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Marie-George Tournoud, Sylvain Payraudeau, Flavie Cernesson, Christian Salles. Origins and quantification of nitrogen inputs into a coastal lagoon: Application to the Thau lagoon (France). *Ecological Modelling*, 2005, 193 (1-2), pp.19 - 33. 10.1016/j.ecolmodel.2005.07.038 . hal-01575634

HAL Id: hal-01575634

<https://hal.science/hal-01575634>

Submitted on 19 Nov 2019

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Origins and quantification of nitrogen inputs into a coastal lagoon: Application to the Thau lagoon (France)

Marie-George Tournoud^a, Sylvain Payraudeau^a,
Flavie Cernesson^b, Christian Salles^a

^a *HydroSciences Montpellier (HSM, JRU 5569 CNRS-IRD-Universités Montpellier 1 et 2),
Maison des Sciences de l'Eau, Université Montpellier 2, 34095 Montpellier cedex 5, France*

^b *Territoires, Environnement, Télédétection et Information Spatiale (JRU CEMAGREF-CIRAD-ENGREF),
Maison de la Télédétection, 34093 Montpellier cedex 5, France*

1. Introduction

Lagoon systems as interfaces between the continent and the sea are extremely vulnerable to the amount of pollutants they receive from various sources. In the case of nitrogen, important loads can lead to the progressive eutrophication of the lagoon (Kjerfve, 1994). The identification of the various sources of nitrogen and the evaluation of their respective contributions make it possible to define, on a hierarchical basis, which measure must be carried out for reducing the eutrophication phenomena (Ryding and Rast, 1992).

Various sources of nitrogen can be distinguished. First of all, the atmosphere, including dry and wet deposits, is a natural source of nitrogen for the lagoon. Even if it is not possible to act on this source, nitrogen loads brought by rainfall events must be evaluated, because it can account for a large fraction of total annual nitrogen contributions in natural areas (Bredemeier et al., 1998). Second, the sea, as it is connected to the lagoon, may be a source or a sink of nitrogen, depending on the level of the exchanges (Sfriso et al., 1994) that prove to be difficult to evaluate. Then urban stormwater drainage systems and sewage networks from cities or industries located along the lagoon shore constitute other sources of nitrogen for the lagoon. Nitrogen coming from these sources can have a strong impact on the lagoon because of the short distance between the source of pollution and the lagoon. The continental catchment area of the lagoon, via rivers or aquifers, constitutes the last, but prevalent, source of nitrogen for the lagoon (Rimmelin et al., 1998) and its contribution to the lagoon is not easy to estimate, because of its spatio-temporal variability and its hydrological complexity.

Each one of these sources has its own temporal variability. On one hand, sea-lagoon exchanges and direct discharges due to human activities have a strong hourly variability but their seasonal variability is, in general,

more limited. On the other hand, atmospheric and continental contributions are primarily event-based, especially in Mediterranean climatic context. The analysis of the various sources of pollution must thus be done at various time scales.

The analysis can be carried out on an annual scale. In LOICZ procedure (Talaue-McManus et al., 2003), mean annual water and mass budgets are calculated. These budgets are useful to weight the different com-

ponents of the system and the priority actions to engage for controlling the eutrophication or degradation of the lagoon (Capodaglio et al., 1995). It can also be done on a succession of years for connecting the impact of socio-economic changes on the catchment area with accumulations of nitrogen in the lagoon (La Jeunesse, 2001). The analysis at rainfall-event scale is essential for Mediterranean lagoons, since a significant part of the annual amounts of pollutants is exported by rivers during rainfall events (Meybeck et al., 1992) and because sudden nitrogen inputs can cause local but important eutrophication damages in lagoons (Souchu et al., 1998; Harzallah and Chapelle, 2002).

This paper reports on the methods for evaluating nitrogen loads for the main sources at various contexts time scales, and presents an application on the Thau lagoon (Etang de Thau, France). The accuracy attached to the methods is discussed and, when possible, compared in the application. In particular, for estimating the river loads, a conceptual mathematical model, called POL (Payraudeau et al., 2002) is used and compared to the available data. The application is conducted for estimating annual and event-based nitrogen loads. To conclude, the main sources of nitrogen are classified, on a daily basis, for the Thau lagoon.

2. Methodology review

Nitrogen loads for a given source can be estimated by different methods according to the availability of data, the time step of analysis (annual or event-based) and the expected level of accuracy. This review of existing methods does not pretend to be exhaustive but to illustrate the diversity of the methods and their operational requirements. A longer development is devoted to river load calculations, since rivers are, most of the time, the major term in nitrogen budget of a coastal lagoon.

2.1. Atmospheric contribution

Nitrogen loads brought by the atmosphere constitute a significant part of total nitrogen loads in coastal environments (Burian et al., 2001; Jassby et al., 1994). Rainwater contains nitrogen in various forms, even if the dissolved ones are predominant. Dry deposits of dust and particles can also be associated with nitrogen.

Total nitrogen concentrations in rainwater range between 0.5 and 2 mg N L⁻¹ (Tabatabai, 1983) and these concentrations are all the more important when the study area is located close to large cities or industrial sites (Loye-Pilot et al., 1990). Atmospheric nitrogen loads can be estimated through direct in situ monitoring, extrapolation methods or physically based models.

