystem. These conditions could be considered, based on what we know today, as a target for admissible nutrient load for the Or Lagoon.

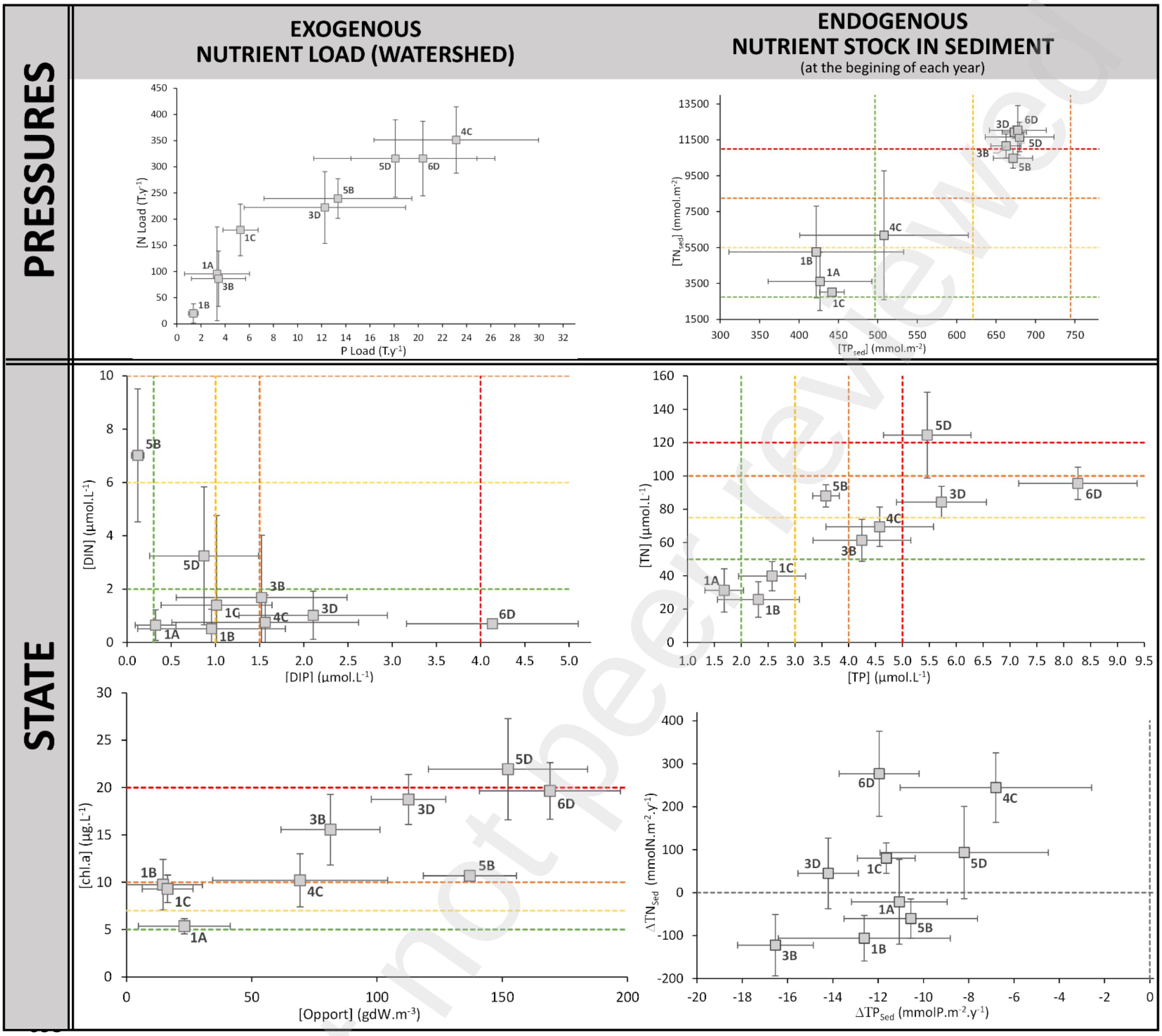

Figure 9: Pressure–state chart linking the state of the ecosystem ($[DIN]_{Lag}$ vs $[DIP]_{Lag}$; $[TN]_{Lag}$ vs $[TP]_{Lag}$; $[chl.a]_{Lag}$ vs $[Opport]_{Lag}$, the annual change in the sediment stock of nitrogen $[\Delta TN]_{sed}$ and phosphorus $[\Delta TP]_{sed}$ and the pressures exerted (from catchment and CRAS inputs and sediment stock) for the different sub-clusters. The horizontal and vertical lines correspond to the WFD thresholds.

