Variability of nutrient and particulate matter fluxes between the sea and a polder after partial tidal restoration, Northwestern France

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Abstract

This paper aims to investigate the patterns of exchanges of nutrients and suspended sediments between the sea and a polder, after partial tidal restoration, and to assess if these are comparable to those observed in natural salt marshes. The study site, situated in the Bay of Veys, in Northwestern France, was embanked in the 1870s and accidentally reconnected to the sea in 1990. Water now flows in and out of the polder by a single communication point with the sea, which facilitated water sampling and flux calculation for dissolved and particulate elements.

The study was carried out for two years, from May 2002 to April 2004. Results showed that for all the months studied the water flowing out of the polder had lower concentrations of nitrates and suspended sediments, which lead to a retention of these elements throughout the year. Nitrates uptakes in the polder were much higher in winter (up to 473.9 g N ha⁻¹ tide⁻¹) than in summer where they were close to zero. The retention of suspended sediment could be over 80% of the import and was mainly composed of organic matter. Finally, the concentrations of dissolved organic carbon were higher in outflow than inflow water, but due to unbalanced water budgets this lead to low quantities imported in summer and higher amounts exported for all other seasons. No interpretable pattern was observed for ammonium.

The nature of these fluxes, according to literature, is close to those observed in immature salt marshes, so as far as restoration is concerned, it has been shown that partial tidal restoration can allow the restitution of the salt marsh exchange functions that were studied.

Keywords: tidal restoration; inter-system exchanges; nitrogen; organic carbon; suspended sediments; France

1. Introduction

One of the most common causes of salt marsh destruction worldwide has been embankment, which has lead to vegetated areas being withheld from the influence of the sea by the construction of dikes. The restoration or the creation of salt marshes is increasingly recommended as a tool for mitigation projects or for reintegrating the valuable ecological functions linked to the original system (Bakker et al., 1997, 2002; Baron-Yelles and Goeldner-Gianella, 2001; Warren et al., 2002). The success of these restoration projects is usually evaluated by their capacity to reestablish a salt marsh that would provide key ecosystem services. Depending on the goal, different criteria are used to assess its fulfillment, such as the appearance of a target vegetation (Boumans et al., 2002; Thom et al., 2002), its use by

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waterfowl (Atkinson et al., 2001) or by fish (Minello and Webb, 1997; Raposa, 2002) for resting or foraging or the recolonization of the sediment by benthic fauna (Craft, 2000). Most studies seem to be based on two or more of these indicators (Havens et al., 1995; Craft et al., 1999), while Kentula (2000) and Neckles et al. (2002) recommend the use of the largest possible array of indicators and insist on the comparability of different studies.

Exchange functions in restoration sites and in particular those dealing with fluxes of matter and nutrient seem, however, rarely to have been monitored (Craft et al., 1988). This contrasts with the number of studies in recent decades dealing with the exchanges of particulate and dissolved elements between natural salt marshes and the sea (Nixon, 1980; Lefeuvre and Dame, 1994; Childers et al., 2000). These studies have revealed the importance of salt marshes in nutrient cycling and organic matter processing, as well as their value for water quality and estuarine food webs. Therefore, it seems essential to study marsh/bay exchange functions as criteria for evaluating restoration projects. The aim is to make sure that restoration leads to the re-establishment of fluxes similar to those observed between natural salt marshes and the sea. This aspect of the restoration is particularly important in areas where water quality has been considerably altered due to intensive farming and former coastal management. This is notably the case along the coastline of the Bay of Veys, in Northwestern France, which had been heavily embanked up to the beginning of the 1970s and is surrounded by agricultural land. In recent time, ecological problems have occurred, such as eutrophic episodes and the disturbance of the sedimentation pattern, which have lead to high shellfish mortality (Larsonneur, pers. comm.). Improving the water quality is thus a great concern in the area, and one solution considered consists in opening polders to the sea for salt marsh restoration. The Carmel polder, in the Bay of Veys, which was accidentally connected to the sea in 1990, was used as an experimental site for testing the value of such a project.