The monitoring of the study area must involve rainfall gauging and sampling. Rainwater must be collected and analysed for each rainfall event for determining the local dynamics of total nitrogen atmospheric (dry and wet) deposits (Gao, 2002). The analytical protocol depends on the forms of nitrogen that are determined (Cape and Leith, 2002; Cornell et al., 2003). Uncertainty associated to the estimates depends essentially on the representativeness of the sampling sites and on the collector efficiency.

When local concentration monitoring are not available, in situ measurements in similar climatic and industrial context can be used as a first estimate and combined to local rainfall height measurements. For example, Spanish (Avila and Roda, 2002) or Greek (Dikaiaikos et al., 1990) measurements are available and give a first evaluation of rainfall nitrogen contents around the Mediterranean Sea. These results compared well with those obtained in Corsica (France) by Loye-Pilot et al. (1990). But in every case, this extrapolation requires a great care to minimize the uncertainties.

The more sophisticated method would be to use a mathematical model. Models were developed by atmospheric physicists to simulate the spatial and temporal variability of the atmospheric deposits (Cocks et al., 1998; Burian et al., 2001; Alcamo et al., 2002). RAINS is an example (Barrett et al., 1995). These models need a lot of in situ measurement data to be calibrated. They are complex to use and nevertheless do not provide accurate estimates.

2.2. The sea-lagoon exchanges

Coastal lagoons are under marine influence. Water volumes exchanged between the lagoon and the sea are associated with dissolved and particulate elements. The impact in terms of nitrogen enrichment and impoverishment periods were shown in Mediterranean lagoons (Souchu et al., 1997). These phenomena depend both on the water volumes involved during the exchanges and on the concentrations of nitrogen in the two aquatic

systems. Even if many empirical equations were proposed to evaluate pollutant exchanges between coastal lagoons and the sea (Yanagi, 2000), nitrogen concentrations measurements are always required both in the sea and in the lagoon, with a sufficient accuracy in space and time. Exchanged volumes also need to be evaluated.

Sea-lagoon exchanges are controlled by the dynamics of water levels and by the geometry of the channel. The variations of sea levels are due to tide and wind effects; evaporation, catchment inflows and wind control water levels in the lagoon. When sea and lagoon water levels are monitored, hydraulic formulae can be applied to evaluate exchanged volumes, given the section of the canal and its roughness (Chow, 1959). Hydrodynamic modelling can also be helpful for this evaluation (Lazure, 1992; Smith, 2001; Umgiesser and Zampato, 2001); these models allow to use refined time steps and their accuracy is good, but they require a lot of data and a reliable calibration/validation process. A global approach, based on water and salinity budget at lagoon scale, such as proposed by LOICZ methodology (Charpy-Roubaud et al., 1990; Talaue-McManus et al., 2003), can also be used. Despite of its simplicity, this method might only be used for annual estimates, moreover, its accuracy depends on the uncertainties affecting the other terms of the water budget.

2.3. Domestic effluents

Effluents of domestic sewage treatment works contain high loads of nitrogen (Calhoun et al., 2003; Lenzi et al., 2003), so this anthropogenic source of nitrogen could be harmful for the lagoon.

There are few operational models to simulate nitrogen loads at the outlet of a sewage treatment work, even if attempts were done (Clifforde et al., 1999). So nitrogen loads are always evaluated using in situ observations or empirical formulae. When flow and concentration are measured at a good frequency, standardized methods are proposed to calculate nitrogen annual loads from a sewage treatment work (OSPAR, 2000). These methods produce weighted averages of instantaneous nitrogen loads according to the sampling frequency. The uncertainty on the annual loads is related to the quality of the data. When no data are available, the estimate can be done using empirical methods (Valiela et al., 2002; Scheren et al., 2004), e.g.

the product of the daily average nitrogen contribution per capita—that can be standardized according to the country (AIF, 1993)—by the theoretical yield of the sewage treatment work (Von Sperling and de Lemos Chernicharo, 2002). This estimate has a low accuracy but gives an order of magnitude for annual evaluation of nitrogen loads of a given sewage treatment work.

2.4. Urban stormwater drainage effluents

Runoff on urban impervious surfaces removes all the pollutants accumulated on these surfaces during the dry period. Collected by the stormwater drainage networks, these pollutants are directly flushed into the downstream aquatic systems. When the urban areas are located along the shore, most of the time the stormwater networks discharge directly into the lagoon.

Several modelling tools exist for the simulation of urban runoff during a rain event: SWMM (Metcalf et al., 1971), Hydroworks (Blanc et al., 1995), Canoe (INSA, SOGREAH, 1999). Water quality modules are associated to these models, which can even be coupled with models of atmospheric nitrogen deposits (Burian et al., 2001). Urban runoff models, even if they were developed for engineering purposes, require a lot of data (network geometry, topography, etc.). Moreover, concerning nitrogen loads, it was shown that the deviation between model results and in situ observations could be important (Brezonik and Stadelmann, 2002).

Many empirical formulae were set up, in various conditions. They link nitrogen yields to rainfall intensities and urban area characteristics: habitat density, street slopes, cleaning processes and types of impervious surfaces (e.g. Brezonik and Stadelmann, 2002; Bourrier, 1997). Even if the accuracy of these methods is not very high and difficult to evaluate when applied on ungauged urban areas, these formulae are often applied because of their easy-to-use.

2.5. Groundwaters

Nitrogen loads diffused by the aquifer into the lagoon, are due to the anthropogenic activities taking place on the continental basin: agriculture, urban area, domestic and industrial activities.

