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# Modelling the eutrophication of the Seine Bight (France) under historical, present and future riverine nutrient loading

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## Abstract

Because of the occurrence of episodic blooms of toxic dinoflagellates, eutrophication of the Seine Bight is a subject of growing concern. In order to better understand the relationships between these processes and human activity in the Seine watershed, two models have been used in connection:

- A model describing nutrient (N, P, Si) transfer processes at the scale of the whole Seine Basin (RIVERSTRAHLER [Billen, G., Garnier, J., Ficht, A., Cun, C., 2001. Modelling the response of water quality in the Seine River Estuary in response to human activity in the watershed over the last 50 years. Estuaries 24, 977–993]), allowing human activity (agricultural practices, waterscape management, urban wastewater management, etc.) to be related to fluxes delivered to the sea.
- A model of 3D hydrodynamic and ecological model of the Seine Bight (SiAM-3D/ELISE [Cugier, P., 1999. Modélisation du devenir à moyen terme dans l'eau et le sédiment des éléments majeurs (N, P, Si, O) rejetés par la Seine en baie de Seine. Thèse de doctorat, Univ. de Caen, p. 241; Cugier, P., Le Hir, P., 2000. Modélisation 3D des matières en suspension en baie de Seine Orientale (Manche, France). C. R. Acad. Sci. Paris, Sciences de la Terre et des planétes 331, 287–294]), capable of reproducing the spatio-temporal variations of sediment transport, thermo-haline stratification and phytoplanktonic development in the plume of the Seine river.

The models are validated by their ability to reproduce observed trends of interannual variations of nutrients delivered by the Seine during the last 50 years, as well as the response of the marine system in terms of diatoms and dinoflagellate development, for which data are available from 1976 to 1984 for the former and from 1987 to 1997 for the latter. The results show clearly that dry years, where silica inputs show a deficit with respect to nitrogen and phosphorus, are those where summer blooms of dinoflagellates are particularly pronounced.

Various scenarios of human activity in the watershed are simulated by the two models, including a reconstitution of the 'pristine' state, a historical state corresponding to the situation at the end of the 18th century, as well as several scenarios corresponding to the present situation with alternative policies of wastewater nitrogen and/or phosphorus treatment.

*Keywords:* Eutrophication; Seine Bight; Seine river; Nitrogen; Phosphorus; Silica

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## 1. Introduction

The Seine Bight, located on the French coast of the English Channel (Fig. 1), is a coastal ecosystem subject to the large freshwater input from the Seine river, delivering an important load of nutrients and pollutants. The drainage area of the Seine river covers 75,000 km$^2$, including intensive agricultural areas, active industrial sites and the huge urban agglomeration of Paris, with 10 million inhabitants. A detailed discussion of the nutrient mass balance of the Seine watershed and its evolution over the last 50 years has been published by Billen et al. (2001). The nutrient enrichment of the Seine Bight leads to frequent eutrophication events and, from the beginning of the 1980s regular toxic dinoflagellate (*Dinophysis*) blooms were reported (Belin et al., 1989; Belin and Raffin, 1998). It is well known that these phenomena are largely related to the imbalance between nitrogen, phosphorus and silica in river loading, and thus depend on the interactions between human activities and natural processes in the watershed which ultimately determine the riverine nutrient delivery into the marine environment (Officer and Ryther, 1980; Nixon, 1995; Conley et al., 1993; Conley, 1999; Billen and Garnier, 1997; Lancelot et al., 1997). Predicting the impact on coastal marine eutrophication of measures taken in the watershed in order to improve continental water quality remains, however, a very difficult question because of the complexity of the physical, chemical and biological processes involved, which interact non-linearly. The use of correctly validated numerical models, integrating the complex interacting processes, is therefore the best way to tackle the question. Many authors have used numerical modelling to study the effect of nutrient river input on the coastal ecosystem dynamics (Lenhart et al., 1997; Dippner, 1998; Savchuk and Wulff, 1999; Lancelot et al., 2002, etc.). Most of these studies, however, consider riverine nutrient delivery as a forcing factor, and explore the impact of nutrient load by theoretically reducing riverine input, without addressing the question of how this reduction can be achieved in terms of modification of human practices in the watershed.

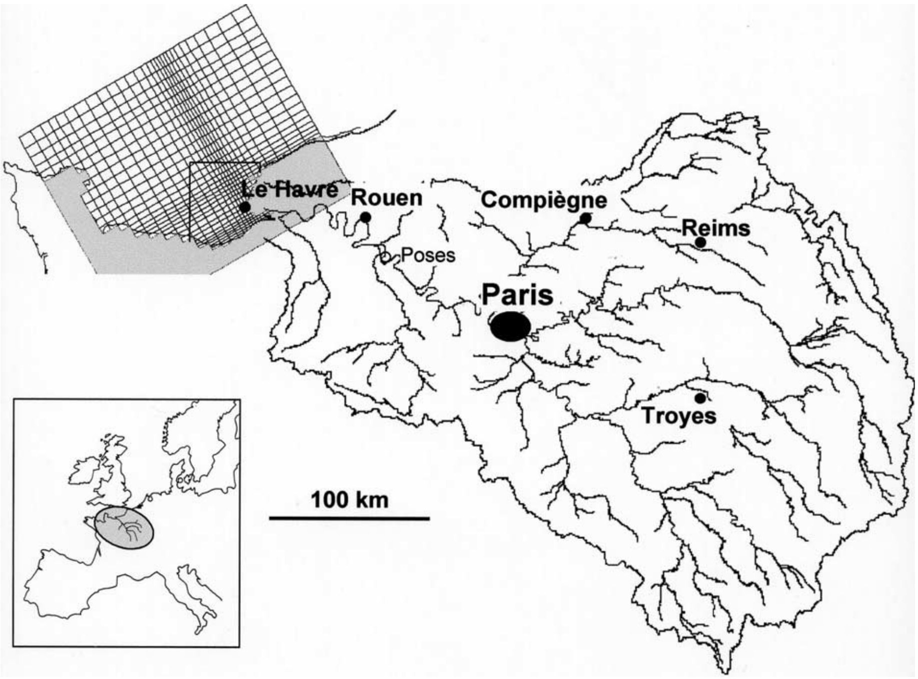

Fig. 1. The Seine Bight and the Seine river watershed. Computational grid of the Seine Bight model (the frame in the Seine plume area indicates the grid cells taken into account for calculation of mean values over the plume).

In this paper, we will present the results of a dialogue between two previously developed models, together covering the whole continuum of systems including the Seine watershed area and its drainage network, the estuary and the Seine Bight:

- the RIVERSTRAHLER model links human activities in the drainage basin to nutrient fluxes brought to the sea (Garnier et al., 1995; Billen et al., 2001)
- the ELISE/SiAM-3D model is a three-dimensional ecological model of the Seine Bight, taking into account the marine bight and the estuarine domain, up to the upstream tidal limit propagation (Cugier, 1999; Cugier and Le Hir, 2002; Cugier et al., accepted) and simulating diatom and flagellate production.

The offline coupling of these models allowed us to directly link anthropogenic activities and land use in the watershed to the resulting eutrophication state of the Seine Bight. Thus, thanks to the two models, variations of nutrient input into the Bight result from modelled upstream change of anthropogenic activities.

This paper deals with this coupling and explores several scenarios of nutrient inputs. After a summarized description of the two models, the procedure of their coupling and their validation is detailed. Two kinds of scenarios will then be explored using both models. The first scenarios, of retrospective nature, attempt to give an idea of the trophic state of the Seine Bight in the past (with no or small anthropogenic influences). The second set of scenarios, of prospective nature, allows us to analyse the effect to be expected in terms of coastal eutrophication from several policies of nitrogen and/or phosphorus removal from urban wastewater.