4. Discussion

Since its creation in 2009, we have deliberately taken a pragmatic approach to continue to develop the GAMELag management tool. It initially provided a simple conceptualisation of the ecological functioning of an ecosystem; subsequently, its application at different sites during the validation process revealed limitations in its use. This led to the choice of more realistic and complex conceptualisations to attempt to overcome these limitations. As noted by Chapra et al. (2003), the continuous improvement of management tools requires research into the scales at which it is necessary and sufficient to describe the functioning of a complex system (Zwirn, 2006). Such an approach is dictated by the operational purpose of management support tools, which must be capable of providing reliable answers to the questions posed by society within a timeframe compatible with decision-making.

The simplicity of the GAMELag tool, linked to the fact that the hydrodynamic processes are not resolved by the model but taken into account via adapted forcing conditions, makes it possible to carry out a large number of simulations (six years simulated in less than 20 minutes on a standard PC), which is essential for the analysis of exploratory scenarios.

4.1. Relevance of the estimation method for admissible load

Our findings show that exploratory scenario analysis carried out in two stages (clustering from an AHC, which is then refined by taking into account ecological criteria) proves to be relevant for describing change in coastal lagoons in response to pressures to which they are subjected, as well as for defining the target for admissible nutrient load in these ecosystems. Considering ecological criteria alone (conditions A to D in Table 5, without taking into account clusters 1 to 6) reveals only contrasting situations in which low exogenous flows are associated with sediment stock in good condition (condition A) or in poor condition (condition B) or, conversely, high exogenous flows are associated with sediment stock in poor condition (conditions C and D). Yet transitional conditions in which trend reversals can occur – i.e. the reduction in exogenous flows necessary to initiate the restoration of the sediment compartment and thus reverse the ecological trajectory of the lagoon – is key information for environmental managers. This information can confirm the relevance of measures to reduce exogenous inflows even before WFD indicators highlight their positive impact (and consequently the investment they require).

4.2. Key compartments

The model provides access to descriptors that may or may not be observable in situ and that allow a detailed description of the simulated functioning of the system. Similarly, by allowing processes to be decoupled, the model makes it possible to quantify the contribution of each process in the overall functioning of the system. This revealed the key role played by macroalgae and the sediment compartment in the functioning of the Or Lagoon.

Macroalgae

The succession of macroalgal and phytoplankton blooms is clearly shown in the model with the assimilation of inorganic forms of nitrogen and phosphorus predominantly by macroalgae in June and then by phytoplankton in July. This phytoplankton–macroalgal competition in June could explain the late start of the summer phytoplankton blooms. Furthermore, the degradation of opportunistic algae between April–May and July is the main source of DIP and could be the cause of the excess phosphate in the water column simulated in the summer period. These changes in the development of macroalgae thus appear to control both the start of the summer plankton bloom and the phosphate concentration in the water column at that time.

In the absence of available data on the biomass of opportunistic algae present in the lagoon, few parameters relevant to the conceptualisation of this compartment were included in the estimation of the biogeochemical parameters of the model. New descriptors for this compartment that link the biomass of opportunistic algae to the eutrophication status of a lagoon (Fiandrino et al., 2022b) will now allow these to be used in global sensitivity analyses to improve the calibration of parameters for this compartment.

A further limitation of the model is that it does not allow the estimation of the WFD 'Macrophyte' indicator based on the recovery rates of reference species. The current conceptualisation of eelgrass beds in the GAMELag model does not include the assimilation of nutrients by the root system, which may account for 50% of nitrogen assimilation (Hemminga et al., 1991; Pedersen and Borum, 1992). Thus, in environmental conditions favourable to its development, the growth of eelgrass would be strongly underestimated by the model. We believe a new descriptor for the 'Macrophyte' compartment based solely on the biomass of opportunistic algae is relevant on the assumption that a detailed understanding of changes in seagrass is not necessary to determine admissible load. We consider that it is sufficient for the model to be able to establish the links between the anthropic pressures exerted on the ecosystem and the environmental conditions favourable to the development of eelgrass. The analysis of simulated scenarios carried out in this study confirms this hypothesis.

The exogenous inputs of nitrogen and phosphorus that the Or Lagoon has received over several decades have degraded this ecosystem, and the management measures put in place since the beginning of the 2000s to reduce these inputs have not yet initiated a restoration dynamic. A further reduction in inputs would have the direct consequence of limiting the production of living matter in the water column (currently, mainly phytoplankton). Lastly, in conditions of reduced phytoplankton production and therefore better light penetration in the water column, nutrients from benthic flux could drive the production of opportunistic algae near the benthic interface to the detriment of phytoplankton production. Such a shift from an ecosystem dominated by phytoplankton to one dominated by opportunistic macroalgae has been described in a lagoon close to the Or (the Méjean Lagoon) following measures aimed at reducing nutrient inputs (Le Fur et al., 2019). This appears to be a first key step in the restoration of eutrophicated lagoon environments. Then, in conditions in which the biomass of opportunistic macroalgae and phytoplankton is compatible with 'good' ecological status, the restoration of the ecosystem could continue with the natural recolonisation of the environment by perennial macrophytes (Le Fur et al., 2019; De Wit et al., 2017).