Groundwater monitoring consists in watertable measurements in piezometers, associated to water sampling and analysis. This monitoring is often done at regular time steps and allows the estimate of groundwater contamination level.

Nitrogen loads flowing through the aquifer can also be derived from these observed data, if the functioning of the aquifer is well known or with the help of a numerical model. But, the estimate of groundwater inputs to the lagoon (in term of flow, nitrogen . . .) requires also defining the connections between the two aquatic systems. Direct measurements are possible using tracer experiments or in the case of existing springs along the coastline (as in the case of the Thau lagoon), however, most of the time such data are not available.

So groundwater nitrogen contribution to lagoons is often the less accurate term in the water or nitrogen budgets of the lagoon.

2.6. Rivers

Rivers that inflow into the lagoon may represent a large part of nitrogen budgets of lagoons or coastal areas (Nedwell et al., 2002). It is easy to control and monitor flow and water quality of the rivers, but loads remain difficult to estimate.

2.6.1. Direct calculation

In fact, if water levels are often continuously recorded and then converted into flow using rating curves, most of the time concentrations are only determined for instantaneous water samples taken at regular time steps: daily, weekly, monthly, etc. Several methods are proposed (Walling and Webb, 1985) for estimating annual or monthly river loads. Interpolation methods put forward hypotheses on the evolution of concentrations between two observed values. Extrapolation methods set empirical flow versus concentration relationships using observed data. Webb et al. (1997) showed that, whatever the method, the accuracy of the result is highly related to the sampling frequency. Moreover, for small basins and in Mediterranean context where nitrogen loads are mainly brought by the flash floods (Meybeck et al., 1992) very short sampling intervals must be set to estimate the river loads during floods.

To overcome this problem, some authors tried to set up statistical relationships between measured loads and

other variables, such as basin properties (land use, area . . .) or rainfall characteristics (Muller-Wohlfeil et al., 2001). But, the statistical adjustment is poor and lead to bad estimates of flood loads in Mediterranean context, as shown by Tournoud et al. (2003).

2.6.2. Annual exportation models

Annual export model is another approach for estimating river loads. Global export coefficients from agricultural areas were established in the main objective of lake management (Vollenweider, 1968; Jorgensen, 1980; US-EPA, 1980; Rast and Lee, 1983; Benetton, 1984). This approach was enhanced by Johnes (1996) and Worrall and Burt (2001) by using variable export coefficients. Payraudeau et al. (2001) use constant export coefficients in a GIS structured model to be able to characterize the spatial evolution of the loads along the river course.

These empirical models can be useful for estimating nitrogen loads in ungauged basins, but they only give an annual estimate and do not take into account inter-annual variations in precipitation and runoff that are an important feature of the Mediterranean climate.

2.6.3. Water quality models

Water quality models are attractive tools for evaluating nitrogen river loads at various time scales. These models combine hydrological and chemical equations and address different chemical species, including all nitrogen species. Chemical elements are transferred to the river through the surface or sub-surface flow, which are evaluated by the hydrological model. Chemical processes occurring in the soil and along the water paths are simulated. Among the large panel of existing models, some of them are often quoted: ANSWERS (Beasley et al., 1980) or AGNPS (Young et al., 1986) models are limited to small agricultural basins (a few square kilometres). HSPF (Donigian, 1984) addresses more specifically for assessing the effects of land-use change or reservoir operations; SWAT (Arnold et al., 1994) or AVGWLF (Evans et al., 2002) are integrated in GIS tools and developed for water management purposes in large agricultural basins.

These models involve numerous parameters and require large dataset for accurate simulation. But, the accuracy of model results is also related to the adequacy between the hydrological model and the hydrological behaviour of the basin. So, since existing water quality

models were developed at field scale or for long-term simulation on a daily time step, they are not really adapted to Mediterranean catchments where floods are very fast and bring the main part of the annual river load.

2.6.4. POL model

POL model (Payraudeau et al., 2002) is an event-based conceptual model designed to simulate nitrogen loads. The model was developed following two rules: parsimony in the number of parameters and adequacy to the behaviour of intermittent rivers. The model generates catchment responses to rainfall events, in terms of total nitrogen (TN) loads. It is based on a semi-distributed spatial delineation: the catchment is divided into hydrological units: sub-catchments and river reaches.

Two processes are considered in the model: (i) the production of TN loads by sub-catchments during the rainfall event and (ii) the transport of these TN loads along river reaches. Two simplifying assumptions are made in representing the complex processes of nitrogen delivery to the catchment outlet: (i) the rainfall triggers the TN mobilisation on hillslopes; (ii) TN loads are conservative along the river reaches during the event. Nitrogen point sources (such as sewage treatment plants) are defined as direct inputs in the river.

Each sub-catchment (Fig. 1a) is represented by a simple linear reservoir. At the beginning of the rainfall event, the reservoir content is a proportion α of the initial nitrogen stock NBV on the whole catchment (α is the ratio of agricultural areas on the sub-catchment to the whole catchment). The lag-time of the production reservoir is assumed to be the same for all sub-catchments. It is related to the rainfall event, through a filter function, which depends on a coefficient F . Each river reach (Fig. 1b) is represented by a series of linear reservoirs. The number of reservoirs depends on the length of the reach. The lag-time T of the reservoirs is assumed to be the same for all reaches.