## 2. Models description and validation

### 2.1. The river network model

The RIVERSTRAHLER model (Billen et al., 1994; Billen and Garnier, 1999; Garnier et al., 1995) couples a description of the kinetics of the various biological and physico-chemical processes affecting organic matter and nutrients in surface water (RIVE: Garnier et al., 1995, 1999, 2002), with an idealized hydrological module, describing the flow of water from the watershed in a number of sub-basins and main branches of the river system. For the purpose of its application to the Seine drainage network, four sub-basins (Eure, Oise, Marne, and upper Seine rivers) and the main branch of the Seine river downstream from Paris have been considered (Billen et al., 2001).

The HYDROSTRAHLER module, based on the concept of streamorder (Strahler, 1957), represents the complex network of tributaries of each sub-basin by a regular confluence scheme of rivers of increasing streamorder with mean morphological characteristics. Given the seasonal variations of rainfall and evapotranspiration, and by means of a two-reservoir description (soil and aquifer) of the rain–discharge relationship, the model calculates the specific flow in each sub-basin as the sum of surface/sub-surface runoff and groundwater base flow. Flow velocity and depth in each stream order are then calculated by the Manning–Strickler formula (Hammer and Mac Kichan, 1981). In the main branch of the river, a precise description of the wetted section is taken into account.

The RIVE module then calculates how the state variables (phytoplankton, heterotrophic and nitrifying bacteria, zooplankton, inorganic suspended matter, oxygen, nutrients) evolve in their way through the drainage network, given the various constraints imposed by (i) the hydrology and morphology of the tributaries, (ii) the meteorological conditions and (iii) the inputs from point and diffuse sources in the watershed. Point sources of nutrients from wastewater plants are taken into account as data files of discharged biodegradable organic carbon, suspended matter, nitrate, ammonium and phosphate. For the present situation, these data were communicated by the Agence de l'Eau Seine-Normandie. Diffuse sources of nutrients are taken into account by assessing, for each sub-basin, a fixed composition of the two calculated components of the discharge, namely (sub)surface runoff and base flow. For the former, nutrient concentration is calculated from data on land cover and fertilization practices in the watershed by means of an empirical relationship based on lysimetric experiments (Billen and Garnier, 1999; Garnier et al., 2002). Nutrient concentrations in groundwater constituting the base flow of rivers in each sub-basin are determined from available survey of groundwater composition. The model also considers a term for retention of nitrate by riparian wetlands from watershed soils and aquifers before entering the drainage network (Billen and Garnier, 1999). As far as silica is concerned, the concentration in surface and groundwater runoff mainly results from rock weathering, and varies between 6 and 12 mg $SiO_2\ l^{-1}$ according to the lithology of the watershed. Significant mobilizable phosphorus concentration is mostly present, under particulate form, in surface runoff: we considered 0.015 mg $P\ l^{-1}$ from forested watershed, 0.045 mg $P\ l^{-1}$ from grassland and 0.15 mg $P\ l^{-1}$ from arable land, based on data collected in headwater streams draining homogeneously occupied watersheds (Billen and Garnier, 1997; Garnier et al., submitted). An Langmuir type equilibrium relationship is assumed between dissolved phosphate and adsorbed phosphate on inorganic suspended matter (Nemery et al., 2004; Garnier et al., 2005). Corresponding dissolved ortho-phosphate concentration is taken in accordance to this relationship.

The model has been widely validated for the recent situation of the Seine river, as well as for its variations during the last 50 years, through its capacity to reproduce the main trends of seasonal and geographical variations of most water quality variables (see Billen et al., 1994, 2001; Billen and Garnier, 1999; Garnier et al., 1995). Simulations of water quality at Poses, the entrance of the estuarine sector, is calculated with the model for two contrasting recent hydrologic years, 1990 and 1994 (Fig. 2). Observed data are given for comparison, and allow the assessment of the degree of accuracy of the simulations at the outlet of the drainage network. The model provides a correct simulation of nitrogen concentration. It slightly overestimates phosphate concentration during summer. It accounts for the observed period of silica depletion during the spring riverine diatom bloom, but slightly overestimates silica concentration during summer.

### *2.2. The Seine Bight model*

The Seine Bight model is composed of the three-dimensional hydrodynamic model ELISE/SiAM3D (Cugier, 1999; Cugier and Le Hir, 2002) which solves the so-called ‘shallow water’ equations, using a finite difference technique on a non-uniform rectangular horizontal computational grid (Fig. 1), a sediment module allowing the management of sediment compartments with erosion–deposition processes (Cugier and Le Hir, 2000) and an ecological module (Cugier, 1999; Guillaud et al., 2000; Cugier et al., accepted) taking into account nutrient cycles and two phytoplankton groups, namely diatoms and non-siliceous algae (including harmful flagellate species). Simultaneous limitation of phytoplanktonic growth by inorganic nutrient (nitrate + ammonium, *o*-phosphate, and silica for diatoms) is taken into account by means of hyperbolic Michaelis–Menten like functions. The possibility of nitrogen fixation is not considered in the model.

The model is forced with tidal harmonic components at the marine boundaries, with measured (or calculated) flows and concentrations at river boundaries, with wind-induced stresses at the surface and with measured meteorological time series for sea temperature computation.

The performance of the physical and the biological models have been tested and validated with a large set of measured data (Cugier and Le Hir, 2002; Cugier, 1999; Cugier et al., accepted). As an example, the seasonal and year-to-year variations are well reproduced when simulations and measurements over 10 years of salinity, dissolved nitrogen and chlorophyll are compared at a station located off Le Havre Harbour (Fig. 3). As Le Havre Harbour is located at the Seine river mouth, the salinity variations reflect those of the Seine river flow. Strong variations of nitrogen are observed, due to phytoplankton consumption and to seasonal variations of the Seine river inputs. Chlorophyll concentration increases at the beginning of spring and remains at a high level until autumn.

## 3. Coastal eutrophication under present conditions

The main challenge of our modelling approach is to simulate potentially harmful flagellate development in the Seine Bight, while available measurements show that diatom biomass always dominates the phytoplankton community (Videau et al., 1998). We