This paper investigates the fluxes of nitrates, ammonium, dissolved organic carbon and suspended solids (mineral and organic) between the sea and the Carmel polder after partial tidal restoration. The fluctuations in these exchanges were investigated throughout the year over a 24-month period and could then be compared to available published data on salt marshes.

This study thus aims to estimate if partial tidal restoration in a polder allows the restoration of exchanges of the same nature as those described for the natural salt marshes to be restored.

2. Materials and methods

2.1. Site description

The study site, the Carmel polder, is located in the Bay of Veys, in Northwestern France (49°21’N; 1°10’W) (Fig. 1), which is a macro-tidal bay with a tidal amplitude...
averaging 7 m. The polder is part of a large embanked area of the Point of Brévands. These polders were built by the construction of dikes to prevent the sea flooding salt marsh areas and were then used as agricultural land. The Point of Brévands lies between two canalarized rivers, the Taute and the Vire, which drain a large watershed which includes large areas of inland freshwater marshes as well as agricultural lands. The Taute runs through the canal of Carentan on the West and the Vire runs through the canal of Isigny on the East.

The Carmel polder was built in 1871 and was mainly used as grazing land for cattle and horses. It was accidentally connected to the sea in 1990 after a storm broke the tidal gate on a water evacuation pipe passing through the dike. It has been managed as waterfowl habitat since then. Its 30-ha surface is divided into two: one half grazed by cows and one half mown to keep a low vegetation cover.

On the sea side of the dikes, a new salt marsh has developed, whose vegetation is dominated by Spartina anglica, Puccinellia maritima and Atriplex portulacoides. The main creek of this salt marsh is linked to the river bed of the Isigny canal, once it has entered the bay. The canal water is flushed back upstream during flood tide, creating a stratification of salt and freshwater that floods the salt marsh and enters the polder. This phenomenon depends on the strength of the flow in the river, which is seasonal and usually higher in winter.

The seawater flows in and out of the polder through a 1-m diameter pipe which runs through the dikes into the main creek of the adjacent salt marsh and is the only connection to the sea. The broken tidal gate is located on the outside of the dike, and is maintained permanently halfway open. On the inside of the polder is a sluice which retains the impoundment water at a minimum level inside the polder. The seawater flows in and out over this sluice for almost every tide, except during the lowest neap tides.

The water level in the polder varies daily as the seawater flows in and out with the tides, and semi-monthly according to the neap/spring tidal cycle. During a month, the water level is the lowest after neap tides and highest after spring tides. Additionally, rainfall also increases the polder’s water level and decreases its salinity. Rainfall is highest in winter, resulting in higher water levels, but also occurs in summer, balancing out some of the evapotranspiration that tends to lower the water level. The variations of the polder’s water level shows a daily maximum amplitude of 20 cm and a monthly variation of 60 cm at the most.

A shallow impoundment with no rooted vegetation takes up more or less 4.1 ha, depending on the season, and 1.7 ha are colonized by temporarily flooded halophytic vegetation. In these areas the dominant species are Salicornia europaea, Spergularia marina and Puccinellia maritima. Intermediate areas, under the impact of salt water seepage but no, or very rare, immersion, are mainly occupied by Glaux maritima, Juncus gerardi, Agrostis stolonfera and Parapholis strigosa. The upper parts are still vegetated by glycophytes dominated by Pulicaria dysenterica, Juncus inflexus and Festuca arundinacea. Phragmites australis is also spreading in most areas occupied by glycophytes (unpublished data). The impoundments are largely colonized by algae, mostly Ulva lactuca, a cover which is especially high in spring and summer. The first observations showed that fish juveniles and waterfowl use the lower parts of the polder for feeding (unpublished data) indicating that some ecological functions have, at least partly, been restored.

2.2. Water sampling

The tides studied were chosen according to their tidal magnitudes of 6 m above Lowest Astronomical Tide, which were the most frequent tides to occur amongst the higher tidal magnitudes in 2002. It was assumed that these tides would have a major influence on the net exchanges, as the water repeatedly flooded large surfaces of the polder, including the halophytic vegetation, and therefore led to favorable conditions for water/vegetation and water/sediment interactions. The water sampling took place once a month, over two years on these chosen tides to facilitate comparability. In addition, intra-monthly variability was studied by sampling three similar tides in February 2003.