The model was run on a data set of 15 floods. The hydrological and water quality data were collected in three intermittent rivers in the South of France. An unbiased criterion was used to check the model for performance and quality. It compares observed and simulated load and event duration of each flood

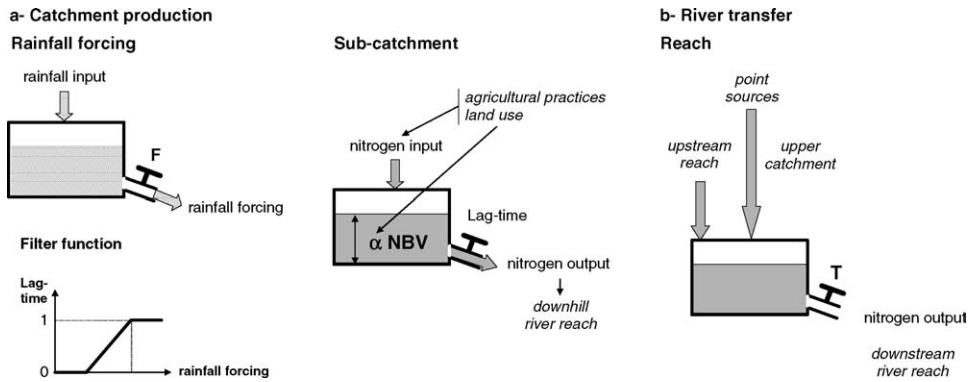


Fig. 1. POL model: (a) catchment production and (b) river transfer.

as following:

Criterion

$$= 1 - \frac{|\text{observed load} - \text{simulated load}|}{\text{observed load}} - \frac{|\text{observed duration} - \text{simulated duration}|}{\text{observed duration}}.$$

The calibration analysis showed that (i) the filter coefficient F can be set regardless of the catchment and the flood; (ii) the river lag-time T is statistically related to the duration of the rainfall event and the total rainfall amount in the 30 days before the event; (iii) the initial stock NBV can be related to crops and agricultural practices (Payraudeau, 2002). Assuming these pre-defined parameter values, the model was re-run on the 15 floods

for validation. The model results showed acceptable agreement with observed data (Table 1).

3. Application site and data

3.1. Thau lagoon

The Thau lagoon is located along the French Mediterranean coast (Fig. 2). It covers an area of 75 km² with an average depth of 4 m. The lagoon is separated from the sea by a sandy lido that links the city of Sète (40,200 inhabitants) to Marseillan beach (3000 inhabitants in the summer time). The catchment area is sparsely populated: about 35,600 inhabitants are

Table 1
POL model: performances with pre-defined parameters

Event	Obs.load (kg N)	Obs.duration (h)	Sim.load (kg N)	Sim.duration (h)	Criterion
1	111 ± 55	34 ± 4	400	63	-2.45
2	4107 ± 2053	77 ± 4	7669	93	-0.07
3	3304 ± 1652	120 ± 4	2949	92	0.66
4	69 ± 34	17 ± 4	26	15	0.23
5	295 ± 147	69 ± 4	1379	68	-2.69
6	16422 ± 8211	200 ± 4	10970	105	0.20
7	3127 ± 1653	79 ± 4	1163	84	0.31
8	3341 ± 1670	168 ± 4	7530	219	-0.56
9	11966 ± 5983	245 ± 4	10640	119	0.38
10	335 ± 167	22 ± 4	3171	19	0.80
11	337 ± 168	19 ± 4	760	27	-0.67
12	733 ± 366	48 ± 4	1513	51	-0.13
13	656 ± 328	33 ± 4	322	27	0.32
14	3674 ± 1837	142 ± 4	2706	97	0.42
15	502 ± 252	33 ± 4	936	30	0.03