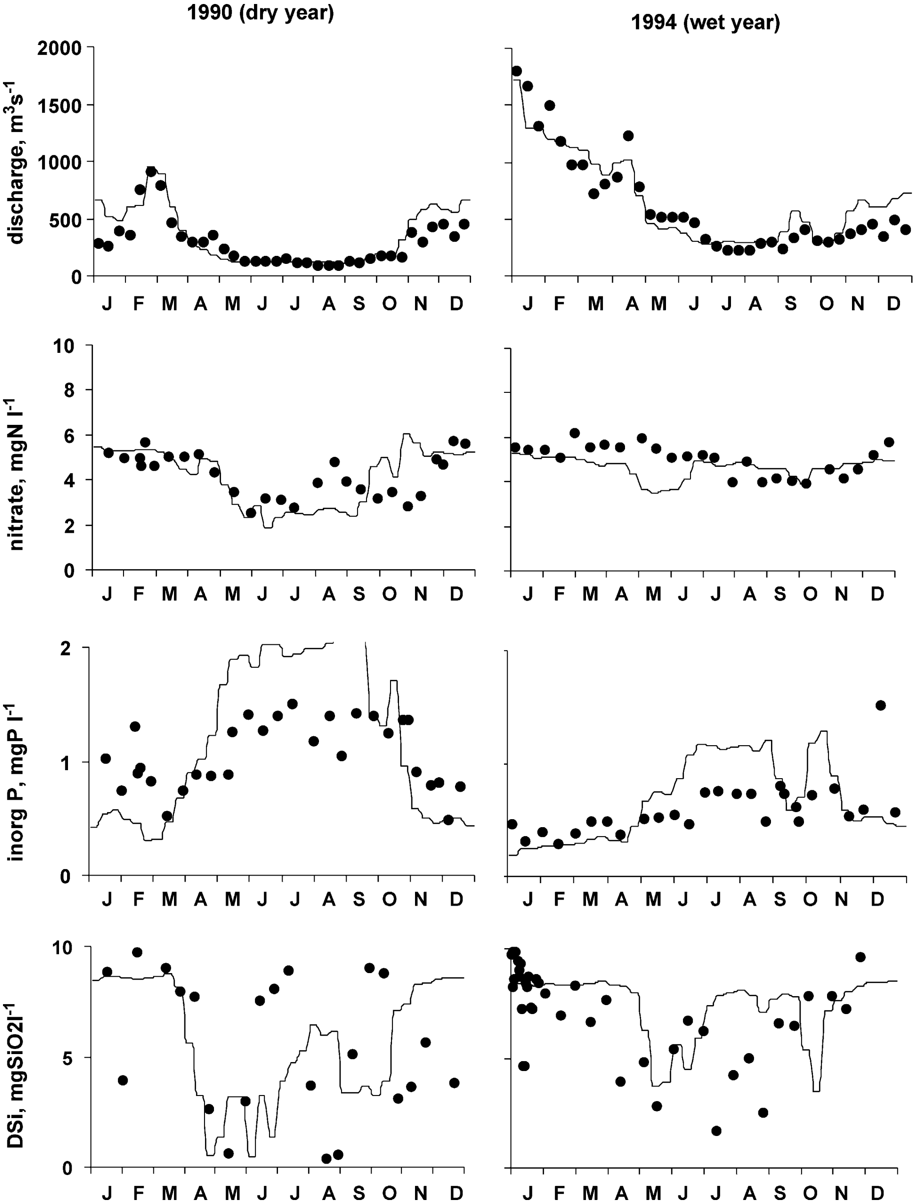

Fig. 2. Simulation by the RIVERSTRAHLER model of seasonal variations of discharge, nitrate, total inorganic phosphorus (particulate and dissolved phosphates) and dissolved silica concentrations at station Poses, for the hydrological conditions of year 1990 (dry year) and 1994 (wet year). Comparison with observed data provided by the SNS (Ficht, pers. comm.).

have therefore to compare the model's results with the observations, not only in terms of total chlorophyll a values, but also in terms of flagellate and diatom biomasses.

Direct microscopic counts of flagellates are available from 1987 to 1997 for the coast of Calvados (the Southern shore of the Seine Bight, Fig. 1) as a result of the French Phytoplankton Network (REPHY) (Belin et al., 1989; Belin and Raffin, 1998). These data are compared with those of total flagellates biomass simulated by the ELISE/SiAM3D model for the same area (Fig. 4), after conversion from μmol N/l, as

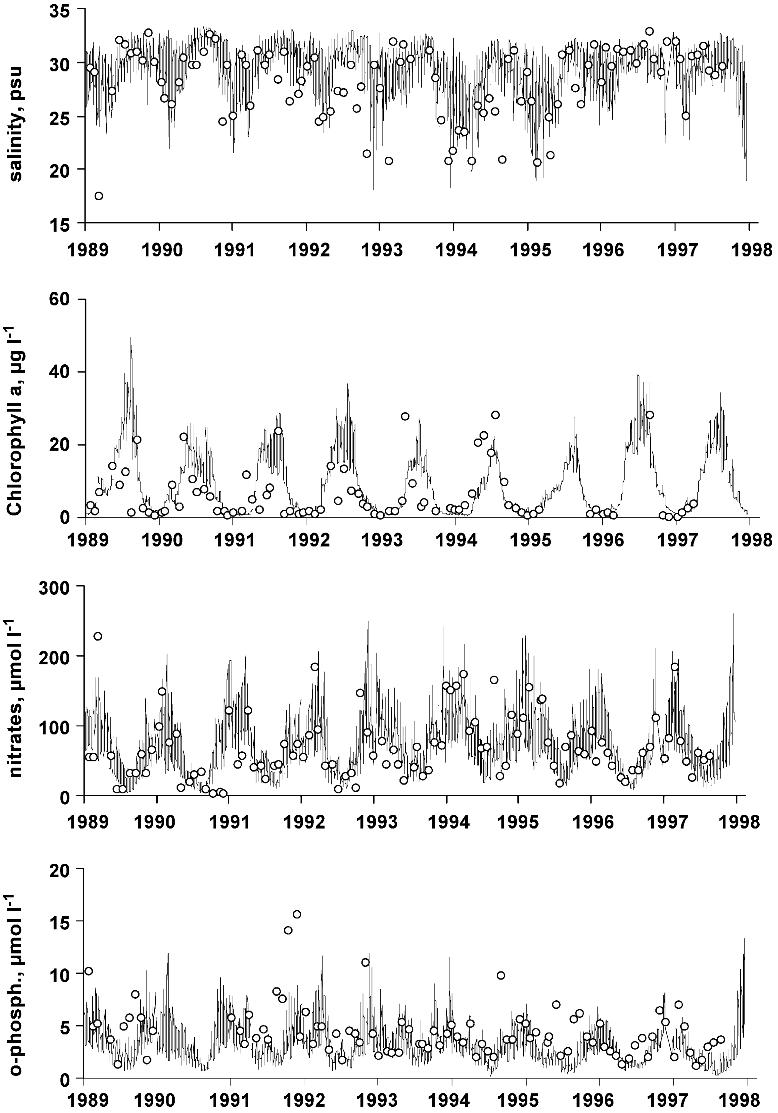

Fig. 3. Comparison between simulated and measured surface salinity, chlorophyll a, dissolved inorganic nitrogen and dissolved inorganic phosphorus in Le Havre Harbour from 1989 to 1998 (model calculated biomass values in µmol N $l^{-1}$ were converted in chlorophyll a values using a conversion factor of 1 µmol N/µg Chla (Aminot et al., 1997).

provided by the model using a conversion factor of 4 pmol N/cell, as determined by Meksumpun et al., (1995). The data show large interannual variations, both in the taxonomic composition of the community (the genus *Dinophysis*, *Gymnodinium* or *Prorocentrum* alternately dominate from one year to the other), and in total flagellate biomass (the highest biomass being reached for the years with low river discharge). This is confirmed by the recent observations in the very dry summer 2003, when intense *Dinophysis* blooms occurred again in the Seine Bight, leading to shellfish catch prohibition, after several very wet years with only minor problems. Although it does not distinguish between the different flagellates taxa, the ELISE/SiAM3D model roughly reproduces the year-to-year variations in total flagellate development,

