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Nutrient transfer in three contrasting NW European watersheds: The Seine, Somme, and Scheldt Rivers. A comparative application of the Seneque/Riverstrahler model

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ABSTRACT

An understanding of the ecological functioning of an aquatic continuum on a multi-regional scale relies on the ability to collect suitable descriptive information. Here, the deterministic Seneque/Riverstrahler model, linking biogeochemistry with the constraints set by geomorphology and anthropogenic activities, was fully implemented to study the Seine, Somme, and Scheldt Rivers. Reasonable agreement was found between calculated and observed nutrient fluxes for both seasonal and inter-annual variations along the networks. Nutrient budgets underline: i) a clear partition of diffuse and point sources with respect to the specific activities of the watersheds, ii) the importance of riparian retention, responsible for 25–50% of nitrogen retention, iii) the role played by benthic processes, resulting in the retention of up to 45% of the phosphorus and 35% of the silica entering the river systems. Nutrient ratios confirmed that fluxes to the Eastern Southern Bight of the North Sea are imbalanced, supporting the potential for undesirable algal blooms.

1. Introduction

Several studies have emphasized the effect of nutrient delivery from river basins on eutrophication at the coastal zone (Billen and Garnier, 1997, 2007; Conley, 2000; Lancelot et al., 2005; Officer and Ryther, 1980; Turner et al., 1998; and many others). In the last 50 years, the river loads of phosphorus and nitrogen have dramatically increased while the silica input has remained rather stable and even decreased with damming (Billen and Garnier, 1997; Garnier et al., 1999b; Humborg et al., 2000, 2006; Sferratore et al., 2008). Concomitant signs of coastal eutrophication in several places worldwide have been reported as in Northern Europe (Cugier et al., 2005; Lancelot et al., 2005), North America (Jaworski et al., 1992; Turner and Rabalais, 1994) or Adriatic (Justic et al., 1995; Marchetti et al., 1989).

The continental coastal zone of the Channel and Southern Bight of the North Sea offers the example of an area where ecological functioning has been strongly affected by coastal eutrophication during several decades, despite huge efforts in the last few years to improve the treatment of polluted effluents in wastewater treatment plants, as required by the European Water Framework Directive (WFD, 2000). The French and Belgium costal zones are currently described as a ‘‘problem area’’ with regard to nutrient enrichment and eutrophication (OSPAR, 2005). Consequently, studies of the

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biogeochemical functioning of the major delivering river systems are needed to assess the transfer and retention of biogenic elements along the entire drainage networks to the sea.

The Riverstrahler model (Billen et al., 1994) associated with a GIS-based approach (Seneque/Riverstrahler: Ruelland, 2004; Ruelland et al., 2007) is one of the few available tools for an in-depth analysis of any drainage network and was applied to evaluate three major rivers (Seine, Somme, and Scheldt, here called ‘‘3S’’) that discharge into the Eastern Channel and Southern Bight of the North Sea (Fig. 1a).

Within this multi-regional area and its trans-boundaries watersheds (France, Belgium, Netherlands), population density, land use, human activities and agricultural practices differ widely but their combined intensities have led to important enrichments of the surface water in nitrogen and phosphorus and in significant alterations of the ratios between those two nutrients and silica. Nutrients exported to the coastal zone are necessary for algal primary production, but an imbalance of these fluxes promotes the growth of undesirable or harmful algae, causing eutrophication.

We first briefly present the newly developed Seneque software, used in this study to implement spatially the Riverstrahler model in direct linkage with broad GIS-databases. Then we describe the contrasting landscapes of the 3S in terms of urbanization, agriculture, morphology of the drainage network, and impoundment of artificial reservoirs, each of which being factors that has direct consequences on nutrient emission, transport, and retention. Specific properties of the basins of the Seine, Somme, and Scheldt Rivers are considered in terms of hydrologic regimes, non-point nutrient sources, and urban discharge of wastewaters. Since our model is based on a deterministic approach, with all parameters set *a priori* without any calibration step, except for the hydrology, a major challenge was the comparison between the simulation results of biochemical water quality variables and available observations. In being able to do so, we were able to validate our understanding of the basic processes taken into account herein and to test the coherence of the input data. Moreover, the results obtained for recent and contrasted hydrological years enabled us to calculate the budgets of nitrogen, phosphorus, and silica cycling. A major emphasis of the discussion is put on the N:P:Si ratios of the fluxes exported to the sea and their potential for supporting the growth of undesirable or harmful algae at the French and Belgium coastal zones.

2. Study site and modeling approach

2.1. *The Riverstrahler approach*

The aim of the deterministic Riverstrahler model is to simulate the impact of human activities on the quality of river systems by describing the kinetics of all microscopic processes occurring within drainage networks. Accordingly, the drainage network of any river system is considered as a combination of basins, idealized as a regular scheme of confluent tributaries of increasing stream order (Strahler, 1957), each characterized by mean morphologic properties and connected to branches represented with higher spatial resolution. The advantage of this representation of the

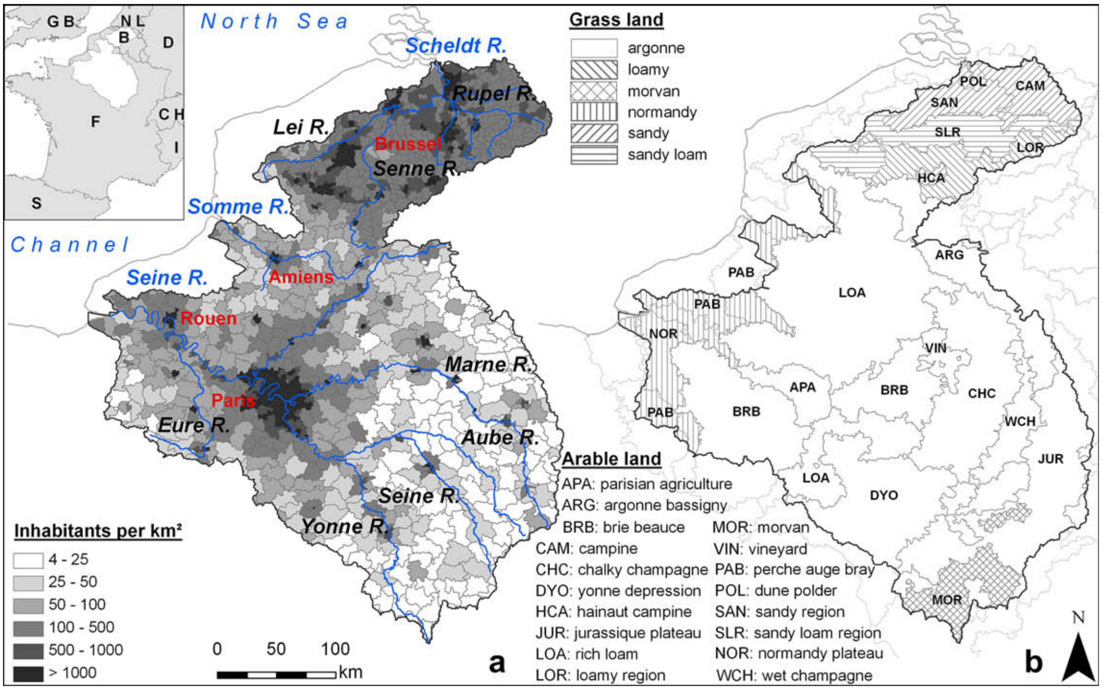

Fig. 1 – (a) General map of the Seine, Somme, and Scheldt Rivers, indicating the main tributaries (blue) and urban centers (red). Population density (inhab km^{-2}) is symbolized in gray graduation levels. (b) Homogeneous agricultural zones used for a spatial segmentation of arable land and grassland. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

drainage network is that the processes occurring in small first-order streams, headwater streams, and large tributaries can all be taken into account.