Samples were collected from the water flowing in and out of the polder through the pipe in the dike. The sampling was conducted throughout one semi-diurnal tidal cycle, during the day time, every month between May 2002 and April 2004. A 1-l sample was collected every hour for 12 h in polypropylene flasks. An average of 5 h of inflow and 7 h of outflow took place, so five samples were collected during the inflow and seven during the outflow. Samples were stored in a cool box and then refrigerated at 4 °C until analyzed the next morning.

2.3. Water analysis

Total suspended sediment (TSS) concentrations were measured by filtering a known volume of water samples on pre-ashed and pre-weighed GF/C 47-mm Whatman filters. The filters were dried for 2 h at 105 °C and weighed for TSS content. Mineral suspended sediment (MSS) was determined by ashing these filters at 450 °C for 4 h. Organic suspended solids (OSS) were calculated as the difference in weight between TSS and MSS.

NO$_3$ + NO$_2$ was analyzed using a Jascow analytic chain, which contains a cadmium reducing column. As nitrite concentrations were mostly under detectable levels, NO$_2$ was not distinguished from NO$_3$. NH$_4^+$
was dosed using Koroleff's method as described in Aminot and Chaussepied (1983). Dissolved organic carbon (DOC) concentrations were calculated using a Shimadzu Total Organic Carbon Analyzer (TOC-5000). The data for the first three months were not reliable because of calibration problems with the TOC analyzer, so they were not included in the data analysis.

The salinity was calculated by converting conductivities measured with a WTW LF 318 field probe from Bioblock Sciences. Water salinity was used as an indicator of seawater mixing with freshwater from the Isigny canal in inflow water, or of dilution by rainfall inside the polder, when it was measured in outflow water.

Continuous water fluxes in and out of the polder were measured as a function of velocity and water level using an ISCO 2150 Area Velocity Flow Sensor. A mean water flux was then calculated for every quarter hour during inflow and outflow.

Mass flux for every 15-min interval was calculated by multiplying each 1/4 hourly water flux by the concentration of the different components analyzed in the water sample taken during the corresponding hour. The net fluxes of each component were calculated by subtracting mass flux for outflow water from mass flux for inflow water. As a consequence, exports are expressed by a negative sign whereas imports are positive. The net fluxes were then divided by the flooded surface of the polder to obtain a flux per hectare and per tide. As the exact flooded surface was not known, the minimal and maximal flooded surfaces were used to calculate an interval of values per hectare for the fluxes, centered on the flux obtained for the mean flooded surface. In summer, fluxes should approach the higher values of this interval, as the flooded surface was minimum, and in winter fluxes would be nearer the lower values. Thus, for the fluxes calculated for the three tides of February 2003, only the maximum flooded surface was used.

2.4. Statistical methods

As the distribution in our data did not show normality, non-parametrical tests were used. Concentrations of elements in inflow and outflow water were compared using a Kruskal–Wallis non-parametrical ANOVA. The same test was applied to months plotted into seasons to test the influence of seasonality on net budgets. A Spearman test was used to find correlations between meteorological parameters (wind intensity, temperature, rainfall) and the concentrations, the inflows, the outflows and the net budgets of nutrients, suspended sediments and water.

3. Results

3.1. Water budget and salinities

The water budget between the coastal area and the polder was mainly negative in autumn, winter and spring and positive in summer. The effects of the season and the moment in the semi-lunar cycle were significant with a \( p \) value of 0.08. The salinities measured in the outflow water, which approximately reflected the salinity of the water inside the polder, was correlated negatively to water outflows (\( r^2 = 0.49; p < 0.001 \) (Fig. 4a).

During one tide, the salinities could be much lower during the first hours of the inflow and then increase up to the last inflow water salinity measurement (Fig. 5). This is due to the freshwater and seawater stratification phenomena linked to the Isigny canal and explains the large error bars in mean inflow salinities (Fig. 3). The most extreme example was in February 2003, where the salinity of the first inflow sample was 4.4 whereas the last was 28.8. During the outflow, the salinities stayed relatively constant and were often lower than those of the last inflow water samples, especially in winter when water inside the polder was diluted by rainfall.
Mean salinities in inflow as well as outflow water (Fig. 3) were lower from late autumn to early spring. Inflow salinities were lowered by higher freshwater inputs during the winter months, due to higher levels of water discharged from the canal.