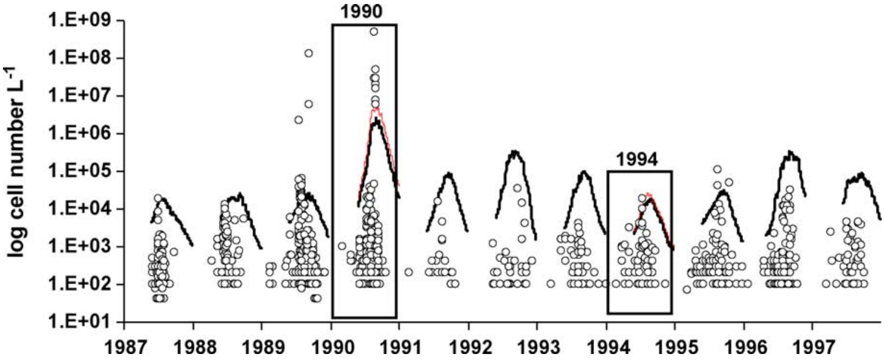

Fig. 4. Simulated and observed interannual variations of flagellate cell numbers along the Southern coast of the Seine Bight (Calvados) from 1987 to 1997. Dots corresponds to cell counts obtained in the scope of the REPHY survey network (Belin et al., 1989; Belin and Raffin, 1998). The bold black curve is the result of the model with observed fluxes of nutrients at Poses, while the light curve, just above the former one, is the calculation with the fluxes at Poses calculated by the RIVERSTRAHLER model for years 1990 and 1994 (see Fig. 2). Calculated values of flagellate biomass, in μmol N $l^{-1}$ have been converted into cell numbers using a conversion factor of 4 pmol N/cell, as determined by Meksumpun et al. (1995).

whether it uses observed or calculated data for the nutrient inputs at Poses (Fig. 4). For instance, among the 10 years, the model points especially well the year 1990 as a very productive one for flagellates, while 1994 is predicted as the less productive. 1990 was a dry year where the average Seine river discharge was about 350 $m^3$/s compared to a standard value of 450 $m^3$/s, whereas 1994 was a wet one with mean river discharge of 660 $m^3$/s.

In 1990, the maximum flagellate biomass, as calculated by the model, is observed at early September in the plume of the Seine river, off the Calvados coast, just downstream the turbidity maximum area (Fig. 5). Analysis of the vertical distribution reveals that this area is weakly stratified and that the maximum flagellate biomass concentrates in the upper, less saline waters. In 1994, flagellate development is hardly perceptible and the maximum biomass is reached in the Northern part of the plume (Fig. 5).

Table 1 summarizes the results of the RIVERSTRAHLER and ELISE/SiAM3D models for the years 1990 and 1994, but also those obtained by the latter model when using either the observed nutrient inputs or the calculated nutrient fluxes at Poses, in order to appreciate the sensitivity to the discrepancies

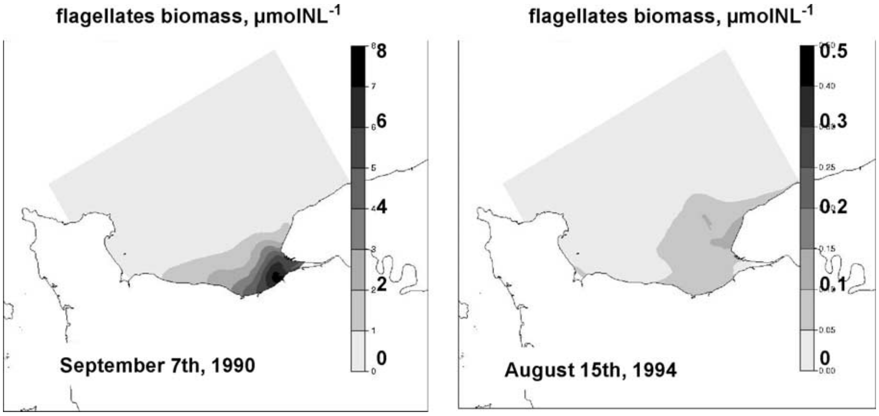

Fig. 5. Calculated distribution of flagellate biomass at the time of their maximum development in the Seine Bight, as calculated by the model for the conditions of year 1990 (dry year) and 1994 (wet year).

Table 1
Results of the coupled RIVERSTRAHLER and ELISE/SiAM3D models concerning the situation of the years 1990 and 1994

| | 1990 (observed) | 1990 (calculated) | 1994 (observed) | 1994 (calculated) |
|---|---|---|---|---|
| *Annual values* | | | | |
| Mean discharge at Poses (m$^3$ s$^{-1}$) | 350 | 343 | 660 | 684 |
| Total N flux delivered at Poses (kTN yr$^{-1}$) | 71 | 84 | 117 | 136 |
| Total P flux delivered at Poses (kTP yr$^{-1}$) | 10 | 8 | 9.5 | 10 |
| DSi flux delivered at Poses (kTSi yr$^{-1}$) | 60 | 37 | 118 | 79 |
| Molar ratios (N:P:Si) | 16:1:7 | 22:1:5 | 28:1:13 | 29:1:8 |
| *Spring values (April)* | | | | |
| Total N flux delivered at Poses (TN d$^{-1}$) | 193 | 178 | 506 | 505 |
| Total P flux delivered at Poses (TP d$^{-1}$) | 30 | 22 | 28 | 30 |
| DSi flux delivered at Poses (TSi d$^{-1}$) | 110 | 34 | 440 | 310 |
| Molar ratios (N:P:Si) | 14:1:4 | 18:1:2 | 40:1:18 | 38:1:12 |
| *Summer values (July–September)* | | | | |
| Total N flux delivered at Poses (TN d$^{-1}$) | 70 | 94 | 147 | 182 |
| Total P flux delivered at Poses (TP d$^{-1}$) | 12 | 22 | 20 | 31 |
| DSi flux delivered at Poses (TSi d$^{-1}$) | 24 | 23 | 89 | 156 |
| Molar ratios (N:P:Si) | 13:1:2 | 9.5:1:1.2 | 16:1:5 | 13:1:6 |
| *Diatom production* (μmol g N m$^{-2}$ yr$^{-1}$) | 85 | 83 | 68 | 94 |
| Diatom maximum biomass (mmol N m$^{-3}$) | 25 | 23 | 25 | 34 |
| Limiting nutrient | Silica | Silica | Silica | Silica |
| *Dinoflagellate production* (g N m$^{-2}$ yr$^{-1}$) | 3.8 | 7.3 | 0.14 | 0.15 |
| Flagellate maximum biomass (mmol N m$^{-3}$) | 4.2 | 9 | 0.1 | 0.1 |
| Main limiting nutrient | Nitrogen | Nitrogen | Nitrogen | Nitrogen |

The columns marked ‘observed’ refers to the values derived from bi-monthy measurements of nutrient fluxes at Poses, and to the results obtained with the ELISE/SiAM3D model with the latter data used as input condition, instead of the results from the RIVERSTRAHLER model.

in nutrient fluxes calculated by RIVERSTRAHLER with respect to observations. Both calculation procedures provide the same general conclusion. The nutrient fluxes delivered by the river are lower in 1990 than in 1994, nearly by a factor of 2, especially for nitrogen and silica, which depends mostly on diffuse sources (Billen et al., 2001). Specific values of nutrient delivery are, respectively, 1030 kg N/km$^2$ per yr, 120 kg P/km$^2$ per yr, 650 kg Si/km$^2$ per yr in 1990 and 1690 kg N/km$^2$ per yr, 130 kg P/km$^2$ per yr, 1310 kg Si/km$^2$ per yr in 1994 (means of observed and calculated values reported in Table 1, expressed by km$^2$ watershed). Consequently, smaller Si:N and Si:P ratios are found in 1990, which favours flagellate production. Integrated flagellate production and biomass are higher by a factor of 10 between the dry year (1990) and the wet year (1994). For diatoms, on the other hand, no striking difference is observed for production or biomass between 1990 and 1994. In a system where diatoms are said to be silicon limited, it might look paradoxical that a doubling of silica input between the 2 years has little effect on the diatom biomass. First of all it must be stressed that the nutrient delivery by the Seine river is not the only source of nutrient for phytoplankton growth, particularly in spring when offshore seawater is still rich in inorganic nutrient, present in concentration close to the Redfield ratio. This obviously buffers both the ratio and the absolute value of the nutrient available for the spring diatoms bloom, with respect to the fluxes delivered by the Seine river. Another explanation for the apparent paradox can be found in the seasonal ecological successions, which appear to be very different between the 2 years. Fig. 6 shows the time course of diatoms and flagellates near the Seine river mouth for the years 1990 and 1994. In 1990 a very high and early bloom of diatoms occurs, reaching biomasses up to 25 μg Chla l$^{-1}$. At the end of spring, the diatom concentration rapidly decreases and stays at a lower level (10–15 μg Chla l$^{-1}$) during all the summer period due to a very strong silicon limitation. This lower summer diatom concentration gives opportunity to flagellates to develop. In 1994, on the other hand, the diatom bloom occurs much later in