The model couples water flows routed through the defined structures of basins and branches with a description of the biological, microbiological, and physicochemical processes occurring within the water masses. The variables comprise nutrients, oxygen, suspended matter, dissolved and particulate non-living organic carbon, as well as algal, bacterial, and zooplankton biomasses. Most of the processes important in the transformation, elimination, and/or immobilization of nutrients during their transfer within the network of rivers and streams are explicitly calculated, including algal primary production, aerobic and anaerobic organic-matter degradation by planktonic and benthic bacteria, coupled with oxidant consumption and nutrient remineralization, nitrification and denitrification, phosphate reversible adsorption onto suspended matter and subsequent sedimentation, etc. A detailed description of the model and of the parameters used can be found in Garnier and Billen (2002) and, for benthic processes, in Thouvenot et al. (2007). The Riverstrahler model was first developed for the Seine River system in France (Billen and Garnier, 1999; Billen et al., 2001, 1994; Garnier et al., 1995, 2004, 2005a), within the framework of the French interdisciplinary PIREN-Seine program. It has also been applied to the Mosel (France, Germany: Garnier et al., 1999a), Danube (Garnier et al., 2002; Marchetti et al., 1989) and Scheldt (Belgium: Billen et al., 2005) Rivers.

For the 3S study, the implementation of the Riverstrahler, through the generic GIS Seneque interface, has involved in the improvement of both databases' description and software functionalities. Indeed, the Seneque application relies on a wide georeferenced database allowing the exploration of the ecological functioning of rivers with a more accurate spatial resolution, including a description of the drainage network morphology and the exact location of point sources as well as information about the land use, lithology, and fluvial corridors' characteristic of each elementary watershed.

2.2. General description of the three basins

The adjacent drainage basins of the 3S rivers ranging from the North-western spread from North-western France to the Dutch border include the main western part of Belgium, with more than 26,000 km of stream length and an overall 100,000 km^2 watershed area.

The Seine drainage consists of five main tributaries: i) the upper Seine (32,450 km^2) and ii) the Marne River (12,640 km^2) drains the south-eastern part of the basin and joins immediately upstream from Paris, resulting in iii) the 7th-order River Seine, which downstream from Paris receives the effluents of the Paris conurbation and, on its right bank in iv) the 7th-order River Oise (17,330 km^2), which drains the northern part of the basin, while v) the River Eure (7020 km^2) joins the Seine in its lower course at the entrance of its estuarine section. The Scheldt drainage network comprises three main sub-basins, with the upper Scheldt and the River Leie basins (respectively, 8125 and 3850 km^2) originating from France and forming the eastern part of the watershed, whereas the Rupel (6475 km^2) basin collects western tributaries. Surrounded by both the Seine and Scheldt basins, the Somme is the smallest river (6800 km^2).

The distribution of the population and the organization of land use widely differ among the three basins. The Somme basin is dominated by intensive cereal agriculture, which forms the major part of the catchment area. The population density is relatively low (100 inhab/km^2), with only three large urban centers. These are settled in the upper part (Saint-Quentin 60,000 inhab), in the middle part (Amiens 160,000 inhab), and along the downstream canalized part of the drainage network (Abbeville 30,000 inhab). For the Seine basin, the population density is double (nearly 200 inhab/km^2) that of the Somme but mostly concentrated along the downstream part of the main Seine branch (from Paris to Le Havre). The middle part of the basin is one of the most intensive agricultural areas in the world, dedicated to the mass production of cereal and industrial crops. Animal farming is highly developed and mainly concentrated in the western and eastern peripheries of the basin. The Scheldt basin is densely populated, with more than 400 inhab/km^2. The Brussels conurbation, drained by the Senne, Dyle, and Rupel Rivers, represents a major attractive pole, with more than 2 million inhab, as is the case for the upstream southern part of the basin grouping the cities of Lille, Tourcoing, Roubaix (in France), and Mons (in Belgium). The area drained by both the Scheldt and Rupel Rivers, which join in Antwerp, is another main urban center with significant industrial activity. Except in the southern part, the Scheldt landscape is dominated by urban areas; these prevent widespread and intensive agricultural activities and lead to a mosaic-type landscape, in which agricultural and cropland areas are mixed with surrounding cities. Agriculture is characterized by intensive cattle farming and, especially in the Flemish region, pig breeding.

3. Towards a restitution of the 3S heterogeneity

3.1. Morphology of the drainage network and hydraulic works

The descriptive database required by the Seneque model is organized around a digitalized representation of the hydrological network and its elementary watersheds (i.e., the direct basin of any first-order river or stretches of river between two confluences).

A reliable digital representation of the drainage network was obtained by classical GIS-based treatments (Tarboton et al., 1991) from the Digital Elevation Model (DEM) that covers Europe with a resolution of 90-m grid cells (Shuttle Radar Topographic Mission). However, the downstream part of the Scheldt, with low elevation and a high drainage density, raises problems regarding DEM-derived output accuracy; thus, additional treatments based on drainage enforcement in DEM (Hutchinson, 1989; Saunders, 2000) were required. The slope and length of each stretch of river were calculated, and their mean width was evaluated by the following relationship (Eq. (1)):

$$W = 0.8 * (A_{\mathrm{wshd}})^{1/2} \quad (1)$$

where W is the mean width of a stretch of river (m) and A_{wshd} is the area of its total upstream watershed (km^2). This relationship has been successfully applied to the 3S river ($n = 97$; $r^2 = 0.89$), except in their downstream – and generally enlarged – parts, where navigation needs make this width information directly available.

The distribution of these basic morphological characteristics according to Strahler's stream order (Table 1) highlights the differences between the three basins in terms of size and drainage density. The Scheldt River is characterized by wider streams but also by a lower slope, ranging from 0.002 to 0.001 m/m, respectively, for first and last stream orders.

Land use and population density in the elementary watersheds were calculated using, respectively, the National Statistics Census and the European Corine Land Cover 2000 database (CLC200: Bossard et al., 2000). Regarding the extent of arable land, the Somme basin is clearly dominated by agriculture, which accounts for up to 75% of total land use compared to 52% and 39%, respectively, for the Seine and Scheldt. The Seine sub-basins have the greatest percentage of forest land (25%), proportionally distributed within all its stream orders. The downstream position of the Paris area is marked at the 6th and 7th orders by a shift in population density, whereas urban areas along the Scheldt already occur at smaller orders.

Specific features such as reservoirs connected to main river branches are also taken into account by the model. The Seine has three wide reservoirs; these are localized, respectively, in the upstream part of on the Aube (170×10^6 m^3), Marne (350×10^6 m^3), and Seine (205×10^6 m^3) Rivers. Daily water inflows and outflows provided by the Seine Basin Dam and Reservoir Management Institution (IIBRBS: Institution Inter-départementale des Barrages-Réservoirs de la Seine) were used to calculate the water balance of the reservoirs and the processes affecting the composition of the water released into the rivers. Along the Scheldt, hydraulic works dating back to the XIX century have deeply modified the natural river runoff, e.g. around the city of Gent, where most of the Leie discharge is diverted westwards through the Schipdonk Channel, which joins the North Sea at Heist.

3.2. *Modeling the hydrology of the three basins*

For Hydrostrahler, the hydrologic part of Riverstrahler, daily rainfall and evapotranspiration data are needed to calculate the seasonal variation of base flow and superficial runoff. This partition of runoff is necessary to integrate diffuse sources of nutrients coming from both the soil–root zone and the groundwater. Daily French meteorological data with an 8-km resolution are available from the SAFRAN grid analysis (MétéoFrance); Belgian data are published by the Belgian Royal Meteorological Institute (IRM) and are acquired at five stations (Uccle; Melle; Wasmuel; Koksijde; Chastre–Blaimont) homogeneously distributed and spatially spread over the Scheldt catchments by the Thiessen polygon method (Thiessen, 1911).

The core of Hydrostrahler is a simple rainfall-discharge model comprising two compartments (soil, aquifer) and four adjustable hydrological parameters (soil saturation, soil superficial runoff rate, infiltration rate from the soil to groundwater compartment, and groundwater runoff rate). Automated GIS procedures (see detailed description in Le et al., 2007) have permitted to optimize the adjustment of these parameters over several years of observed daily

Table 1 – Comparison of total and mean (*) morphological, demographic, and land-cover characteristics of the Seine, Somme, and Scheldt drainage networks according to the stream order.