3.2. Nitrogen

Nitrate concentrations were, all year round, higher in inflow than in outflow water (Fig. 4). Inflow nitrate concentrations were highly and negatively correlated to inflow water salinity \( (r^2 = 0.48; p < 0.0001) \), and mean daily temperatures \( (r^2 = 0.74; p < 0.001) \). A net seasonality was observed for inflow concentrations \( (p < 0.05 \text{ for ANOVA}) \). The outfluxes of nitrates were inferior to the influxes for every tide, resulting in net imports to the polder, except for September 2003, where a small export was observed (Fig. 6). The imports were the highest \( (p < 0.05 \text{ for ANOVA}) \) in winter and beginning of spring due to the higher concentrations of nitrates in inflowing water. The quantities of nitrates retained in the polder increased from October to March, reaching a maximum of 473.97 g N ha\(^{-1}\) tide\(^{-1}\) and then dropped in April. In summer, inflow and outflow water contained very low concentrations of nitrates and resulting fluxes were close to zero.

The ammonium concentrations observed in the water flowing in and out of the polder were up to 10 times lower than those of nitrates (Fig. 5). These concentrations were highest in 2003, from January to March and from June to August. No net budget pattern was shown throughout the year for ammonium (Fig. 6), which was either imported or exported out of the polder. All net fluxes were very low compared to the amount of nitrogen transported as nitrates. Peaks of export were observed in January (137.19 g N ha\(^{-1}\) tide\(^{-1}\)) and March (33.14 g N ha\(^{-1}\) tide\(^{-1}\)) as well as an import peak in July (53.49 g N ha\(^{-1}\) tide\(^{-1}\)). No correlation was observed with meteorological factors except between net ammonium flux and wind intensity \( (r^2 = 0.21; p < 0.05) \).

3.3. Suspended sediments

Total suspended sediment (TSS) concentrations were generally higher in inflow than in outflow water (Fig. 5),
except in May 2003. The outflow concentrations showed little variation over the months compared to those in the inflow water. The inflow concentrations of TSS were negatively correlated to inflow water salinity ($r^2 = 0.31; p < 0.0001$, Fig. 4c) and the outflow concentrations to mean daily temperatures ($r^2 = 0.49; p < 0.001$).

Higher influxes of TSS than outfluxes resulted in a net retention of TSS all year round in the polder (Fig. 6), with the exception of May in both years when the budgets were close to zero. The retention of TSS showed that variations according to the seasons also were not significant, with the highest values being during the winter months.

TSS was mainly composed of OSS: from 64% to 90% in inflowing water, and from 49% to 85% in outflows. OSS and MSS fluxes followed approximately the same pattern: high influxes and lower outfluxes in autumn, winter, and beginning of spring and altogether low exchanges in summer. The increase of OSS influx was much higher in winter than that of MSS and accounts for the peaks of TSS that are observed. OSS fluxes present a significant seasonal variation (ANOVA: $p < 0.05$), but not MSS fluxes. However, a seasonal pattern was observed for MSS inflow concentrations with significantly lower values in summer.

3.4. Dissolved organic carbon

DOC, contrary to dissolved mineral nitrogen and suspended sediments, was more highly concentrated in inflow than in outflow water (Fig. 4). Concentrations were higher in winter for both inflow and outflow. DOC outflow concentrations were highly correlated to OSS inflow concentrations ($r^2 = 0.62; p < 0.001$). The net fluxes were strongly correlated to the water budget ($r^2 = 0.60; p < 0.001$) resulting in analogous patterns showing negative DOC budgets in autumn and winter and positive budgets in summer (Fig. 6).

