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Subregional and downscaled global scenarios of nutrient transfer in river basins: Seine-Somme-Scheldt case study

Vincent Thieu,¹ Emilio Mayorga,² Gilles Billen,^{1,3} and Josette Garnier^{1,3}

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[1] In an attempt to downscale the global prospective scenarios established by the Millennium Ecosystem Assessment to the level of three individual watersheds (the Seine, Somme, and Scheldt rivers), we examined the application of the regional RIVERSTRAHLER model, based on a mechanistic representation of in-stream processes, in tandem with the semiempirical Global Nutrient Export from Watersheds (NEWS) model, by downscaling the input data of the latter into information required by the former. Overall, the model simulates the major trends of the changes that occurred in 1970–2000, although with some discrepancies revealing the weakness of certain hypothesis in the global approach. For the future, the prediction is a significant decrease in total nitrogen and phosphorus fluxes into the sea compared to those of 2000. We showed the benefits of combining a process-based approach of nutrient transfer at the local scale with the use of global-scale models for integrating the development of socioeconomic driving forces acting at the global level.

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1. Introduction

[2] In many places in the world, eutrophication has become a major problem affecting large estuaries [Cugier *et al.*, 2005; Turner and Rabalais, 1994], coastal bays (e.g., Chesapeake [Jaworski *et al.*, 1992] and San Francisco [Cloern, 1996] bays), and open coastal areas (e.g., the continental coastal water of the North Sea [Lancelot *et al.*, 2005, 2007]). One of the primary controls of eutrophication is the nutrient levels, especially nitrogen (N), phosphorus (P), and silica (Si), as the amount and the ratio of these elements are key factors determining algal development [Billen and Garnier, 2007; Officer and Ryther, 1980]. Together with a high concentration of human activity along the seashore, the nutrient load issued from human activity within the watershed and discharged by large river systems into coastal bodies of water is also at the origin of environmental deterioration of marine ecosystems. Consequently, the concerns of policy-makers involved in integrated water management have evolved from local analyses of human activities and their proximate impact on river systems to a more consistent regional approach at the basin scale [Kronvang *et al.*, 1999; Wolf *et al.*, 2005].

[3] A significant amount of research has been devoted to simulations of nutrient delivery to coastal zones. One of these approaches is the use of empirical models [Alexander *et al.*, 2002; Boyer *et al.*, 2002; Galloway *et al.*, 2003; Green *et al.*, 2004; Howarth *et al.*, 1996; Seitzinger *et al.*, 2002a, 2005] that express nutrient fluvial transport as a function of several explanatory variables, including morphological and hydrological information, indicators of human activities in the watersheds, and including sometimes quantitative components of the nutrient landmass balance. A limitation of this type of model is the availability of sufficient data sets to calibrate the models parameters, although recent improvements in world database accessibility [e.g., Meybeck and Ragu, 1996] make this approach widely transferable to an increasing number of well-documented rivers systems or allow globally applicable calibration based on global river data. Alternatively, mechanistic/deterministic models [Billen *et al.*, 1994; de Wit and Bendricchio, 2001; Everbecq *et al.*, 2001; Whitehead *et al.*, 1998] evaluate the transfer and retention properties of river networks by describing the kinetics of the main processes involved in nutrient dynamics. The robustness of these models relies on their capacity to reproduce observed trends for the variable considered, without the need for a calibration stage.

[4] Both the empirical and the mechanistic model have become more complex in terms of the need to explain (mechanistic approach) or describe (empirical approach) recent changes affecting the ecological functioning of the world's river systems. Indeed, continental aquatic systems originally driven by natural factors have been modified by

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human actions during the last several decades [Vitousek *et al.*, 1997]. Some of these anthropogenic forcings act across the physical boundaries of watersheds and must therefore be analyzed at a larger scale. This is, by definition, the case of societal drivers or even economic globalization but it also includes more global changes affecting any other compartment of the Earth (atmosphere, lithosphere) that interacts with river systems [Meybeck, 2003].

[5] As an alternative to highly complex and uncertain predictions of how the future will evolve, a scenario approach integrates several projections by gathering multiple assumptions within consistent storylines [Verburg *et al.*, 2006]. Along the same lines initiated by the Intergovernmental Panel on Climate Change (IPCC) assessment [IPCC, 2000], the *Millennium Ecosystem Assessment (MEA)* [2005] proposed four scenarios, using storylines that explore aspects of plausible global futures and their implications for ecosystem services (defined as the benefits that people obtain from the environment [MEA, 2005]). These storylines represent a qualitative approach for describing the continental and worldwide dynamics controlling economic, demographic, and even sanitary development. However, the assessment of changes in human activities and their related impact on river basins and coastal ecosystems must be quantitative and include the use of global models. Accordingly, such models have been developed by the Global Nutrient Export from Watersheds (NEWS) working group [Seitzinger *et al.*, 2010] by adapting previous models [Fekete *et al.*, 2002; Netherlands Environmental Assessment Agency (MNP), 2006; Seitzinger *et al.*, 2005] with the aim of (1) translating the MEA storylines into quantitative scenarios, (2) computing nutrient loading of the landscape and of river systems, and (3) using semiempirical models to assess future nutrient river export to coastal ecosystems.