	Number	Length (km)	Width* (m)	Slope* (m/m)	Area km^2	Population density Inhab/km^2	Arable land (%)	Grassland (%)	Forest (%)
Seine	**5163**	**22,402**	**10.6**	**0.0098**	**76,370**	**202**	**52.7**	**10.2**	**25.8**
1 (order)	2594	11,026	2.6	0.0151	39,010	116	55.7	9.6	26.7
2	1263	4965	5.6	0.0062	14,575	133	54.5	11.7	24.3
3	693	3078	12.2	0.0033	9554	170	48.2	13.2	26.4
4	290	1383	22.2	0.0023	4802	149	52.2	12.6	22.3
5	174	977	50.6	0.0014	3899	99	52.7	6.6	25.5
6	115	601	88.9	0.0013	2416	914	39.0	1.8	23.3
7	34	372	203.3	0.0011	2113	1909	21.8	8.0	27.0
Somme	**169**	**712**	**11.4**	**0.0074**	**6190**	**101**	**76.8**	**4.1**	**7.6**
1 (order)	85	207	3.7	0.0130	2898	67	80.7	4.9	6.1
2	48	276	8.3	0.0023	1717	105	76.9	3.2	7.8
3	14	94	16.1	0.0013	611	120	71.4	1.1	13.3
4	22	135	44.8	0.0010	964	181	68.7	5.2	8.2
Scheldt	**446**	**3265**	**20.3**	**0.0020**	**19,860**	**496**	**39.4**	**8.2**	**7.7**
1 (order)	224	1637	5.8	0.0025	12,556	395	43.1	8.3	8.2
2	106	811	12.2	0.0018	3495	567	34.7	9.5	6.2
3	54	370	21.7	0.0011	1873	890	38.3	6.7	9.3
4	45	322	46.2	0.0011	1414	521	31.5	7.2	5.4
5	10	84	77.9	0.0011	358	633	8.5	7.7	5.6
6	7	41	347.2	0.0010	165	1730	4.2	1.0	8.3

discharges. The goal of this calibration step over long time periods is to integrate the delayed response of groundwater, and *in fine* be able to compute the partition between groundwater and superficial runoff for a selection of the sub-basins within the 3S watersheds. Although this method is strongly influenced by the availability and the location of the observed discharge values, it has allowed us to improve Hydrostrahler simulations covering the three basins for a period of seven continuous years (Fig. 2). The low seasonal variability of specific runoff of the Somme River, compared with the other two rivers, is directly related to the chalky nature of the watershed, with a high base flow index, especially during the low-water season. To assess the ecological functioning of the three drainage networks, contrasting hydrologic years have been selected: 1996 as a typical dry year, 2000 as an average year, and 2001 as a wet year. The mean specific runoff calculated for the years 1996 and 2001 showed higher values for the Scheldt (6.3–15.3 l/km^2/s) than for either the Seine (4.8–13.1 l/km^2/s) or the Somme (4–11.8 l/km^2/s), in agreement with the higher rainfall over the former basin.

3.3. *Land use and non-point sources of nutrients*

Diffuse sources of nutrients entering the drainage network are taken into account by associating surface and sub-root water flow components, and by defining each one for yearly mean concentration of nitrogen (nitrate and ammonium), total inorganic phosphorous (TIP), suspended matter (SM), and dissolved silica (DSi). These concentrations are related to different types of land use and the European CLC2000 database has provided an accurate description of the 3S land use area. For some generic land cover classes, such as urban or forest areas – among the highly detailed CLC nomenclature – nutrients diffuse sources are considered respectively homogenous whatever their location within the 3S territory. For these land-use classes, superficial and groundwater concentrations are based on observed values within the Seine basin, and are considered to be valid enough to be transposed to the Somme and the Scheldt. However, for arable land and grassland classes, a further distinction has been made to deal with the diversity of agricultural practices within and between the three basins. French ‘‘small agricultural regions’’ (SAR) and Belgian ‘‘agricultural regions’’ (BAR) have been considered as additional agricultural features as they provide well-documented zoning (Mignolet et al., 2007). Previous work performed on the Seine (Ledoux et al., 2007) basin was used to aggregate the 165 SAR, and the result was merged with that of the BAR to obtain a homogeneous segmentation of the entire territories, which were studied in the form of 18 agricultural areas (Fig. 1b). Within this seamless agricultural landscape, information

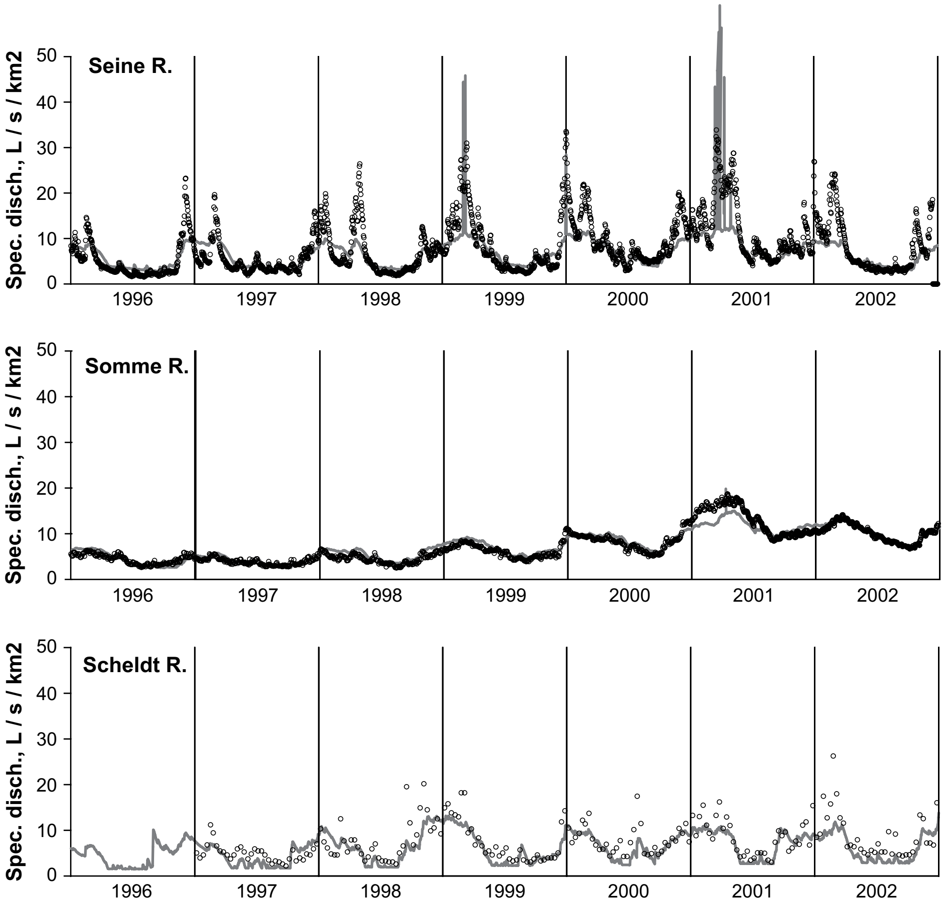

Fig. 2 – Specific runoff calculated (gray line) by the Hydrostrahler model and the observed value (dark circle). The data covered the period between 1996 and 2002 and were obtained at key stations of the Seine (Caudebec), Somme (Cambron) and Scheldt (downstream part of the Dendre affluent).

regarding the spatial variability of diffuse sources was drawn from a compilation of the available literature (see below) and agricultural census (French: Agreste, 2000; Belgium: NIS, 2000) and then used to estimate mean values of nutrient concentrations for sub-root water and groundwater (Table 2).