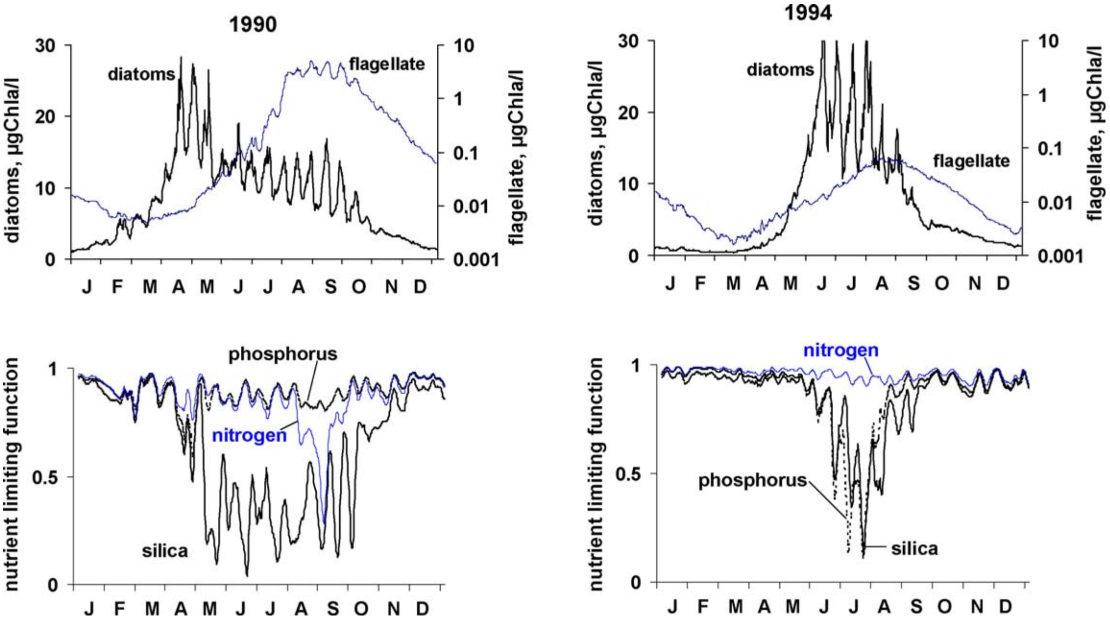

Fig. 6. Seasonal variations of diatoms and flagellate biomass near the Seine river mouth in 1990 (left) and 1994 (right). The variations of the limiting effect of nitrogen, phosphorus and silica on diatom growth is also shown (lower panels) (the limiting function is defined as the ratio $N/(N+K_n)$ where $N$ is the ambient concentration of the considered nutrient, and $K_n$ the half-saturation constant of diatom growth for this nutrient).

spring because of lower water temperature (2 or 3 °C less than in 1990) due to bad weather conditions. Nevertheless, the diatom bloom reaches a concentration up to 30 µg Chla $l^{-1}$, higher than in 1990, and remains at this level during all the summer period, giving no place for flagellate development.

## 4. Retrospective scenarios

The purpose of exploring retrospective scenarios is to answer the question about the occurrence of potentially harmful flagellate blooms under pre-industrial conditions of land use and urban discharges in the watershed. Two retrospectives scenarios have been explored, one corresponding to the pristine state and another to a traditional cottage economy. Considering these scenarios as targets for future environmental management of the watershed would be completely irrelevant and unavailing: they simply represent references to assess how deeply the biogeochemical functioning of the system has been affected by human action since the last two centuries. Due to the strong contrast between the dry and the wet years for flagellate development, the retrospective scenarios were implemented for both situations using meteorological and hydrological conditions of the dry year 1990 and the wet one 1994.

### 4.1. Scenario description

The *pristine state* represents an hypothetic situation of a watershed totally deprived of humans. Forest is assumed to cover the whole Seine basin and the river is described without hydraulic regulation. The nutrient fluxes brought to the surface water are originating from forest soil leaching and litter fall. Billen and Garnier (1997) discussed in detail the quantitative aspects of this scenario. The calculated resulting nitrogen and phosphorus fluxes delivered at Poses for both dry and wet hydrological situations are two order of magnitude lower than present values (Table 2). Silicate fluxes, on the other hand, as they do

Table 2
Results of the coupled RIVERSTRAHLER and ELISE/SiAM3D models concerning the pristine and 18th century scenarios for the hydrological and climatic situation of the years 1990 and 1994

| | 1990 (dry year) | | | 1994 (wet year) | | |
|---|---|---|---|---|---|---|
| | Pristine | XVIIIc | Present | Pristine | XVIIIc | Present |
| *Annual values* | | | | | | |
| Mean discharge at Poses ($m^3\ s^{-1}$) | 343 | 343 | 343 | 684 | 684 | 684 |
| Total N flux delivered at Poses ($kTN\ yr^{-1}$) | 2 | 13 | 84 | 4 | 22 | 136 |
| Total P flux delivered at Poses ($kTP\ yr^{-1}$) | 0.14 | 0.6 | 8 | 0.2 | 0.8 | 10 |
| DSi flux delivered at Poses ($kTSi\ yr^{-1}$) | 44 | 40 | 37 | 84 | 82 | 79 |
| Molar ratios (N:P:Si) | 38:1:350 | 46:1:72 | 22:1:5 | 41:1:390 | 56:1:107 | 29: 1: 8 |
| *Spring values (April)* | | | | | | |
| Total N flux delivered at Poses ($TN\ d^{-1}$) | 4.6 | 29 | 178 | 17 | 82 | 505 |
| Total P flux delivered at Poses ($TP\ d^{-1}$) | 0.2 | 1.9 | 22 | 0.9 | 2.5 | 30 |
| DSi flux delivered at Poses ($TSi\ d^{-1}$) | 93 | 76 | 34 | 329 | 329 | 310 |
| Molar ratios (N:P:Si) | 43:1:440 | 33:1:44 | 18:1:2 | 42:1:400 | 72:1:145 | 38:1:12 |
| *Summer values (July–September)* | | | | | | |
| Total N flux delivered at Poses ($TN\ d^{-1}$) | 1.8 | 14 | 94 | 5.4 | 32 | 182 |
| Total P flux delivered at Poses ($TP\ d^{-1}$) | 0.1 | 1.0 | 22 | 0.3 | 2.3 | 31 |
| DSi flux delivered at Poses ($TSi\ d^{-1}$) | 37 | 30 | 23 | 115 | 105 | 156 |
| Molar ratios (N:P:Si) | 47:1:489 | 32:1: 33 | 9.5:1:1.2 | 44:1:467 | 31:1:50 | 13:1:6 |
| *Diatom production* ($g\ N\ m^{-2}\ yr^{-1}$) | 50 | 61 | 83 | 41 | 48 | 94 |
| Diatom maximum biomass ($mmol\ N\ m^{-3}$) | 9 | 11 | 23 | 9.5 | 12 | 34 |
| Limiting nutrient | Nitrogen | Nitrogen | Silica | Nitrogen | Phosphorus | Silica |
| *Dinoflagellate production* ($g\ N\ m^{-2}\ yr^{-1}$) | 0.04 | 0.05 | 7.3 | 0.03 | 0.03 | 0.15 |
| Flagellate maximum biomass ($mmol\ N\ m^{-3}$) | 0.017 | 0.019 | 9 | 0.016 | 0.016 | 0.1 |
| Main limiting nutrient | Nitrogen | Nitrogen | Nitrogen | Nitrogen | Nitrogen | Nitrogen |

The results calculated for the present situation are given for comparison.

only depend on rock weathering, are very close to present values and thus are largely in excess compared with nitrogen and phosphorus, with respect to the requirement of diatom growth.