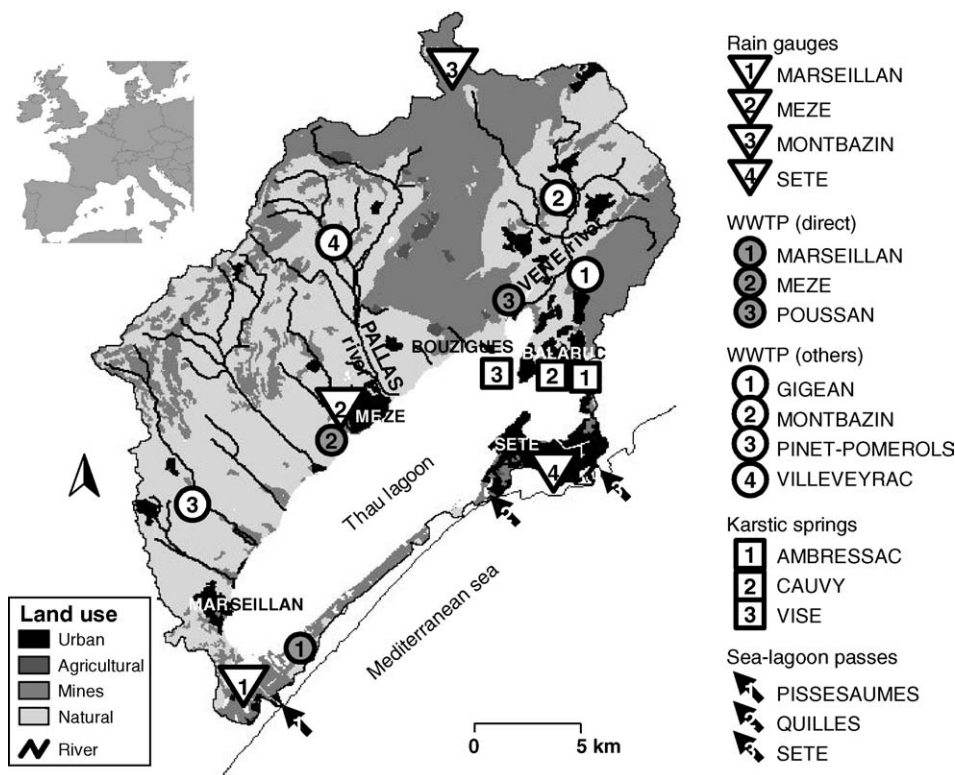


Fig. 2. The Thau lagoon and its environment.

spread in small villages. Even if tourism is an important economical activity around the lagoon (the population doubles in summer), the main activity remains shell-fish farming. All over the year the lagoon is highly productive, but dystrophic crisis often happen during the summer period due to the excess of nutrients in the lagoon (Souchu et al., 1998).

Small villages are settled on the shoreline: Balaruc-les-Bains, Bouzignès, Marseillan, and Mèze. Their stormwater drainage systems output directly in the lagoon, draining up to 6.8 km² of urban areas. The city of Sète is also partly drained directly into the lagoon (7.3 km²). Three sewage treatment works discharge directly into the lagoon (Marseillan, Mèze and Pousan); they use extensive processes with stabilization ponds. There are some industries around the lagoon, located close to Balaruc: they locally impact on nitrogen concentrations in groundwater.

The lagoon catchment (area of 269 km²) consists of karstified limestone and marls from the Miocene. The

basin is drained by small intermittent rivers that show a long dry period between May and September and flush flash floods during the wet season. The Vène River (67 km²) is the most important one and the only one fed by karstic springs; the Pallas River drains an area of 52 km²; the other rivers have smaller catchment areas. The main part of the Thau basin (54% of the total area) is devoted to agricultural activities: mainly vineyards (25% of basin area), plus orchards and market gardening. The impervious zones cover 9% of the basin and include urban centres as well as industrial and commercial zones. Nitrogen inputs in the basin are mainly due to the provision of fertilizers on the fields, in particular for market gardening. The industrial activities are linked to agriculture: wineries (private or cooperative) and poultry farms are the main ones. Cooperative wineries and poultry farms have their own treatment devices or are connected to a sewage treatment work. Private wineries have small outputs and do not seem to have an impact on the lagoon in terms of nitrogen

inputs. The rivers receive the effluents of four sewage treatment works (Pinet-Pomerols, Villeveyrac, Montbazin, Gigean) that use stabilization pond processes.

The western part of the basin is lying on a karstic aquifer that shows several outfalls into the lagoon:

a sub-marine spring (Vise spring) and two shoreline springs (Cauvy and Ambressac). It was shown that the western porous aquifer does not impact on the lagoon or on the intermittent rivers.

The lagoon is connected to the sea by three passes: two shallow passes (Pissesaumes and Quilles) through the sandy lido are blocked; the deep canal crossing the city of Sète contributes to the main part of the sea–lagoon exchanges.

3.2. Nitrogen load calculation

Nitrogen loads from the different sources were estimated for the Thau lagoon for the period stretching from September 1998 to August 1999 (hydrological year 1998–1999) and for one significant flood event in November 1999.

Table 2

Rainfall event (11–12 November 1999) at Montbazin station

Rain event beginning	11 December 1999, 21 h and 15 min
Maximum intensity over 5 min (mm h^{-1})	26.4
Total rainfall (mm)	167.2
Rainfall event duration (h)	73

The Montbazin rain gauge was used to evaluate rainfall amounts and intensities for the reference period and event. The hydrological year (September 1998 to August 1999) was a dry year with a total rainfall amount of 517 mm (local annual average value: 750 mm). The storm event of November 1999 (Table 2) had lasted about 3 days with high peak intensity and a total amount of 167 mm within 72 h.

Table 3 summarizes the available data for each source of nitrogen during the reference period and event. The data were collected during research projects, funded by local authorities and the French Ministry of environment (Contrat pour l'Etang de Thau, 1997;

Table 3

Thau lagoon—synthesis of the available data and methods of evaluation

N source	Measurement	Location	Time interval	Frequency	References
Rainfall	Rainfall height	Montbazin	Since July 1994	Continuous	Contrat pour l'Etang de Thau (1997) Salles (unpublished data)
	Concentration		In 2003–2004	Some events, bulk	
Sea–lagoon exchange	Discharge	Sète Canal	January 1994–December 1996	Hourly	Contrat pour l'Etang de Thau (1997)
	Concentration			Hourly samples during five tidal events	
Domestic effluent	Discharge Concentration	Marseillan and Mèze	Since 2001	Almost monthly	Local authorities
Urban drainage	None	—	—	—	—
Groundwater	Discharge	Vise, Cauvy, Ambressac	January 1998–May 2000	Monthly till August 1999, then in November 1999 and May 2000	Contrat pour l'Etang de Thau (1997)
	Concentration				Tournoud et al. (2004)
Rivers	Discharge	Vène River	Since September 1994	Continuous	Contrat pour l'Etang de Thau (1997)
	Concentration	Pallas River		Monthly, plus hourly samples for some floods	Tournoud et al. (2004)