Regarding suspended matter (SM), previous work on the Seine River (Garnier et al., 2005a) has proposed a relationship between SM in the river at high flow (>20 l/km^2/s, when it best represents the surface runoff composition) and the fraction of arable land in the catchments. This relationship has been retrieved by Billen et al. (2007), who integrate the influence of buffer strip and riparian wetlands on the transfer of particulate matter, and proposed a mean concentration of suspended solids of 350 mg/l in all arable land before any retention. We assigned a mean concentration of 250 mg/l for most of arable lands of the 3S watersheds, and also considered that the susceptibility of soils to be eroded and the types of agricultural practices in use, account for the variation in SM mean load. For this reason we made differences among arable lands, from uncovered soils (e.g. Vineyard: 300 mg/l) to sandy soils (e.g. Campine, Sandy Region: 150 mg/l).

Estimate of diffuse particulate inorganic phosphorous inputs is calculated from the SM inputs based on the exchangeable phosphorous content of soil (cPIP) which differs according to the land use from 0.1 for forest to 1.7 gP/kg for the most intensive breeding area (Normandy grassland), intermediate values (0.7–1.4 gP/kg) being observed in the central area of the Parisian basin (Némery et al., 2005). Associated to this, the dissolved inorganic phosphorus concentration (PO_4) is calculated using the adsorption–desorption equilibrium relationship proposed by Billen et al. (2007):

$$\mathrm{cPIP} = \mathrm{Pac} * \mathrm{PO_4}/(\mathrm{PO_4} + \mathrm{KPads})$$

$$\text{or } \mathrm{PO_4} = \mathrm{cPIP} * \mathrm{KPads}/(\mathrm{Pac} - \mathrm{cPIP}) \tag{2}$$

where Pac = 0.0055 gP/kg (P saturation level) and KPads = 0.7 mgP/l (adsorption half saturation constant).

The ammonium concentration in soil leachate is relatively low (except in urban areas), with a mean of 0.06 mgN/l

Table 2 – Land-use types and corresponding nutrient concentrations in surface and base flows.

	Surface runoff						Base flow					
	NO_3 (mgN/l)	NH_4 (mgN/l)	TIP (mgP/l)	SM (mg/l)	DSi (mgSi/l)	BSi (mgSi/l)	NO_3 (mgN/l)	NH_4 (mgN/l)	TIP (mgP/l)	SM (mg/l)	DSi (mgSi/l)	BSi (mgSi/l)
Urban area	0.7	0.7	0.16	70	3.64	2.52	0.4	0.35	0.13	20	3.64	0.10
Heterogeneous	11	0.05	0.25	200	3.64	1.01	3	0.02	0.12	20	3.64	0.10
Forest	0.4	0.02	0.03	100	3.64	1.01	0.3	0.01	0.02	20	3.64	0.10
Arable land												
Paris agriculture	21	0.05	0.29	250	2.80	3.78	7	0.02	0.12	20	2.80	0.10
Argonne bassigny	14	0.05	0.29	250	1.68	3.78	11	0.02	0.12	20	1.68	0.10
Brie beauce	18	0.05	0.29	250	2.80	3.78	7	0.02	0.12	20	2.80	0.10
Chalky champagne	26	0.05	0.45	150	5.60	1.26	8	0.02	0.26	20	5.60	0.10
Wet champagne	14	0.05	0.29	250	3.36	3.78	11	0.02	0.12	20	3.36	0.10
Yonne depression	14	0.05	0.45	150	2.80	3.78	8	0.02	0.26	20	2.80	0.10
Rich loam	18	0.05	0.29	250	2.80	3.78	11	0.02	0.12	20	2.80	0.10
Morvan	14	0.05	0.29	250	3.92	3.78	11	0.02	0.12	20	3.92	0.10
Perche auge bray	26	0.05	0.59	250	2.80	3.78	8	0.02	0.26	20	2.80	0.10
Jurassic plateau	14	0.05	0.29	250	1.68	3.78	11	0.02	0.12	20	1.68	0.10
Normandy plateau	26	0.05	0.45	150	2.80	3.78	8	0.02	0.26	20	2.80	0.10
Vineyard	4	0.05	0.33	300	5.60	5.04	8	0.02	0.12	20	5.60	0.10
Campine	21	0.42	0.22	150	5.60	2.52	13	0.21	0.12	20	5.60	0.10
Hainaut campine	21	0.42	0.22	150	5.60	2.52	13	0.21	0.12	20	5.60	0.10
Dune polder	18	0.21	0.65	250	5.60	3.78	13	0.11	0.29	20	5.60	0.10
Loamy region	18	0.05	0.29	250	2.80	3.78	11	0.02	0.12	20	2.80	0.10
Sandy region	21	0.14	0.49	150	5.60	2.52	11	0.07	0.29	20	5.60	0.10
Sandy loam region	28	0.06	0.25	200	4.20	3.53	11	0.03	0.12	20	4.20	0.10
Grassland												
Sandy loam	4	0.06	0.14	70	4.20	0.35	3	0.03	0.11	20	4.20	0.10
Loamy	3	0.05	0.14	70	2.80	0.35	2	0.02	0.11	20	2.80	0.10
Sandy	5	0.14	0.37	70	5.60	0.35	4	0.07	0.29	20	5.60	0.10
Argonne	3	0.04	0.14	70	1.68	0.35	2	0.02	0.11	20	1.68	0.10
Morvan	2	0.03	0.14	70	3.92	0.35	2	0.01	0.11	20	3.92	0.10
Normandy	4	0.04	0.33	70	2.80	0.35	8	0.02	0.26	20	2.80	0.10

for arable land, where bacterial activity rapidly oxydises ammonium into nitrate and where adsorption prevents intense leaching. However, the exchange capacity of organic or sandy soil, as in the Belgian sandy agricultural region of Campine is low, yielding to a higher concentration of ammonium in leachate (0.14–0.42 mgN/l) as noted by De Becker (1986).

The greatest heterogeneity between agricultural practices and land use concerns nitrate contamination of superficial and base-flow runoff. For surface water, data from lysimetric (Ballif et al., 1996; Bonniface, 1996) or suction-cup experiments (Benoît et al., 1995) as well as results from nitrogen-transfer calculations (Lixim, Beaudoin et al., 2005) or agronomical models (STICS, Ducharne et al., 2007) have been used for the French part while in Belgium specific measurements in the Scheldt, as reported by Billen et al. (2005) and De Becker et al. (1984), were used to estimate the yearly mean value of nitrate in surface water. The latter yielded in-stream measurement values, with a mean 50% of riparian retention used to define the nitrate leaching value.

Nitrate concentrations in groundwater, resulting from infiltration and phreatic circulation together with long residence times, were determined from an inventory of aquifer compositions. Available observations (ADES, 2003) or model results (Viavattene, 2006) reported lower concentrations of nitrate in groundwater than in sub-root water since the two components are not yet in equilibrium following the recent intensification of agricultural practices, which have affected both surface and sub-root water. The Riverstrahler model also takes into account a calibrated term for riparian retention, since it influences the nutrient composition of sub-root water and groundwater flow from the watershed before the nutrients enter the surface water (Billen and Garnier, 1999; Sebilo et al., 2003).

Regarding their structural definition, the agronomical units (SAR aggregation and BAR) take into account lithological information and allowed us to associate a dominant parent material within each unit. According to the previous works by Meybeck (1986) and Garnier et al. (2005b), dissolved silica concentrations, mostly resulting from rock weathering, have been defined for each type of soil/rock and transposed according to the scales of the different agronomical units. At this stage, the model does not take into account the potential influence of soil cover or other interactions with terrestrial vegetation, both of which might alter dissolved silica release. Biogenic forms of silica (BSi, from phytoliths erosion) were calculated on the basis of SM load, with a mean content of 4.9 mgSi g^{-1}, as observed in soils and winter suspended matter in the Seine catchments by Sferratore et al. (2006).