3.5. Intra-monthly comparison

The three tides of similar magnitude sampled in February 2003 (Fig. 7) were used to estimate intra-monthly differences, while seasonal effects were excluded. Nitrate concentrations were lower in outflow than in inflow water, as was observed for the tides all year round. The concentrations decreased in the inflow water from the first to the third tide together with increasing mean inflow salinities, which suggests an increase in the proportion of seawater. The correlation between nitrate inflow concentrations and inflow salinities was stronger for these three tides ($r^2 = 0.88; p < 0.0001$) when isolated from the rest of the two-year samples ($r^2 = 0.48; p < 0.0001$). All three net budgets were positive and, even though the inflow concentration differed highly, the retentions of nitrates were quite similar, ranging from 186.4 to 242.9 g N ha$^{-1}$ tide$^{-1}$. Ammonium concentrations differed in inflow and in outflow water for the three tides sampled in February, with no explainable pattern. This resulted in budgets of different nature: two tides exported ammonium while the other showed an import.

TSS inflow concentrations (Fig. 7) increased from the first to the last tide, and were highly correlated to inflow salinities ($r^2 = 0.51; p = 0.0025$). As observed for nitrates, this correlation was stronger when the three tides from February were isolated from the samples of all the other months (where $r^2 = 0.31$ and $p < 0.0001$).
Despite different TSS inflow concentrations for the three tides, outflow concentrations were similar and significantly lower, thus resulting in TSS retention inside the polder for the three tides.

For DOC, results were only available for two tides out of the three sampled in February (Fig. 7). These show different inflow and outflow concentrations, one having higher inflow concentrations and the other higher outflow concentrations. Both, however, resulted in an export of DOC to the sea, due to the differences in the water budgets.

4. Discussion

4.1. Water budget and salinity

Water budgets varied greatly between sampling campaigns (Fig. 2), even though the tides which were sampled had the same tidal magnitude. They should therefore have had approximately the same water level at high tide, even though it can sometimes be lowered or increased by strong wind. They were therefore expected to have similar water budgets. It appeared, however,
that the moment in a lunar tidal cycle when the sampling was undertaken had an impact on the observed water budget. For example, following a spring tide, the water level was high in the polder, favoring higher outflows, whereas following a neap tide, the water level in the polder was lower, leading to inferior outflow velocities. This partly explains why the water budgets were globally positive when sampled before a spring tide and negative when sampled after. Independently from the tidal cycle, the water budgets were mostly negative in winter and positive or negative but low in summer. Outflows were shown to be negatively correlated to the salinity of the water inside the polder and were lowest in winter, when rainfall is higher. The rainfall increased the water level inside the polder and thus increased the outflows, leading to negative water budgets. The variation in water budgets could have a significant effect on some exchanges such as those of dissolved organic carbon.

The inflow water usually had a lower salinity during the first 2 h of flood tide than during the next hours (Fig. 4) showing that freshwater, coming from the Isigny canal, was entering the polder, as a result of river water being flushed upstream by the sea into the salt marsh main creek which is connected with the polder. This explained the high variation of inflow nitrate (up to 81% variation) and of total suspended sediments concentrations (up to 88% variation), as river water is usually much richer in these elements than seawater. This was verified by the significant negative correlations between salinity and nitrate and between salinity and TSS.

The results show that there is more freshwater flowing into the polder in winter, probably due to higher levels of river water. This leads to lower levels of water salinity inside the polder. Rainfall also dilutes the salinity. Both these factors explain the lower outflow concentrations in winter. In summer rainfall is lower than in winter, but it can balance out evaporation induced by higher temperatures, and could explain that the salinities remained lower in the polder than in inflowing seawater.

4.2. Nitrogen exchanges

A net seasonality was observed in the nitrate concentrations of water flowing into the polder, as it was for salinities, which suggests that the seasonal inputs of freshwater from the Isigny canal is highly concentrated in nitrates. High seasonal fluctuation of nitrate inputs into bays via river water have been reported in many papers (Koch et al., 1992; Page et al., 1995; Sutula et al., 2003) and have been shown to affect salinity of the water flooding salt marshes and to alter the nature of salt marsh–bay exchanges. River nitrate concentrations in the Isigny canal were highest in winter (DIREN data, pers. comm.), resulting in high inflow concentrations of nitrates into the polder. Inflow concentrations were very low in summer, with values close to zero, probably due to lower river inputs coupled with high estuarine biological activity.