The *traditional cottage economy* scenario represents the situation in the watershed in the second half of the 18th century, when Paris already counted about 500,000 inhabitants and most of the watershed was still exploited according to three-annual crop rotation associated with farm-breeding. Hydraulic management of headwaters with numerous ponds, made the landscape quite retentive with respect to the nutrient loss by leaching and erosion of arable land (Billen and Garnier, 1997; Benoit et al., 2002). The calculated nitrogen and phosphorus fluxes delivered at Poses for this scenario are much higher than in the pristine scenario, as a result of human activity, but remain one order of magnitude lower than the present levels (Table 2). The silicate flux remains in excess compared to nitrogen and phosphorus.

### 4.2. Phytoplankton and nutrient in the Seine Bight for retrospective scenarios

The calculated annual production and maximum biomass of diatoms and flagellates of the plume area of the Seine river for the two retrospective scenarios and the dry and wet years are compared with the results for the corresponding present situations (Table 2, Fig. 7). The limiting nutrient at the time of maximum biomass is also mentioned.

For both scenarios, the predicted diatom production and biomass level are lower by a factor of only 2, compared to the present situation. This means that the Seine Bight should have already been a rather productive area in these ancient times. Human activity in the watershed, as it was in the 18th century, apparently did not severely affect the overall coastal diatom productivity. In the opposite, predicted flagellate biomass and production for the two retrospective scenarios, are drastically lower (by a factor

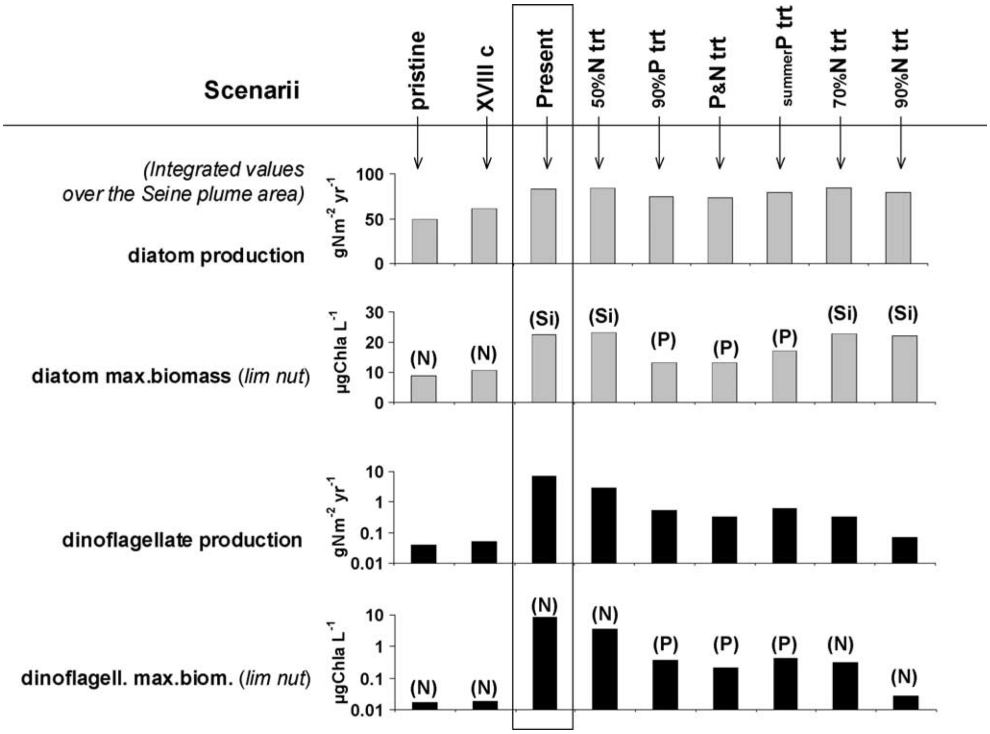

Fig. 7. Effect on algal blooms in the Seine Bight of different retrospective and prospective scenarii of human activity in the Seine watershed, calculated for the hydrological and meteorological conditions of year 1990. Pristine, entirely forested watershed; XVIII c, traditional cottage economy at the end of the 18th century; Present, present reference situation; *xx*% N/P trt, treatment of nitrogen or phosphorus in urban wastewater with a resulting *xx*% elimination of the total urban loading; P&N, combination of 50% nitrogen abatement and of 90% phosphorus abatement from urban wastewater loading; summerPtrt, P treatment of urban wastewater (90% abatement) restricted to the summer period (April to September).

100 in the dry situation) compared with the present levels (Fig. 7). Nitrogen is invariably the most limiting nutrient for both phytoplankton groups, except for diatoms in the 18th century and wet situation, when phosphorus played that role. In both situations, silicate fluxes are in excess compared to nitrogen and phosphorus, allowing diatoms to outcompete flagellates.

## 5. Prospective scenarios

Besides exploring the past ecological state of the system, the chain of models covering the river–estuary–coastal continuum presented in this study can also be used for predicting the effect of the watershed management in terms of marine eutrophication reduction. Among possible control actions able to reduce nutrient contamination of surface water, only urban wastewater treatment is expected to provide measurable effect in the short term. As the aquifers of the Seine Basin are characterised by very long residence times, a reduction of diffuse agricultural sources of nitrogen, especially, should only give results in the long term. Due to the time lag caused by nitrate accumulation in the unsaturated soil zone and in the aquifers, prospective models of ground and surface water contamination in the Seine basin predicts further increase of nitrate concentration during the next decade, even for the hypothesis of a systematic improvement of farming practices (Gomez, 2002; Gomez et al., 2003). In the prospective scenarios tested here, we will therefore only explore the effect of phosphorus and/or nitrogen tertiary treatments of urban wastewater (including urban diffuse sources), assuming constant agricultural diffuse sources of nutrients, which is an optimistic hypothesis. The scenarios will be only run under dry hydrological conditions, the most critical for the development of potentially harmful algae.

### 5.1. Scenario description

Technically, a drastic reduction, up to 90%, of the phosphorus load discharged with domestic and industrial effluents is feasible at the scale of the entire Seine watershed with a reduced cost, using the same infrastructure available for ordinary activated sludge process. The drawback of this treatment lies on the need for flocculating reactive and on the larger amount of sludge produced during the process. Because phosphorus input to the surface waters mainly originates from point sources of urban wastewater at the scale of the whole Seine basin, the effect of such a scenario can lead to significant reduction of the phosphorus fluxes delivered to the sea, bringing the phosphorus flux not far from the pre-industrial level (Table 3).