3.4. *Wastewater point sources*

Point sources were taken into account as a mean daily amount of SM, organic matter, phosphorus, and the various forms of nitrogen discharged into surface water as urban wastewater. The present study focused on the recent period (1996–2002), with a total of 2216 domestic wastewater release points (for the year 2000). The data were gathered with the help of the Artois–Picardie and Seine Normandy Water Agencies for France and the upper Scheldt; for the Belgian Scheldt, data were provided by the SPGE (Société Publique de Gestion de l'Eau) and the VMM (Vlaamse Milieu Maatschapij), respectively, for the Walloon and Flemish regions. For each discharge point, the exact location was assigned and daily fluxes calculated based on per-capita emission, according to the nature of the performed treatment (including the absence of any treatment) and the effective capacity (in terms of inhabitant-equivalent) (Table 3). These discharged values were determined on a sample of water purification treatment observed on the Seine basin (Garnier et al., 2006; Servais et al., 1999) and assumed to be widely applicable to the 3S WWTPs. Dissolved and biogenic silica releases refer to the values quoted by Sferratore et al. (2006) and remained unchanged irrespective of the treatment plant.

Organization of population densities within the Seine basins leads to a highly contrasted distribution of point sources. First-order rivers, which drain more than 50% of the catchment areas, receive only 8.5% of the total wastewater

Table 3 – Identification of the main water treatments for the three basins, effective treatment capacity as integrated by the Riverstrahler model, and corresponding per-capita values for the main components of the effluents (SM: suspended matter; OM: organic matter; NO_3: nitrate; NH_4: ammonium; PO_4: phosphate; DSi: dissolved silica; BSi: particulate biogenic silica).

	Effective treatment capacity (inhabitant-equivalents × 1000)			SM (g/inhab/d)	OM (gC/inhab/d)	NO_3 (gN/inhab/d)	NH_4 (gN/inhab/d)	PO_4 (gP/inhab/d)	DSi (gSi/inhab/d)	BSi (gSi/inhab/d)
	Seine	Somme	Scheldt							
Lagooning	144	8	81	4	1.8	5	4	0.7	0.3	0.5
Biological treatment (Bt.)	8417	271	1393	10	4	0.1	8	1.6	0.3	0.5
Bt. + Dephosphatation (Dpho.)	–	–	1376	8	3	0.1	8	0.2	0.3	0.5
Bt. + Nitrification (Nit.)	4539	–	57	8	2.4	8	2	1.7	0.3	0.5
Bt. + Nit. + Dpho.	32	–	251	8	2.4	8	2	0.2	0.3	0.5
Bt. + Nit. + Denitrification (Dnit.)	1732	46	610	8	2	4	1	1.7	0.3	0.5
Bt. + Nit. + Dnit. + Dpho.	2495	93	1059	8	2	4	1	0.2	0.3	0.5
Other treatments	1038	–	42	–	–	–	–	–	–	–
No treatment	–	–	953	80	24	0	9	1.5	0	0.8

inputs, while rivers of the highest orders (6 and 7) receive 40% of total wastewater inputs, although their direct watersheds represent less than 6% of the total area. For the Scheldt, population density remains high in the estuarine part and in the surroundings of Antwerp, but rivers with low stream orders (1–3), with important urban poles such as Lille (northern France) or Brussels, constitute the major part (more than 85%) of the total wastewater input. The situation of the Somme basin, where the mean population density is lower (100 inhab/km^2), is also very different; most of the total wastewater (70%) input is injected into the upstream, middle, and downstream parts of the main Somme branch from the only three large urban centers.

Regarding the level of the water treatment efficiency, the Scheldt is a step behind. In spite of an important sewage network, to which 90% of the population is connected, a large portion of urban emissions is released directly into the river, which, in 1995, had only a 35% connection to wastewater treatment plants (Billen et al., 2005). The situation has improved in the last decade and the connection to wastewater treatment plants in recent years is now more than 53% (Scaldit, 2004). The case of the Brussels conurbation is striking, as this large city did not have any wastewater treatment facilities before the Brussels South plant came on line in 2000 and the Brussels North plant in 2006, with respective capacities of 360,000 and 1,100,000 inhabitant-equivalents.

The Riverstrahler model integrates population constraints starting from the collection of household emissions into the sewage network until their release into the river with or without treatment. Difficulties for gathering reliable data on non-treated emissions led us to reconstruct the recent period by considering that, before the date of operation of a wastewater treatment plant, a discharge of non-treated water occurred at the same position, unless the new plant replaced an older one. This analysis was restricted to the most important point source, i.e., with capacities above 20,000 inhabitant-equivalents. It led to an overall estimate for the Scheldt population of a 49% connection to the wastewater treatment plant, in agreement with the official value previously quoted. By contrast, French Water Authorities Databases do not mention any non-treated effluent release for the Seine and the Somme basins.

The collection of information and the construction of the georeferenced database were essential to represent fully the urban discharges over the 3S basins and to ensure the spatial homogeneity of the model inputs in terms of accuracy. However, because of difficulties in acquiring reliable and homogeneous data on pollutant fluxes generated by French industrial activities, only industrial release connected to municipal sewage network was considered for the Somme and the Seine basins, i.e., excluding industries equipped with their own treatment facilities.

4. Simulated and observed surface water qualities

For the three river systems, the Riverstrahler model was run for three different years: 1996 (dry), 2001(wet), and 2000 (hydrologically medium). The year 2000 was also defined as the reference for land-cover information, which was considered unchanged during the study period. Comparisons of simulations with observed values are presented for the last downstream stations to assess the contribution of the entire watershed to nutrient fluxes exported to the sea (Fig. 3). Nitrate concentrations depend mainly on hydrological conditions. A good fit was obtained for the simulations involving the Seine River, while those for the Somme slightly overestimated the seasonal variations of nitrate. The simulations run for the Scheldt underestimated nitrate values systematically in summer, and in a large extent for whole dry year. This discrepancy suggests an underestimation groundwater contribution either in terms of runoff or in terms of nitrate concentration. It also pleads for a too low level of nitrification activities simulated in this part of the Scheldt, with respect the concomitant overestimation of ammonium and oxygen concentrations.

Regarding silica and phytoplankton biomass, in both the Seine and the Scheldt Rivers, the calculated seasonal variations of dissolved silica were in general agreement with available data, showing depletion during periods of intense phytoplankton growth. However, during dry years some of phytoplankton levels were underestimated in the Seine River, but this potential underestimation of nutrient uptake will not affect significantly nutrient concentrations (taking into account the ratios defined by Redfield et al., 1963 for the phytoplankton). No such variations were simulated for the Somme River, and, despite a lack of observations for silica and chlorophyll concentrations at this site, the findings were consistent with the view that intense algal development only occurs in large rivers when the residence time of the water is higher than the dilution factor (Garnier et al., 1995), which does not seem to be the case for the Somme drainage system.

For ammonium and phosphate, seasonal variations are linked with the number of point sources, and concentrations are higher with lower discharge. These trends were correctly simulated by the model, except for the Scheldt in which phosphate levels during low water for the dry year (1996) were overestimated. This discrepancy is partially explained by the major changes that have occurred since 1996 with respect to the treatment of household effluents and to the method implemented to reconstruct the corresponding total untreated load. However, the model reproduced correctly the phosphorus profile of 2000 along the Senne affluent of the Scheldt, which receives two large urban discharges (Fig. 4), and thus justifies the use of the method for more-recent periods. Local analyses of point-source impacts on ammonium and phosphate concentrations were also carried out at the scale of the main branch of the Seine and the Somme Rivers, where the highest population density is found (Fig. 4). This attests to the ability of the Seneque/Riverstrahler model to simulate correctly the impact of urban emissions on river-water quality once a high-resolution dataset with exact positioning of point sources is available.