During ebb tide, a decrease of nitrate concentrations was observed in the polder, resulting in decreasing outflow concentrations. The resulting retention of nitrates was positively correlated to the quantity (mass flow) of nitrate into the polder. This is consistent with other studies which showed that nitrate uptake in salt marshes and estuarine sediment was dependent on the
nitrate concentration in flooding water (Wolaver et al., 1983; Whiting et al., 1989). In our study site, this resulted in a net retention ranging from 0.35 g N ha\(^{-1}\) tide\(^{-1}\) in summer to 473.97 g N ha\(^{-1}\) tide\(^{-1}\) in winter. Wolaver et al. (1983) and Whiting et al. (1989) studied monthly exchanges of nitrates between two salt marshes and the adjacent bay and both showed imports of nitrates throughout the year. The first showed peaks of nitrate imports at three different times of year, ranging up to around 75 g N ha\(^{-1}\) tide\(^{-1}\), most of the other months being under 25 g N ha\(^{-1}\) tide\(^{-1}\). The second showed peak import of nitrates in summer (near to 15 g/ha/h) and low imports (lower than 5 g/ha/h) for the other seasons. These results are in the same range as those of this study even though the maximum uptake is higher in the Carmel polder, probably due to the impoundment which allows longer exchanges between water and sediment.

Amongst microbial processes using nitrates, denitrification is a form of respiration, used by anaerobic bacteria, where nitrates play the role of the electron acceptor. The result of this process is the transformation of NO\(_3^-\) into N\(_2\) and N\(_2O\). If nitrate concentrations are fairly constant throughout the year, the activity of denitrifying bacteria is highly dependent on environmental variables such as temperature (Herbert, 1999). However, when nitrate concentrations vary in the overlying water, denitrification activity becomes reactive to this fluctuation (Nowicki, 1994; Cornwell et al., 1999). Denitrification will increase with rising nitrate concentration even with low temperatures, usually considered as limiting (Koch et al., 1992; Eriksson et al., 2003). Therefore, this process could be the main factor explaining the pattern of nitrate uptakes observed throughout the year in the polder.

Uptake of NO\(_3^-\) by halophytic vegetation and algae could also explain the retention of nitrates in the polder. Large strands of Ulva lactuca grow in the impoundment and could take up large amounts of nitrogen as NH\(_4^+\) and NO\(_3^-\) (Naldi and Viaroli, 2002; Runcie et al., 2003). This uptake was shown to depend on the development cycle of the algae (Bergamasco and Zago, 1999; Tyler et al., 2001). It should be maximum in spring and beginning of summer, during the growing period and then decrease and stop as the thalli start their senescence. Halophytic vegetation has the same growth pattern and thus should take up the most nitrates at the same periods. This pattern does not fit the annual variation of nitrate uptake in the polder, so the denitrification hypothesis is privileged.

No annual export or import tendency was observed for ammonium exchanges and their nature seemed to be dependent on temporary local events (storms, strong winds) rather than on seasonal meteorological changes. Wind, for instance, can contribute to the re-suspension of ammonium accumulated in the sediment by creating turbulences in the water column. A positive correlation between ammonium fluxes and wind intensity seems to corroborate this hypothesis. The export peak in January could otherwise be explained by anoxic conditions due to vegetation decomposition (including large amounts of Ulva sp.) leading to the depletion of oxygen by the bacterial activity (Flindt et al., 1999) which temporarily blocks the nitrification process of ammonium. The import peak in July could be explained by high phytoplankton and Ulva sp. uptake.

The nitrogen budget due to NH\(_4^+\) in the studied polder, seems negligible compared to NO\(_3^-\) in relation to N cycling functions of the polder, except for a few peaks. This is generally not the case in natural salt marshes, where NH\(_4^+\) can present exchanges of the same range or higher than those of NO\(_3^-\) (Davis et al., 2001; Eriksson et al., 2003; Sutula et al., 2003).