Table 4
Sea–lagoon exchanges: available data

Campaign	#1	#2	#3	#4	#5
NO ₃ concentrations ^a (g N L ⁻¹)					
Tidal cycle from sea to lagoon					
Average	28	40	142	42	57
1/2 max–min	5	17	15	18	12
Tidal cycle from lagoon to sea					
Average	32	30	124	19	49
1/2 max–min	12	11	9	21	7
NH ₄ concentrations ^a (g N L ⁻¹)					
Tidal cycle from sea to lagoon					
Average	8	26	14	7	21
1/2 max–min	6	6	8	8	4
Tidal cycle from lagoon to sea					
Average	5	25	8	14	9
1/2 max–min	3	20	5	3	3

^a Calculated from hourly observed concentrations during the cycle.

Tournoud et al., 2004). GIS data were also available for the lagoon catchment: digital elevation model (from BD Alti[®] IGN), land-use map (from Sagot, 1999), geological map (from BRGM), river network (from BD Carto[®] IGN), locations of urban drainage outlets, sewage treatment works (STW) and industries (from BD Carto[®] IGN and Hérault Province). Agricultural practices were studied by Dauriac (2000). The data are gathered in Tables 3–8. For each source of nitrogen, we retained the method that best fits the available data.

3.2.1. Atmospheric input

Nitrogen loads from the atmosphere were estimated by combining of continuous rainfall heights with

Table 6
Characteristics of urban areas

	Inhabitants	Urban area 2 (km ²)	Population density 2 (inhab./km ²)
City of Sète	26361	7.3	3596
Other villages	20274	6.8	2999

Table 7

Karstic springs: observed nitrogen loads									
(kg N day ⁻¹)	WISE	CAUVY	AMBRESSAC						
	NT	NO ₃	NH ₄	NT	NO ₃	NH ₄	NT	NO ₃	NH ₄
Average ^a	13	9	0	18	15	0	98	60	7
Half min–max interval	12	6	0	36	30	0	129	94	51
High water period	22	14	0	72	62	0	460	283	30
Low water period									
In summer	4	4	0	3	3	0	17	16	0
In winter	10	8	0	17	14	0	40	24	2

^a

Calculated from monthly data (1998–1999), January–December: 10, 8, 0, 17, 14, 0, 40, 24, 2, 67, 46, 2.

bulk nitrogen concentrations measured during rainfall events.

No concentration data were available during the reference period. So, concentrations of nitrates and ammonium in the atmospheric deposits were estimated on the data collected between September 2003 and April 2004. Bulk rainfall concentrations ranged between 0.2 and 0.6 mg N L⁻¹ for nitrates and between 0.1 and 0.7 mg N L⁻¹ for ammonium (Salles, unpublished data). The loads were calculated using the same concentration value for nitrates and ammonium (0.3 mg N L⁻¹). The uncertainty is set to be the half of the min–max interval.

Table 5
Characteristics of sewage treatment works

Sewage treatment works	Population (nb permanent inhab.)	Connection ratio (%)	Treatment yield (%)	Output loads (kg N day ⁻¹)
Directly flowing into the lagoon				
Marseillan	7587	84	37	42 ± 30
Mèze	3507	88	39	21 ± 18
Poussan	1815	88	78	^a
Inside the watershed				
Gigean	3552	99	18	^a
Montbazin	2214	94	78	^a
Pinet-Pomerols	2686	89	64	^a
Villeveyrac	1974	89	72	^a

Table 8

Vène River flood (November 1999): flood characteristics and nitrogen loads

Flood event beginning	12 December 1999, 5 h and 55 min
Base flow ($\text{m}^3 \text{s}^{-1}$)	0.266
Peak flow ($\text{m}^3 \text{s}^{-1}$)	29
Total flood volume (10^3m^3)	7220000
Flood duration (h)	156
Total nitrogen load	
Observed (kg N)	9770
POL model (kg N)	10700
Peak nitrogen load	
Observed (kg N h^{-1}) ₁	226.7
POL model (kg N h^{-1})	203.8

3.2.2. Sea–lagoon exchanges

Nitrogen exchanges between the Thau lagoon and the sea were only considered through the Sète canal and restricted to nitrates and ammonium. Sea–lagoon exchanges were monitored in 1995 and 1996; hourly flow data and five sampling campaigns were available during this period. The mean value of the net daily volume exchanged through the canal was estimated, over the 2 years, to about 250,000 m^3 seaward: in average, the lagoon outflows into the sea about 5,300,000 m^3 but inflows about 5,050,000 m^3 per day. Nitrogen concentrations showed low variations within a tidal cycle, but large differences between the five observed cycles (Table 4). Regarding the limited number of data, no attempt to link observed loads to climatic conditions were done. So, arbitrary choices were made for sea–lagoon exchange calculations.

For each campaign, daily net nitrogen loads exchanged through the canal were evaluated as the difference between in-load and out-load: out-load was defined as the product of daily average volume by average nitrogen concentration observed during seaward tidal cycles (in-load referred to lagoonward tidal cycles). The minimum and maximum net daily loads were obtained for #1 and #3 campaigns, respectively. During the #1 campaign (20 June 1995), the net daily nitrogen load was evaluated to -14 kg N the negative value indicating that the in-load (182 kg N) is lower than the out-load (196 kg N). The #3 campaign (9 December 1995) took place just after a large storm event (57.2 mm of rainfall recorded in one day at Montbazin station). The net daily nitrogen load was esti-

mated to 88 kg N, with an in-load of 788 kg N per day (717 kg N in nitrates and 71 kg N in ammonium) and an out-load of 700 kg N per day (657 kg N in nitrates and 42 kg N in ammonium). The mean net daily value was defined as the average between the two campaigns. The uncertainty was set to half of the min–max interval, it reached 100%.