With the aim of establishing nutrient budgets throughout the entire drainage network, the performance of the model had to be evaluated on the basis of nutrient flux predictions, especially at the outlet of the three basins. "Observed" nutrient fluxes were calculated as the product of discharge-weighted

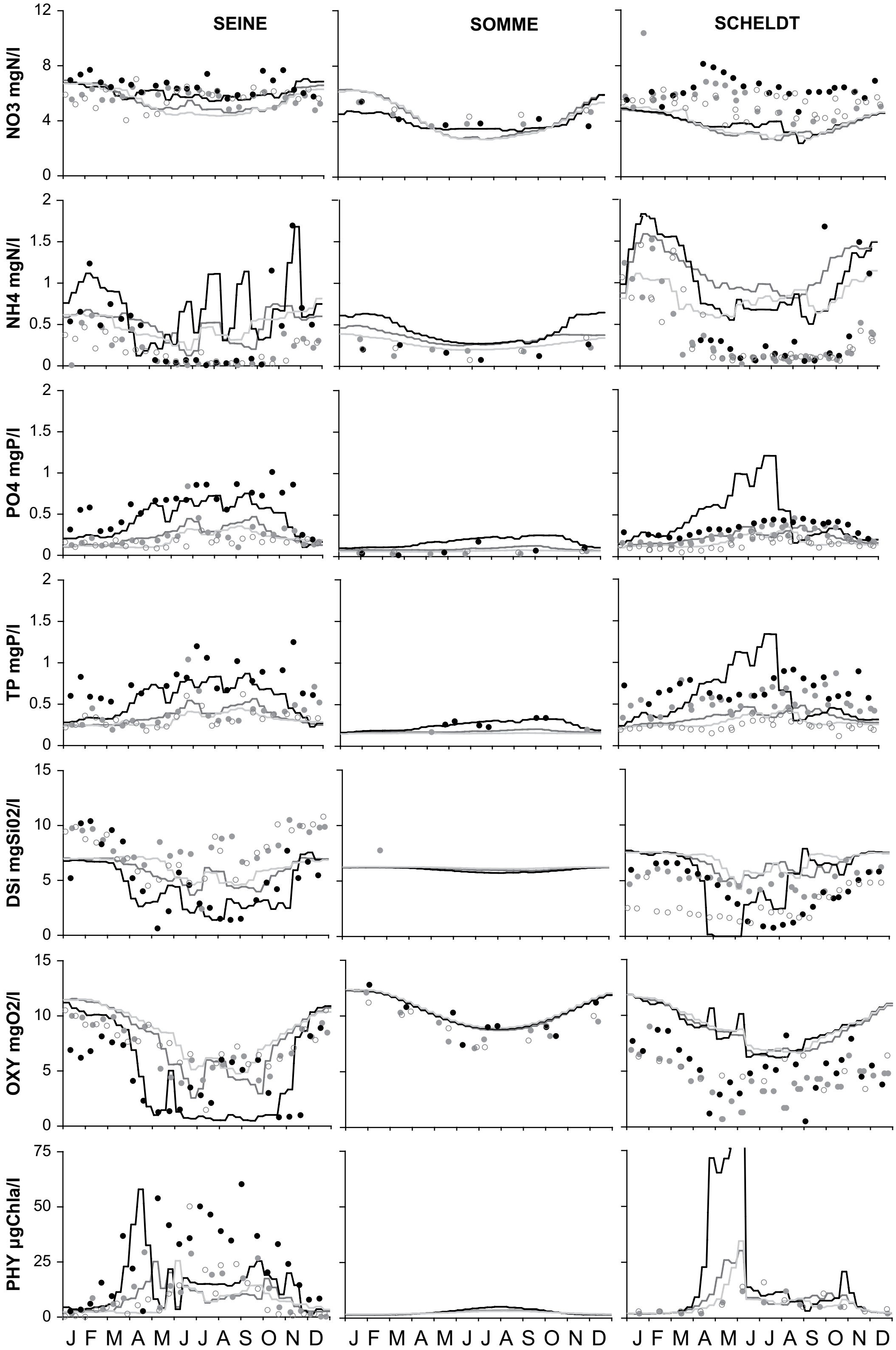

Fig. 3 – Results of simulations (line) and observations (circle) at the downstream stations Caudebec (Seine), Cambron (Somme), and Doel (Scheldt) in the dry year of 1996 (black), the hydrologically medium year 2000 (dark gray) and the wet year 2001 (light gray).

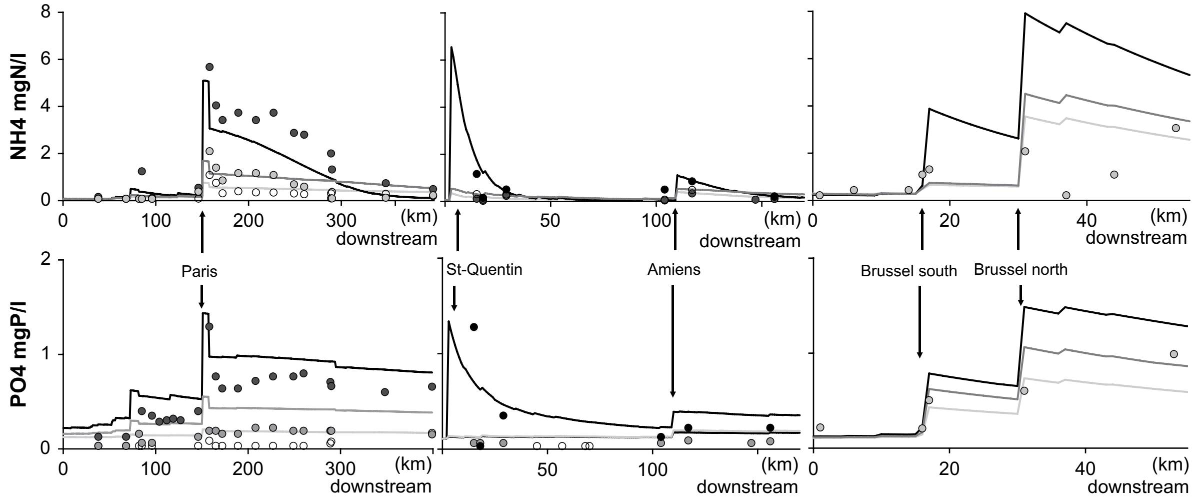

Fig. 4 – Comparison of the simulations (line) made by the Seneque/Riverstrahler model and the observations (circle) along longitudinal profiles in 1996 (black), 2000 (dark gray), and 2001 (light gray). Downstream part of the Seine (left), main axis from the upstream part to the outlet of the Somme (middle), and the Senne affluent of the Scheldt River (right) are shown.

mean measured concentrations and mean discharges, according to the formula (Eq. (3)) recommended by Moatar and Meybeck (2007), at the most downstream stations of the main tributaries of each river system:

$$F = \frac{\sum_{i=1}^{N_s} C_i Q_i}{\sum_{i=1}^{N_s} Q_i} \overline{Q}_r \qquad (3)$$

where C_i and Q_i are, respectively, the instantaneous values of river concentration and discharge at the day of sampling, N_s is the number of samples, and Q_r is the mean annual discharge as evaluated from daily discharge data.

For the sake of comparison, the fluxes were expressed per km^2 of watershed and compared with the values calculated by the model (Fig. 5). Dissolved inorganic nitrogen (DIN) deliveries were correctly predicted, with a clear gradient related to discharge. The difficulties of the Riverstrahler model to simulate correctly the variability of particulate SM (brought in during wet conditions) point out a shortcoming of the model for total phosphorus. Conclusions regarding silica fluxes resulting from rock weathering were acceptable for the three contrasted hydrological years, with a slight underestimate for the wet year.

Heterogeneities in point sources and land-use distributions have led to different types of contamination of the three studied rivers. The Seneque interface of the Riverstrahler model is an optimized tool for assessing the spatial distribution of overall water quality. In the case of ammonium contamination (Fig. 6), the central position of the Paris conurbation in the Seine resulted in a shift of the water quality status from medium (0.4–1.5 mgN-NH_4/l) to very poor (>4 mgN-NH_4/l). In the Scheldt basin, important urban emissions upstream have led to poor water quality (1.5–4 mgN-NH_4/l) starting from small-order streams and sustained in the downstream part by the overall high population density. In the Somme, upstream ammonium released by the St. Quentin wastewater treatment plant is rapidly transformed into nitrate, leading to very good water quality (below 0.08 mgN-NH_4/l) until the conurbation of Amiens, where the quality reverts to medium.