Sediment

At present, the model cannot reproduce the change in sediment nitrogen stock over several years. Variation in this stock results from the net balance between the sedimentation of degraded organic matter and the release of ammonium resulting from the remineralisation of this matter. Observations made in different Mediterranean lagoons (Ouisse et al., 2013; 2014) show that the flux intensity of dissolved inorganic forms measured at the interface between the benthic compartment and the water column varies primarily according to the season and the quantity of nitrogen and phosphorus in the sediment (diffusive nutrient fluxes). These results are consistent with data acquired in other Mediterranean lagoons (Chapelle et al., 1994; Le Fur, 2018; Zaaboub et al., 2014) and Australian lagoons (Eyre and Ferguson, 2002), and the order of magnitude of DIN flux measured in lagoons with poor eutrophication status is in the order of 5 – 8 mmol $N.m^{-2}.d^{-1}$. These values are higher than the simulated remineralisation rates in the Or Lagoon, which vary between 0.4 (in winter) and 0.8 mmol $N.m^{-2}.d^{-1}$ (in summer). This underestimation of the remineralisation of organic matter in sediment probably explains the overestimation of nitrogen storage in the sediment.

The inability of the tool to carry out simulations over the medium to long term does not, however, call into question its use in determining admissible load. The scenario analysis is carried out on an annual scale (one element = one year) and is based on a complete set of descriptors and the use of eight different parameterisations that allow changes in the compartments from the 'current' situation to be correctly represented (with the exception of the nitrogen stock in the sediment). Each parameterisation reflects specific simplifying assumptions made during the conceptualisation stage and therefore has specific repercussions on the simulation of ecosystem functioning. Taking these eight parameterisations into account leads to eight possible simulations of ecosystem functioning that are compatible, in part, with the observed reality.

Nonetheless, in order to allow simulations to be carried out over the medium to long term, certain simplifying assumptions should be reassessed. At present, the sediment layer is assumed to be oxic, but this assumption has not been verified, particularly during the summer period when the thickness of the oxic sediment layer is very low (a few millimetres). Different models of the nitrogen and phosphorus cycle in sediment take into account the oxygenation conditions in a more or less realistic way (Chapelle, 1995; Plus et al., 2021). An early diagenesis module that takes into account the oxygenation state of the sediment and the water column is currently being developed in the GAMELag tool to account for anoxia phenomena in these coastal lagoons used for shellfish farming (Le Ray et al., 2023).

4.3. Collaboration between science and management

Due to the limitations inherent in management tools discussed above, it is essential that their development and deployment in given ecosystems be carried out within the framework of projects that have been co-constructed, from their inception, by scientists and environmental managers with shared objectives and interests. The application of the GAMELag model to the Or Lagoon to address the problem of restoring this hypereutrophic environment has benefited from such collaboration between scientists and managers, with substantial technical and financial efforts made to acquire specific data and deploy adapted simulation tools.

This first experience using the GAMELag tool in operational conditions allowed us to review the right level of balance between the scientific requirements linked to model development and the operational expectations motivating this model. Given the constraints of developing a 'usable' tool within an acceptable timeframe so that it can be 'used', choices were jointly made and accepted by scientists and environmental managers, in particular by taking into account the limitations of the tool by providing the uncertainties associated with the various descriptors in the pressure–state chart. Its use has allowed recommendations to be made for supplementary monitoring that could be carried out. In parallel with the measures planned in coming years to reduce exogenous inputs, it will be important to monitor changes in sediment stocks of nutrients. In addition to WFD monitoring, this data on sediment stocks would enable the lagoon to be better positioned in the pressure–state chart in terms of internal pressures.

5. Conclusion

The current version of the GAMELag tool is the result of a long period of close collaboration between lagoon managers, technical experts and scientists. Its application to various Mediterranean lagoons, in particular the Or Lagoon, has confirmed its adaptability to sites with complex functioning, and it is now available as a reference tool to assist managers of French Mediterranean lagoons who want to adopt an admissible load approach.

With this approach, the GAMELag model is one key component in a global mission carried out by lagoon managers with the support of scientific and technical experts. The improvements currently being made to the tool should help make it possible to understand the time required to restore eutrophicated lagoon ecosystems and to respond to issues involved in managing environments and their uses (for example, shellfish farming) in a context of climate change.

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