3.2.3. Domestic effluents

No data were available during the reference period and event. Table 5 shows the present characteristics of sewage treatment works. Process yields and connection rates were given by the local water authorities. Annual and daily loads were estimated using present measurements, when available (Marseillan and Mèze). For the other sewage treatment works, average contribution per capita was combined to process yield: an empirical value of 15 g N per day and per inhabitant (AIF, 1993) was used here. Uncertainty was given by the observed range of variability.

3.2.4. Urban stormwater effluents

No in situ data are available for evaluating stormwater effluents around the lagoon. Nitrogen loads in urban runoff (NLUR in kg km^{-2}) were evaluated using the following formula (Bourrier, 1997):

$$\text{NLUR} = 4.725 \times 10^{-2} (0.14 + 0.1 \times \bar{\text{population density}}) \text{ rainfall amount.}$$

Urban zones around the lagoon were mapped to evaluate the impervious areas. The population data were issued from the last population inventory. Data are gathered in Table 6.

3.2.5. Groundwaters

The three karstic springs flowing into the Thau lagoon were monitored in 1998–1999, on a monthly basis. Monthly nitrogen loads were evaluated by combining estimated flow values with measured nitrogen concentrations. Table 7 presents a summary of observed nitrogen loads. The two shoreline springs showed highly variable loads, Ambressac spring was subject to high contamination from local industries. Since the monitoring period corresponds to a dry year, no attempt was done to link observed data to hydrological conditions. So, the annual groundwater load was estimated with the average value. The event load was

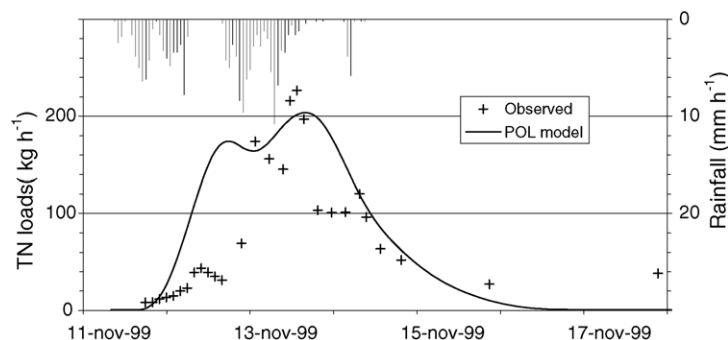


Fig. 3. Vène River—total nitrogen loads (11–18 November 1999)—POL model simulation.

estimated from high flow daily value. Uncertainty was set to half of the max–min interval; it reached 100%.

3.2.6. Rivers

Flow data are only available for Vène and Pallas Rivers during the reference period. Monthly sampling was carried out during the same period. During November 1999, a significant flood event occurred: samples were collected and analysed for nitrogen contents in the Vène River. Since only two rivers (among 10) were monitored, river loads were calculated using POL model.

The accuracy of the model was first tested on November 1999 flood event. Table 8 and Fig. 3 present the characteristics of the observed flood and the model results. The peak load produced by the model compares well to the observed values. The deviation is less than 12% for the total load. The temporal dynamic is also

Table 9

Pallas River (year 1998–1999): annual nitrogen load

POL model (tonnes N)	Annual export model ^a (tonnes N)	Direct calculation ^a (tonnes N)
15	40	8

^a Payraudeau et al. (2002).

well reproduced by the model. One-year simulation was then carried out on the year 1998–1999 (Fig. 4); the results compared well to the monthly observed loads.

The uncertainty of the model estimates was checked on an annual run on the Pallas River (1998–1999). Annual nitrogen loads (Table 9) compare well to the estimate given by an annual export model (Payraudeau et al., 2001) and to a direct calculation done from available monthly data (Payraudeau et al., 2001). As already mentioned, the hydrological year 1998–1999 was dry: the Pallas River was only flowing during a

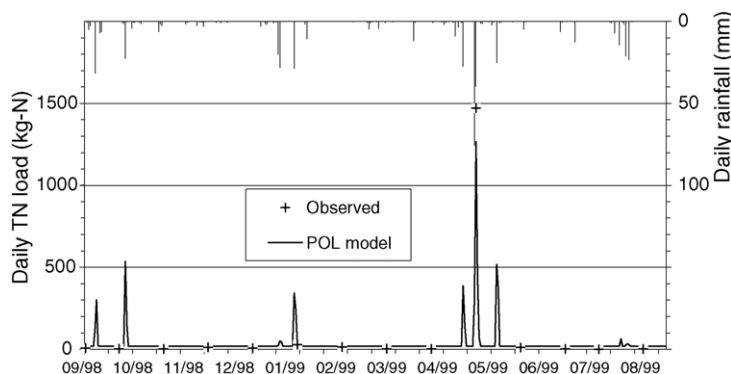


Fig. 4. Vène River—total nitrogen loads (September 1998–August 1999)—POL model simulation.

few weeks. So, the export model overestimates the nitrogen load during this dry year since it calculates an inter-annual average value. Considering the difference between direct calculation and model result, the uncertainty on POL model was set to $\pm 50\%$.