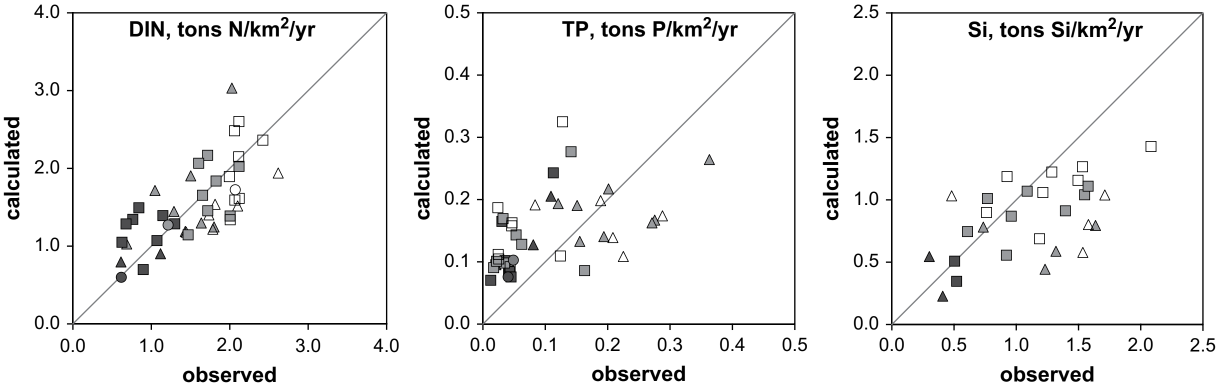

Fig. 5 – Comparison between model results (calculated) and data-based estimated fluxes of nutrients (observed) at several downstream stations of the Seine (square), Somme (circle), and Scheldt (triangle) drainage networks, in the years 1996 (black), 2000 (dark gray), and 2001 (light gray).

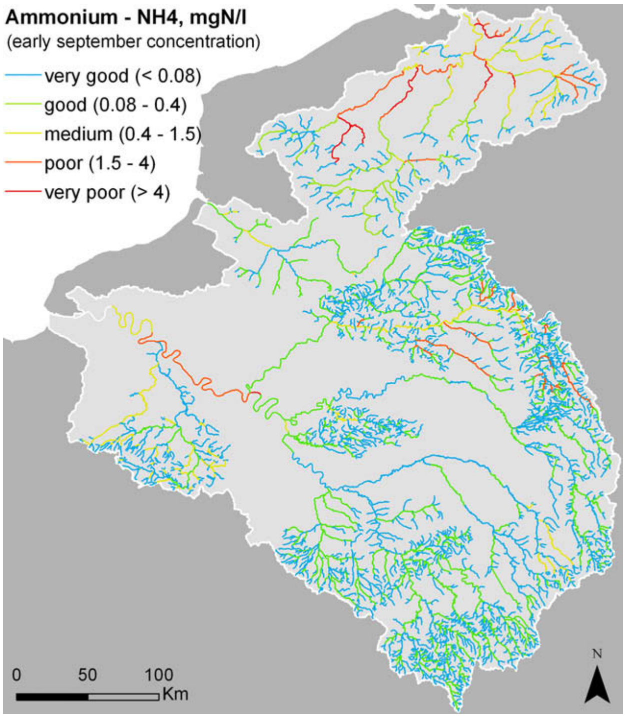

Fig. 6 – Distribution of ammonium concentrations over the three drainage networks beginning in September 2000, as calculated by the Seneque/Riverstrahler model.

5. Computation of N, P, and Si budgets

The deterministic Seneque/Riverstrahler model was used to establish a detailed budget of nutrient transfer and retention on the scale of the entire drainage network. This budget (Table 4) quantified the respective contributions of reservoir, riparian or in-stream benthic retention processes, and the temporary storage of nitrate in aquifers. It also considered the year 2000 for point and non-point sources, as well as the hydrological conditions of the two contrasting years 1996 (dry) and 2001 (wet).

Within the three drainage networks, the Scheldt – with the highest population density and the lowest wastewater treatment efficiency – has proportionally the most important point-source inputs of nitrogen and phosphorus. Within the Somme basin, the dominance of agricultural lands makes urban emissions of nitrogen insignificant (<10%). Even if their respective distributions widely vary, agricultural diffuse sources of nitrogen in the Scheldt are equivalent to those calculated for the Seine, ranging from 2000 to 4000 kgN/km^2/yr depending on the hydrological conditions. Silica production as a by-product of human activities was very low, such that inputs were dominated by diffuse contributions and controlled by hydrological conditions. Phosphorus point and non-point sources were well balanced for the 3S, non-point sources prevailing during dry years and the opposite during wet years.

Outputs from the Scheldt drainage network included those of the Leie tributary diversion, representing 10–15% of N, P, and Si outputs. It was assumed that the corresponding nutrient fluxes are discarded from the Scheldt system at its point of derivation in Gent, and that there is no contribution from any process occurring within the Schipdonck channel.

The processes involved in phosphorus retention are the uptake by planktonic algae followed by immobilization within the sediment as well as the deposition of particulate phosphorus associated to SM having adsorbed dissolved phosphorus released by point sources. The incidence of the latter process increases by high discharge, such that benthic retention during wet years increased for the Seine (34–58 kgP/km^2/yr) and the Somme (9–52 kgP/km^2/yr). Specific benthic retention of phosphorous (61–82 kgP/km^2/yr) and nitrogen (51–81 kgN/km^2/yr) within the Scheldt drainage network was higher than in the two other basins. This contradicts the view that higher retention is generally related to lower specific runoff, as suggested by the comparative study of Behrendt and Opitz (2000), because in this study specific runoff was higher in the Scheldt than in the other basins. However, this may have been related to the morphology of the Scheldt River, whose course is very flat, leading to lower flow velocities and increased sedimentation.

Regarding nitrogen, riparian processes are the most efficient retention mechanism, eliminating 25–50% of total nitrogen inputs, while in-stream processes such as benthic storage in sediments or denitrification contribute 2–10%. Denitrification in the Seine reservoirs is also quite important, with up to 50% removal of incoming nitrogen, i.e., close to the percentage retention based on experimental values (Garnier et al., 1999b). However, this denitrification only affects a small fraction of the river discharge. Temporary storage in aquifers represents a significant part of the apparent retention of nitrogen, with a mean 15% retention of the total nitrogen inputs from the watershed. Among the various processes accounting for nitrogen retention, riparian areas' efficiencies integrate some of the uncertainties about the diffuse sources of nitrate.

The major uptake of dissolved silica is due to diatom blooms during springtime, such that the deposition of biogenic silica in the sediment accounts for the significant 15–30% retention of the total inputs.

Nutrient fluxes exported to the sea integrate the impact of hydrologic conditions, the respective importance of point and non-point sources, and the retention processes occurring within the drainage network, all of which, in turn, affect the ratio between nitrogen, phosphorus, and silica. Analyses of mean annual fluxes delivered to the coastal zone showed that Si/N and Si/P ratios are systematically below the requirements of diatoms, based on the Redfield ratios, except for the Somme during wet conditions (Table 4). This means that nitrogen and phosphorus are delivered in excess over silica. Intensification of agricultural practices and the recent prohibition of polyphosphates in washing powders have contributed to increase greatly the N/P ratio. Consequently, coastal marine phytoplankton production is now mainly controlled by phosphorus, which is the limiting nutrient at the outlet of the three basins. This nutrient imbalance at the coastal zone could promote the development of non-siliceous algae, with subsequent blooms having the negative impact of eutrophication (Billen and Garnier, 1997; Cugier et al., 2005; Lancelot et al., 2007). Based on nutrient fluxes and Redfield ratios, Billen and Garnier (2007) introduced the ICEP (indicator of coastal eutrophication

Table 4 – N, P, Si transfer budgets calculated by the Riverstrahler model and ratios of the nutrients delivered yearly at the outlets of the Seine, Somme, and Scheldt Rivers, for wet and dry conditions.