In some salt marshes, nitrogen was processed (Boorman et al., 1994) and exported as dissolved nutrients, which was not the case in this polder study, where an import of NO\(_3^-\) was observed. Other studies of salt marshes (Childers, 1994; Childers et al., 2000), however, showed that nitrate and nitrite (NN) exchanges depended on the tidal range, NN being exported for large tidal ranges whereas these elements were imported for small ones. In the Carmel polder, fluctuation of water level does not exceed 0.6 m on a monthly basis which leads to expecting an import of NN, which was the case. These results are also consistent with a review by Valiela et al. (2000), who concluded that all “young” salt marshes either imported or presented no net flux of NO\(_3^-\). This could be expected in this study site as the flooded vegetation of the Carmel polder mainly consists of pioneer salt marsh vegetation.

### 4.3. Organic matter

The study of organic matter focused on organic suspended solids (OSS) (included in the suspended material) and dissolved organic carbon (DOC) forms of organic carbon which can be directly used by the first heterotrophic organisms in the food web and thus could be important in contributing to the functioning of the polder as a source of food for the estuary.

Concentrations of DOC generally increased during ebb tides in outflow water, probably the result of its production within the polder. Thus, exports of DOC should be expected for all studied tides. Dominant imports of DOC were, however, observed in summer, when water budgets were negative, showing a dominant inflow. As DOC and water budgets were correlated, when inflows were dominant, the DOC produced inside the polder was not totally exported but some was retained inside the polder. In autumn and winter, larger surfaces of the polder were flooded leading to more extensive flooding of senescent halophytic vegetation. The decomposition of this vegetation in addition to the
decomposing algae can explain the higher outflow concentrations of DOC leading to higher exports in autumn and winter, which were enhanced by higher water outflows.

The exchanges for the Carmel polder amounted to an average import of 126 ± 121 g C ha⁻¹ tide⁻¹ in summer and maximal export of 1991 ± 1530 g C ha⁻¹ tide⁻¹ average in autumn. These results are coherent with those observed by Taylor and Allanson (1995) and Roman and Daiber (1989), where the studied marsh exported DOC all year round but with very low exports in summer (respectively, an average of 80 ± 30 g C ha⁻¹ tide⁻¹ and between 22 and 67 g C ha⁻¹ tide⁻¹) and highest exports in autumn or winter (a mean of 1170 ± 470 g N ha⁻¹ tide⁻¹ in autumn for the first study and 3100 g C ha⁻¹ tide⁻¹ in January for the second). In these two studies, even though the exchanges in summer led to exports of DOC, these were very low compared to those observed for the other seasons. These results and those observed for the Carmel polder are in the same range despite differences in size and vegetation between the study sites.

4.4. Suspended sediments

TSS inflow concentrations tended to increase with high inputs from the Isigny canal in winter, while the lower inflow concentrations in the polder in the summer coincide with lower river flows and turbidity. The diminution in TSS concentrations in outflow compared to the inflow water is most likely due to an efficient and quick sedimentation of the particulate matter inside the polder, facilitated by the relative shelter given by the dikes and the stagnation of the inflow water in the polder before it flows out during ebb tide (Neubauer et al., 2002). As a consequence, the Carmel polder acted as a sink for a large proportion of the imported suspended sediment (TSS) (more than 80% for some tides). This is consistent with the results of Stumpf (1983) which showed that quick sedimentation took place when the flood water moved across a levee in a natural salt marsh which lead to an 80% drop in sediment concentrations. The lightest particles, nonetheless, stay suspended in the water and may be exported back to the bay in rather constant concentrations (Davidson-Arnott et al., 2002). Both organic and mineral suspended sediment followed this pattern in the studied site.

In the Carmel polder, TSS was mainly composed of organic matter, which contrasts with natural salt marshes, where mineral matter is usually dominant (Leonard et al., 1995; Day et al., 1999; Bel Hassen, 2001). The watershed origin of the TSS, which may include large quantities of organic matter coming from the drainage of inland marshes and/or manure spreading could contribute to this difference.

The positive OSS net fluxes showed a retention of OSS inside the polder which implies that most of the organic matter produced in and imported to the polder is decomposed in situ or is immobilized in the soil, either by sedimentation or by deposition of macrodetritus. Correlation between OSS inflow concentrations and DOC outflow concentrations tends to corroborate a high decomposition rate in the polder. The halophytic vegetation seems to decompose totally inside the polder as no litter deposits were observed, whereas a large amount of the senescent Ulva lactuca settled at the bottom of the impoundment and was covered by sediment before total decomposition. It therefore seems that both immobilization and decomposition take place in the polder.