POL model was then run on each river draining the Thau lagoon catchment during the reference period and the flood event.

4. Results and conclusion

4.1. Nitrogen load input into the Thau lagoon

Table 10 gathers estimates of total nitrogen inputs to the Thau lagoon for the different sources; when possible the estimates in term of nitrates and ammonium are also given.

4.1.1. Annual loads

The total amount of nitrogen brought to the Thau lagoon by external sources can be estimated to about 190 tonnes with an uncertainty of at least 83%.

Rivers and aquifer represent more than two-third. Concerning the other sources, it is remarkable that for the year 1998–1999, rain and domestic effluents have the same weight while urban runoff seems to be negligible. Even if the calculation refers to a very dry year the most important nitrogen sources for the Thau lagoon is related to rainfall that trigger urban runoff, river discharge and aquifer flow.

These figures do not take into account the sea–lagoon exchanges. Available data on the Sète canal are too poor to allow an accurate estimate of the

nitrogen loads involved in the sea–lagoon exchanges. The annual load depends on the methodology used to extrapolate the observed values. The different tests have shown a so large range of result values that it is impossible to conclude if there is enrichment or impoverishment of the Thau lagoon through the Sète canal during the year. If uncertainties on the other sources of nitrogen are reduced, it will then be possible to estimate this term using a budget method (like LOICZ for example).

4.1.2. Event loads

An intense storm event occurred in November 1999. The total rainfall height during the event represented one-third of the annual rainfall recorded the previous hydrological year (Table 2). As recorded at the Vène outlet, the flood event lasted 7 days. The nitrogen loads were evaluated over the same duration. Sea–lagoon exchanges were not evaluated here.

More than 40 tonnes of nitrogen was brought to the lagoon in 7 days, that is to say a quarter of the annual amount calculated for one dry year (1998–1999). Assuming the perfect mixing of the lagoon and combining nitrogen input to lagoon volume, the nitrogen concentrations in the lagoon will increase by 0.2 mg N L^{-1} . Rivers and rain brought more than 85% of the total amount. The aquifer, since its response is much slower and more attenuated than the river, seems to have a lower impact.

4.1.3. Daily loads

Daily loads were calculated on average, during the flood event and during dry day. Comparing an average day to a rainy day (Table 11), the same conclusion can

Table 10
Nitrogen inputs in the Thau lagoon: during 1 year; during one storm event

(tonnes N)	One year, September 1998–August 1999			During one flood event, 11–18 November 1999			Uncertainties (%)
	TN	NO ₃	NH ₄	TN	NO ₃	NH ₄	
Rain	23	12	12	7.5	3.7	3.7	± 100
Rivers	80	–	–	30.9	–	–	± 50
Groundwater	58	38	6	3.6	2.3	0.2	± 100
Urban areas	2	–	–	0.6	–	–	?
WWTP	25	–	–	0.7	–	–	± 70
Total	188	–	–	43.3	–	–	
Sea exchanges	13	6	7	–	–	–	± 125

–: No data available.

Table 11

Nitrogen inputs in the Thau lagoon: during 1 day in different hydrological conditions

TN (kg N day ⁻¹)	Daily average	Storm event	Dry day, in summer	Dry day, in winter
Rain	63	1071	0	0
Rivers	219	4414	43	71
Groundwater	159	514	24	67
Urban areas	5	86	0	0
WWTP	68	100	110	60
Total	515	6186	177	242
Sea exchanges	36	—	—	—

—: No data available.

be drawn: nitrogen sources associated to rainfall (rain, rivers, aquifer and urban runoff) prevails over domestic effluents.

But, in summer, when rivers and aquifer are almost dry, sewage treatment works become the major input of nitrogen for the lagoon, all the most because of the increase in population. The continuous input of treated water contributes to the accumulation of nitrogen close to discharge location and may lead to local dystrophic crisis during the summer period (Souchu et al., 1998).

4.2. Conclusion

Estimating nitrogen inputs into a lagoon is not an easy task, even when a large set of data is available as it is for the Thau lagoon. It was impossible to reach our initial goal: comparing methods. Moreover, uncertainties are difficult to determine.

For the Thau lagoon, the budget of external nitrogen sources shows the great importance of rain-driven sources compared to direct domestic effluents. Since river and groundwater loads are predominant (except in the summer period), reliable estimation tools have to be developed. POL model that was built in this aim gives already good results for small Mediterranean rivers. Yet it must be enhanced, because it does not take into account nitrogen species.

The large uncertainties attached to sea–lagoon exchanges must be reduced: the solution could be to use hydrodynamic models. Urban area nitrogen loads to the lagoon need to be better known, but seems to be negligible in the budget. At last, direct rainfall was demonstrated to be a significant input of nitrogen for the lagoon and must be taken into account in the nitrogen budget for a lagoon.

Acknowledgments

The authors want to thank Prof. B. Picot (Université de Montpellier 1), P. Souchu (IFREMER), N. Dorfliger (BRGM) for the availability of the data and C. Rodier (CNRS) for the database management. This study was driven in the framework of two research projects: Programme National d'Environnement Côtier Lagunes Méditerranéennes and DITTY project (EU EESD Project EVK3-CT-2002-00084) (European Union, 2002).

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