Yearly hydrological conditions	Seine				Somme				Scheldt			
	dry		wet		dry		wet		dry		wet	
Nitrogen, $kgN/km^2/yr$ (%)												
Inputs												
Diffuse sources	1970	*(78.1)*	3961	*(87.7)*	1838	*(90.8)*	5571	*(96.8)*	1583	*(61.0)*	3087	*(75.3)*
Urban point sources	553	*(21.9)*	553	*(12.3)*	186	*(9.2)*	186	*(3.2)*	1013	*(39.0)*	1013	*(24.7)*
Outputs												
Delivery to coastal zone	1378	*(53.7)*	2311	*(51.8)*	639	*(32.2)*	1829	*(31.1)*	985	*(44.0)*	1568	*(40.7)*
Diversion & withdrawals	110	*(4.3)*	107	*(2.4)*	0	*(0.0)*	0	*(0.0)*	228	*(10.2)*	516	*(13.4)*
Storage in groundwaters	356	*(13.9)*	707	*(15.9)*	427	*(21.5)*	877	*(14.9)*	193	*(8.6)*	392	*(10.2)*
Riparian retention	524	*(20.4)*	1161	*(26.0)*	885	*(44.6)*	3072	*(52.2)*	607	*(27.1)*	1167	*(30.3)*
Retention in reservoirs	13	*(0.5)*	40	*(0.9)*	–	–	–	–	–	–	–	–
In-stream benthic denitrification	119	*(4.6)*	65	*(1.5)*	24	*(1.2)*	27	*(0.5)*	174	*(7.8)*	126	*(3.3)*
In-stream retention in sediments	66	*(2.6)*	67	*(1.5)*	11	*(0.6)*	81	*(1.4)*	51	*(2.3)*	81	*(2.1)*
Phosphorus, $kgP/km^2/yr$ (%)												
Inputs												
Diffuse sources	46	*(39.2)*	92	*(56.2)*	20	*(45.7)*	96	*(80.1)*	64	*(39.0)*	117	*(53.8)*
Urban point sources	72	*(60.8)*	72	*(43.8)*	24	*(54.3)*	24	*(19.9)*	101	*(61.0)*	101	*(46.2)*
Outputs												
Delivery to coastal zone	87	*(68.7)*	100	*(61.4)*	31	*(77.9)*	61	*(54.1)*	74	*(49.6)*	96	*(47.8)*
Diversion & withdrawals	5.6	*(4.4)*	4.1	*(2.5)*	–	–	–	–	14.8	*(9.9)*	23.4	*(11.6)*
Retention in reservoirs	0.1	*(0.1)*	0.8	*(0.5)*	–	–	–	–	–	–	–	–
In-stream retention in sediments	34	*(26.8)*	58	*(35.6)*	9	*(22.1)*	52	*(45.9)*	61	*(40.5)*	82	*(40.6)*
Silica, $kgSi/km^2/yr$ (%)												
Inputs												
Diffuse sources	861	*(94.3)*	1688	*(97.0)*	445	*(95.8)*	1645	*(98.8)*	1027	*(91.8)*	1891	*(95.4)*
Urban point sources	52	*(5.7)*	52	*(3.0)*	20	*(4.2)*	20	*(1.2)*	91	*(8.2)*	91	*(4.6)*
Outputs												
Delivery to coastal zone	525	*(60.5)*	1143	*(62.1)*	363	*(84.0)*	1140	*(66.0)*	636	*(59.5)*	1157	*(56.9)*
Diversion & withdrawals	50	*(5.7)*	58	*(3.2)*	–	–	–	–	113	*(10.6)*	315	*(15.5)*
Retention in reservoirs	6	*(0.7)*	23	*(1.3)*	–	–	–	–	–	–	–	–
In-stream retention in sediments	287	*(33.1)*	615	*(33.4)*	69	*(16.0)*	588	*(34.0)*	319	*(29.9)*	561	*(27.6)*
Nutrients ratios (molar)												
N/P (Redfield ratio = 16)	35.0		51.0		45.4		66.5		30.1		38.7	
Si/N (Redfield ratio = 1)	0.2		0.2		0.3		0.3		0.3		0.4	
Si/P (Redfield ratio = 20)	6.7		12.6		12.9		20.7		9.3		13.7	
Limiting element (P or N)	P		P		P		P		P		P	
ICEP indicator, $kgC/km^2/d$	6.5		4.2		1.2		–0.2		5.4		4.3	

potential), which, as shown in the following equation (Eq. (4)), expresses the potential for new production of non-siliceous algae sustained by riverine deliveries:

$$\mathrm{ICEP} = [\mathrm{NFlx}/(14*16) - \mathrm{SiFlx}/(28*20)]*106*12 \quad \text{if N/P} < 16 (\text{N limiting})$$

$$\mathrm{ICEP} = [\mathrm{PFlx}/31 - \mathrm{SiFlx}/(28*20)]*106*12 \quad \text{if N/P} > 16 (\text{P limiting}) \tag{4}$$

where ICEP is expressed as carbon per day ($kgC/km^2/d$), PFlx, NFlx, and SiFlx are, respectively, the mean specific fluxes of total nitrogen, total phosphorous, and dissolved silica (expressed as $kgP/km^2/d$, $kgN/km^2/d$, and $kgSi/km^2/d$) delivered at the outlet of the river basin.

A negative ICEP value, as for the Somme (–0.2 $kgC/km^2/d$) during wet conditions, indicated that silica was present in excess over the limiting element (P); i.e., there was no "potential" eutrophication problem. On the contrary, positive values indicated that the amount of phosphorus (limiting nutrient) was in excess of the requirements for diatom growth, possibly leading to the development of non-siliceous algae, which are often responsible for harmful blooms. Wet conditions provide a trusty assessment of ICEP values that have been calculated from both model observations ($ICEP_{Seine} = 4.2$; $ICEP_{Scheldt} = 5.4\ kgC/km^2/d$) and observed nutrient fluxes ($ICEP_{Seine} = 4.0$; $ICEP_{Scheldt} = 3.6\ kgC/km^2/d$). During dry years ICEP values (observation: $ICEP_{Seine} = 6.5$; $ICEP_{Scheldt} = 4.4\ kgC/km^2/d$) tend to increase as nitrogen fluxes are reduced. This trend is well reproduced but affected by the underestimated TP simulations that lead to high ICEP value (simulation: $ICEP_{Seine} = 11$; $ICEP_{Scheldt} = 13\ kgC/km^2/d$) especially on the Scheldt.

Billen and Garnier (2007) have proposed to calculate the ICEP for a number of rivers from different climatic regions of the world and for different time periods. Among these rivers, most of the temperate European and North American rivers have a positive value of ICEP and are known to suffer from eutrophication problem in their coastal areas. As for example the Gulf of Mexico under the influence of the Mississippi River or the North Adriatic Sea dominated by the inflow of the Po River with respectively ICEP values of 2 and 3.

6. Conclusions

Implementation of the Riverstrahler model has led to a comprehensive description of the ecological functioning of the Seine, Somme, and Scheldt Rivers' systems.

- The assumption of process unity throughout the three drainage networks and the complete control of nutrient fluxes by morphological or anthropogenic constraints, provides an elegant and reliable deterministic approach.
- For the first time, the ability of the model to calculate a consistent and conservative budget of nutrient transfer and retention based on detailed calculations of all in-stream processes, has been demonstrated (with a mean of less than 5% discrepancy between total input and total calculated output).
- The calculated imbalance of N,P and Si exports from the three watersheds has highlighted their potential to sustain the development of harmful algae in receiving coastal and marine areas.

As presently validated, the model – in its spatially implemented version (Seneque) – offers an optimized tool to explicitly assess the impact of any change in human activity and to investigate management scenarios for recovering well-balanced nutrient deliveries along the French and Belgian coastal zones.

Acknowledgements

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