4.5. Intra-monthly comparison

The three tides of the same tidal magnitude studied in February 2003 allowed an evaluation of the intra-monthly variations of the exchanges, while excluding seasonal variability. The net fluxes for all studied components followed the same trend than for the other months (i.e. the retention of nitrate and sediments in the polder, the export of dissolved organic carbon, and no clear trend for ammonium), even though the values could differ considerably between tides. Such differences could be related to the decreasing inputs of freshwater form Isigny canal from the 5th to the 22nd of February leading to decreasing inflow values for TSS and nitrates.

Nitrate inflow concentrations were highly variable between the three February tides, but the nitrate quantities retained in the polder were very close. This result contrasts with expectations. Indeed, denitrification, considered here as the main factor for nitrate uptake in the polder, was expected to positively respond to increasing input of nitrates. The results, obtained for a constant temperature range, thus suggest that beyond a certain threshold in nitrate concentrations denitrification activity attains a plateau. Similar ranges of nitrate retentions in other winter months support this idea. By contrast, the lower retention of nitrate recorded in December could be explained by the significantly lower concentration in the inflow water. Temperature could act as a limiting factor in the biological processes implied in denitrification and accordingly, an increase in temperatures could explain the peak of uptake observed in March. Uptake of nitrates by the algae that are starting their growing season could also significantly account for this increase of nitrate retention in March. Ammonium budgets were negligible during the three February tides. This balance between inputs and outputs suggests that the nitrogen cycling was efficient in the polder, releasing no ammonium into the water column.
During the three tides sampled in February, despite highly variable inflow concentrations of TSS, similar outflow concentrations were observed. Sedimentation thus lead to a retention of TSS in the polder which was proportional to the inflow concentrations.

Finally, these tides also confirmed the trends observed during the two years of the study, which was an export of dissolved organic carbon during the winter months. DOC exchanges over the different months was found, as mentioned earlier on, to be a function on water budgets. As such, an import of DOC was expected on the 16th while on 22nd February, an export was expected. Exports were, however, observed in both cases. There is thus no univocal rule relating DOC exchanges and the water budget.

The study of the three tides in February helped to corroborate the processes taking place inside the polder for nitrates and total suspended sediments, and the trends of exchanges for DOC. These results also showed the importance of multiplying the sampling before one can establish a quantitative annual budget, as budgets differ amongst tides of similar magnitudes on both a monthly basis and a yearly basis.

5. Conclusion

This study has demonstrated that the Carmel polder, after partial tidal restoration and the development of young salt marsh vegetation on part of its surface, acted as a sink for nitrates as well as for particulate matter (mineral and organic) and as a source of dissolved organic carbon. No net pattern was deduced for $\text{NH}_4^+$. This was observed for one particular tidal magnitude throughout the year and should be confirmed by further sampling on different tidal magnitudes during at least one lunar tidal cycle.

This study allowed little quantitative comparison with other exchange data, as its results cannot be extrapolated to annual budgets without further sampling. Another problem was the variability of units used to express exchanges, some of which could not easily be converted. The results of this study however allow a comparison with the trends of exchanges observed in natural salt marshes and demonstrate that the observed exchanges resemble those of immature salt marshes. As far as restoration is concerned, it has therefore been shown that partial tidal restoration can lead to the restitution of the salt marsh exchange functions which were studied.

In its current state of connection to the sea, the Carmel polder plays a role in reducing the quantity of suspended material and nitrates in the bay water as well as producing dissolved carbon available for the use by the first links of the food chain. It is clear, however, that considering the size of the actual opening, the exchanges between sea and polder are limited due to the small volumes of water involved compared to those observed in open natural salt marshes. On a larger scale, however, by opening other polders along the coast, such an experiment could be highly beneficial for the water quality of the bay.

However, the functional processes involved in these exchanges are not totally determined and will need further investigation. To this end, experiments are currently being undertaken to estimate the sediment’s denitrifying activity, as well as the respective uptake of nitrogen by halophytic vegetation and Ulva lactuca.

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