Nitrogen treatment of wastewater is technically more complex. The ordinary activated sludge process retains about 20% of the raw nitrogen load in the produced sludge. When operating at low loading rates, biological treatment plants achieve the aerobic nitrification of the ammonium produced by mineralisation of organic nitrogen. The re-circulation of a part of these nitrified effluents at the head of the biological treatment leads to denitrification provided anaerobic conditions are maintained there. Such a process allows a maximum reduction of 50% of the nitrogen load. A more drastic reduction of nitrogen in wastewater is technically possible by processes implying a tertiary denitrification step with addition

Table 3
Results of the coupled RIVERSTRAHLER and ELISE/SiAM3D models concerning the prospective scenarios with the application of various tertiary treatment of urban wastewater

| | Present | 50% N trt | 90% P trt | P&N | sumP trt | 70% N trt | 90% N trt |
|---|---|---|---|---|---|---|---|
| *Annual values* | | | | | | | |
| Total N flux delivered at Poses (kTN yr$^{-1}$) | 84 | 66 | 84 | 67 | 84 | 58.7 | 51 |
| Total P flux delivered at Poses (kTP yr$^{-1}$) | 8 | 9 | 1 | 1 | 5 | 10 | 10 |
| DSi flux delivered at Poses (kTSi yr$^{-1}$) | 37 | 36 | 40 | 40 | 39 | 36 | 36 |
| Molar ratios (N:P:Si) | 22:1:5 | 16:1:4 | 176:1:43 | 147:1:44 | 38:1:9 | 13:1:4 | 11:1:4 |
| *Spring values (April)* | | | | | | | |
| Total N flux delivered at Poses (TN d$^{-1}$) | 178 | 122 | 173 | 122 | 173 | 101 | 80 |
| Total P flux delivered at Poses (TP d$^{-1}$) | 22 | 25 | 4 | 4 | 4 | 27 | 27 |
| DSi flux delivered at Poses (TSi d$^{-1}$) | 34 | 33 | 74 | 74 | 74 | 29 | 29 |
| Molar ratios (N:P:Si) | 18:1:2 | 11:1: 1 | 103: 1: 22 | 76: 1: 23 | 103: 1: 22 | 8:1: 1 | 6:1: 1 |
| *Summer values (July–September)* | | | | | | | |
| Total N flux delivered at Poses (TN d$^{-1}$) | 94 | 62 | 96 | 65 | 96 | 44 | 27 |
| Total P flux delivered at Poses (TP d$^{-1}$) | 22 | 26 | 3 | 3 | 3 | 25 | 25 |
| DSi flux delivered at Poses (TSi d$^{-1}$) | 23 | 21 | 35 | 35 | 35 | 19 | 19 |
| Molar ratios (N:P:Si) | 9.5:1:1.2 | 5:1:0.9 | 74:1:14 | 52:1:14 | 74:1:14 | 4:1:0.8 | 2.4:1:0.8 |
| *Diatom production* (g N m$^{-2}$ yr$^{-1}$) | 83 | 84 | 74 | 74 | 79 | 84 | 79 |
| Diatom maximum biomass (mmol N m$^{-3}$) | 23 | 23 | 13 | 13 | 17 | 23 | 22 |
| Limiting nutrient | Silica | Silica | Phosphorus | Phosphorus | Phosphorus | Silica | Silica |
| *Dinoflagellate production* (g N m$^{-2}$ yr$^{-1}$) | 7.3 | 3 | 0.5 | 0.3 | 0.6 | 0.3 | 0.07 |
| Flagellate maximum biomass (mmol N m$^{-3}$) | 9 | 3.7 | 0.4 | 0.2 | 0.4 | 0.32 | 0.028 |
| Main limiting nutrient | Nitrogen | Nitrogen | Phosphorus | Phosphorus | Phosphorus | Nitrogen | Nitrogen |

Present, present reference situation; *xx*% N/P trt, treatment of nitrogen or phosphorus in urban wastewater with a resulting *xx*% elimination of the incoming total loading; P&N, combination of 50% nitrogen abatement and of 90% phosphorus abatement from wastewater loading; sumPtrt, P treatment of urban wastewater (90% abatement) restricted to the summer period (April–September). The hydrological and climatic conditions are those of the dry year 1990.

of an external electron donor like methanol or ethanol. This kind of treatment allows reduction of the nitrogen load down to 70%, or even 90%, but at a much higher cost. Moreover, because of the prevalent diffuse origin of nitrogen input (especially from agricultural soils), the effect of the generalization of these treatments to all wastewater treatment plants of the Seine basin, would only weakly reduce the total annual nitrogen delivery to the coastal zone (Table 3). During summer low flow conditions, however, the contribution of nitrogen point sources to the total nitrogen load is much higher, so that the effect of nitrogen treatment could be more significant.

The conditions of algal growth in the Seine Bight have been calculated using several hypotheses of phosphorus and/or nitrogen treatment of urban wastewater in the basin. For nitrogen, scenarios with 50, 70, and 90% reduction of point sources have been considered (50, 70 and 90% N trt, respectively). For phosphorus, a generalized 90% reduction throughout the year was tested (90% P trt), as well as this reduction limited to the vegetation period (from April to October) (summer90% P trt) The latter was shown to be effective in limiting algal blooms in the river (Garnier et al., 2005). Finally, a scenario combining a reduction of both phosphorus and nitrogen loads (90 and 50%, respectively: P&N trt) was explored.

### 5.2. Phytoplankton and nutrient in the Seine Bight for prospective scenarios

The effect of phosphorus reduction in wastewater (90% P trt) on phytoplankton blooms, calculated as annual production and maximum biomass integrated over the Seine plume is important (Table 3, Fig. 7). Diatom maximum biomass is divided by a factor of 2. A shift from silicon to phosphorus limitation is observed, reinforced during spring by the lower silicate retention in the drainage network owing to lower spring diatom development in the upstream Seine river and tributaries, as a result of the phosphorus reduction. Nevertheless, the Seine plume area remains productive in terms of diatoms. The effect on flagellates is more striking with a 10-fold reduction for maximum biomass and annual production with respect to present levels, phosphorus also becoming the limiting factor. Phosphorus treatment of wastewater thus appears as a quite effective measure to reduce the potentially harmful algal blooms in the Seine Bight. Treating phosphorus during the productive period only (summer90% P trt) gives approximately the same result on flagellates as when the treatment is conducted all year long. In the Seine Bight, flagellate blooms especially occur in the river plume area directly under the influence of nutrient inputs (Fig. 5). The Seine river flow and the tidal dynamics lead to a short resident time of freshwaters in that area. Therefore, winter nutrient inputs are rapidly exported into the English Channel, so that the phytoplankton production is mostly dependent on recent nutrient inputs.

Reduction of nitrogen point sources does not affect the diatoms growth or production. Silica remains the most limiting factor whatever be the degree of nitrogen treatment of the wastewaters (Fig. 7). However, the flagellate biomass and production, limited by nitrogen with a 50% reduction, decrease by a factor of 2. To reach a result similar to that with phosphorus, the nitrogen reduction should be carried up to 70%. However, a phosphorus treatment is technically and economically easier. Note that a reduction of 90% in nitrogen inputs would have a very strong impact on flagellate production (reduction by a factor 100), evidencing the non-linear response of the system to nutrient fluxes.

Combining a 50% nitrogen reduction and a 90% phosphorus reduction of point sources in the watershed does not provide any significant improvement in terms of flagellate blooms compared to the sole phosphorus treatment. In fact, the nutrient limiting effect due to phosphorus for the 90% P trt scenario is greater than the one due to nitrogen in the 50% N trt scenario.

## 6. Discussion

The results of the various scenarios explored in this paper confirm the high sensibility of the Seine Bight phytoplankton ecosystem to the nitrogen, phosphorus and silicate balance in the Seine river inputs. Previous study carried out with the Seine Bight model have already enlightened this point (Cugier, 1999), showing that low Si:N and Si:P ratios in the Seine river inputs, linked to dry hydrological conditions, are favourable to flagellate blooms. This is confirmed by

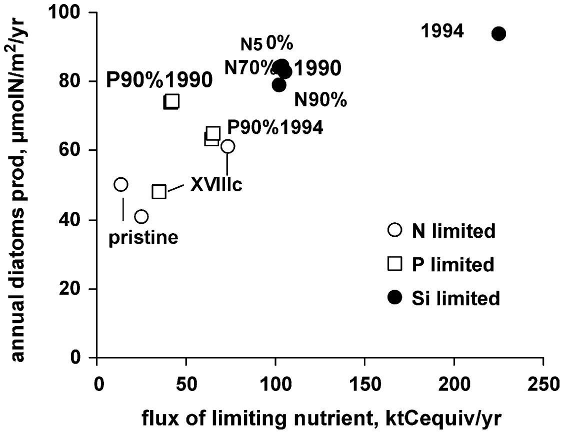

Fig. 8. Annual diatom production over the Seine plume area (see Fig. 1) for each scenario tested in this work, plotted against the flux of limiting nutrient (either N, P or Si) in the Seine annual delivery, expressed in carbon equivalent according to the Redfield ratio.

the recent observations of high *Dinophysis* blooms during the dry and hot 2003 summer. Exploring the retrospective and prospective scenarios presented here newly illustrates the dependence of diatoms and flagellates blooms on nutrient inputs from the Seine river.

As far as diatoms are concerned, the limiting nutrient at the time of the maximum biomass can be either nitrogen, phosphorus or silica. The N:P:Si ratios of the annual nutrient flux delivered by the Seine river appear to be good indicators of this limitation, silicon being the limiting element when either the Si:P or the Si:N ratio is, respectively, lower than 15 or 0.3 (mol:mol). On the other hand, when silica is not limiting, either phosphorus or nitrogen is the limiting nutrient according as the value of the molar N:P ratio is higher or lower than 50. Exactly the same conclusions are reached from the observations of the N:P:Si ratios of the nutrient flux delivered for example in April, when the diatom bloom generally occurs. The fact that these thresholds differ significantly from the conventional Redfield ratios is not surprising, in view of the complexity of the interactions between nutrient river delivery and utilization by phytoplankton in the production plume area. The annual production of diatoms, calculated for each scenario by integration over the Seine plume area, obeys an increasing relationship when plotted against the annual flux of limiting nutrient (either N, P or Si) delivered by the Seine, expressed in terms of equivalent carbon, according to the Redfield ratios (Fig. 8).

Concerning flagellate development, the molar ratios of the nutrient fluxes delivered during the summer months (July–September) appears as a good indicator of the limiting nutrient of flagellates growth, with N being the limiting one below a N:P ratio of about 22, phosphorus above this threshold. When the maximum flagellates biomass reached within the Seine plume area in each scenario is plotted against the Si:N ratio (for N limited blooms) or against the Si:P ratio (for P limited blooms) in the summer nutrient flux delivered (Fig. 9), it is seen that significant development only occurs for molar Si:N below 1, or for Si:P below 20. In Fig. 10, the maximum flagellates biomass reached in each scenario has been plotted against the mean daily summer flux of limiting nutrient (either N or P) in excess over

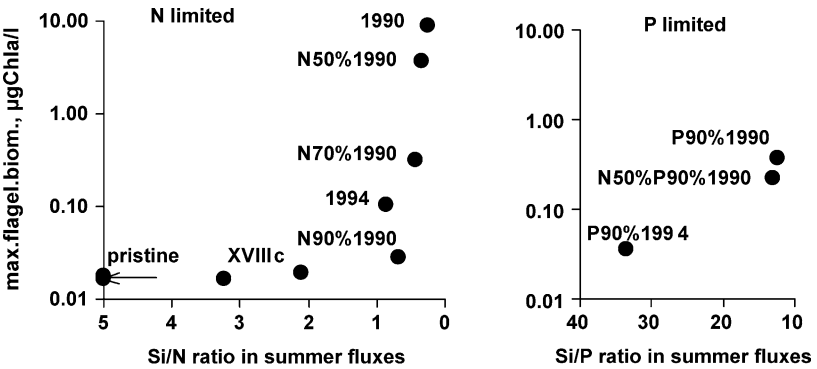

Fig. 9. Maximum flagellate biomass developed over the Seine plume area (see Fig.1) plotted against the Si/N or Si/P ratio in the summer nutrient flux delivered by the Seine river.

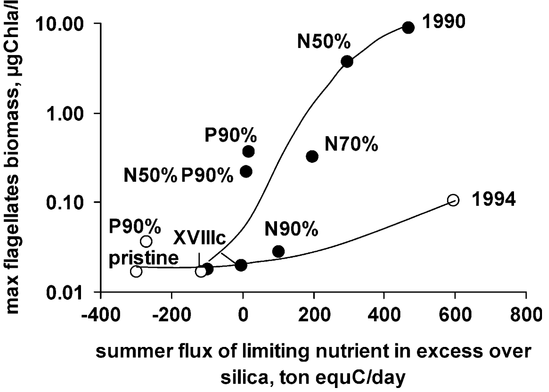

Fig. 10. Maximum flagellate biomass developed in the Seine plume area (see Fig. 1) plotted against the flux of limiting nutrient (either N or P) delivered by the Seine river during summer months in excess over the silica flux, according to the Redfield ratios. Closed symbols refer to scenarios calculated with hydrological and meteorological conditions corresponding to the dry year 1990, while open symbols refers to situations calculated with the conditions of the wet year 1994.

the silica flux according to the Redfield ratios. A general increasing trend is apparent. However, the existence of two distinct relationships for situations calculated with the 1990 and 1994 hydrological and meteorological conditions, shows that the fluxes of nutrient delivered are not the only factors involved in controlling the biomass of flagellates blooms. As indicated above, the climatic conditions, including temperature and incident light intensity, are indeed different between 1990 and 1994.

## 7. Conclusion

The modelling chain resulting from a river model coupled to a coastal ecosystem model represents a powerful tool to study several hypotheses of river basin management and their impact on the marine ecosystem. It provides a better understanding of how human activities in the watershed govern the functioning of the river–estuary–coastal sea continuum.

In the past scenarios (pristine and 18th century), nitrogen seems to have been the main limiting factor for phytoplankton blooms at their maximum of biomass. Silicon was largely in excess, even in the 18th century scenario. Thus, in the past, the Seine Bight seems not to have been a favourable place for flagellate development. Nevertheless, it was already a productive area with intense diatom blooms (Fig. 7).

In the present time, the increased phosphorus and nitrogen inputs cause silicon to be the main limiting factor for diatom production, favouring flagellate summer blooms which use the nitrogen and phosphorus left over after diatoms have depleted silica. The recent decreasing trend of phosphorus inputs from domestic and industrial sources (Billen et al., 2001; Garnier et al., 2005) and the availability of simple and relatively unexpensive technology for phosphorus treatment of wastewater, could well lead in the future to the restoration of a situation of silicon excess in the Seine Bight, with a shift of the ecosystem from silica and nitrogen to a general phosphorus limitation. In this case, however, nitrogen would remain in far excess over silica, and would be exported to surrounding marine areas.

Reducing nitrogen from wastewater is technically possible but more expensive than phosphorus treatment. The easily reached 50% abatement of point sources would not lead to significant improvement of the system in terms of flagellate blooms reduction. More effective nitrogen reduction from urban wastewater, up to 90% elimination, is possible but at much higher cost. Only such a treatment, however, would lead the trophic state of the Seine Bight back to levels of flagellate development comparable to that of pre-industrial periods (Fig. 7).

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