[6] Because of the complexity of the global economic system, prospective scenarios of human activities in watersheds should be conceived at the global level and include regional-scale to global-scale interactions. However, there is also a need to increase the spatial resolution of the simulated scenarios, in order to examine them at a smaller scale, more adapted for management. This can be feasible with subregional, mechanistic models, better able to represent local dynamic processes, providing that they are able to make use of “large-scale scenario” constraints as a background and to improve them by integrating subregional dynamics. Among the several models that describe the ecological functioning of river systems, this study examines the outcome of coupling of the Riverstrahler model [Billen *et al.*, 1994] with global models. Beyond a simple comparison between “global-empirical” and “local-mechanistic” models, our aim was to explore their potential cooperation in order to achieve a refined prediction of the amount of nutrients delivered to the sea at the local to regional scale.

[7] As an extension of the work by Sferratore *et al.* [2005], this work focuses on the case study of the continental coastal waters of the North Sea which are severely affected by eutrophication and examines the contribution of the Seine, Somme, and Scheldt rivers nutrient fluxes. First, the heterogeneity of the three basins is discussed through a downscaled description of their landscapes and human

activities. In the context of a joint modeling approach, the conceptual river system representation by the two models is compared and the sensitivity of the Riverstrahler model to be upscaled into a single basin is tested. The consistency and accuracy of global inputs is then analyzed with respect to a subregional-scale high-resolution database, and a methodology for downscaling the former is proposed. On the basis of the downscaled global input, a mechanistic assessment of nutrient exported to the sea is first validated for the recent period (1970–2000) and then extended to integrate the four scenarios of the MEA. Finally, this approach is used to test the potential impact on river retention of plausible future “inner basin” changes.

2. Study Area

[8] The basins of the Seine, Somme, and Scheldt rivers spreading across France, Belgium, and the Netherlands (Figure 1) are a major source of input for the continental coastal waters of the North Sea [Lacroix *et al.*, 2007]. The three individual watersheds, 6,000 km² for the Somme, 19,800 km² for the Scheldt, and up to 76,000 km² for the Seine, have quite contrasting characteristics. The Somme supports the lowest population density (101 inhabitants km⁻²), and 81% of its area is devoted to farming activities. The Seine, by contrast, flows through large urban areas such that the population density is twofold higher than that along the Somme (200 inhabitants km⁻² on average) whereas agricultural land covers only 63% of the catchment area. With an average population density of 496 inhabitants km⁻², the Scheldt is the most populated system, with less than 50% of its area used for agricultural activities.

[9] Beyond this clear general anthropogenic gradient, the spatial distribution of land use and human settlements as well as the morphological properties within each basin greatly differ. The central Paris conurbation accounts for the majority of the Seine population. Around it, a region of intensive cereal crop is followed at the periphery of the basin by an area of mixed cattle farming. The main subcatchments join in the central part of the basin, where the Seine becomes a seventh-order river. Three large reservoirs (total volume of 750 million m³) have been built to regulate the discharge upstream of the overcrowded Paris conurbation.

[10] The fourth and last order of the Somme is deeply embanked by a chalky zone that crosses almost the entire basin. Dominated by areas of intensive cereal crop cultivation, the river comprises only three major urban centers that act as three main point sources scattered from upstream to downstream.

[11] The Scheldt does not have a similar clear organization; rather, urban areas are spread throughout the basin resulting in a landscape of mixed urban and agricultural activities [Billen *et al.*, 2005]. Two systems that drain important cities (including Lille, in France, and Brussels, in Belgium) join in the very downstream part of the river (30 km from the outlet) to form its sixth order. Low-resolution databases, such as the Simulated Topological Network, with a spatial resolution of 30 min (STN-30) [Vörösmarty *et al.*, 2000], used by NEWS 2 models, do not depict this scheme of stream confluence in flat downstream areas. Accepting that

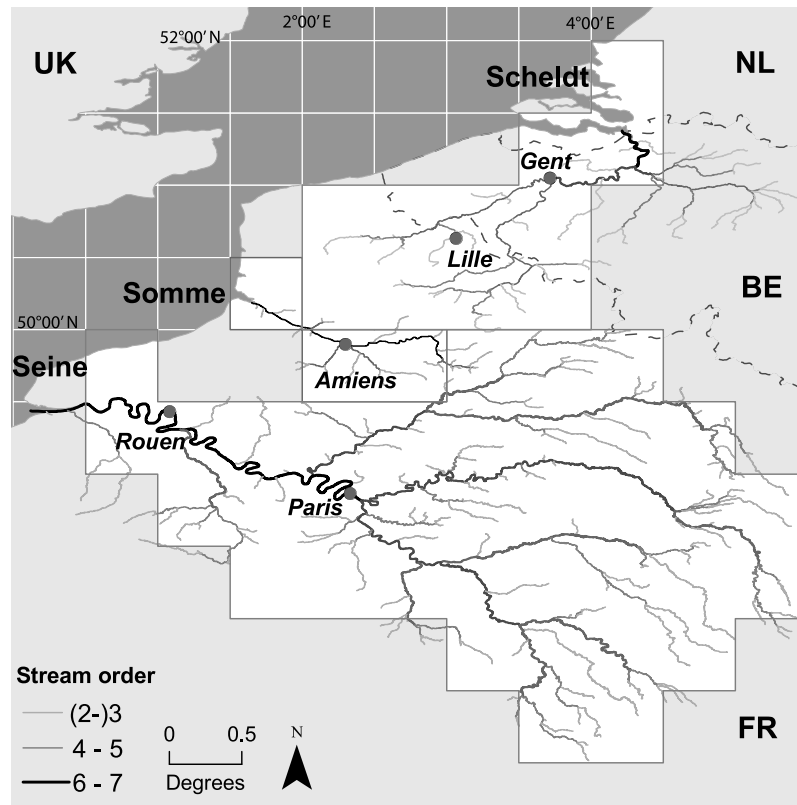


Figure 1. Map of the Seine, Somme, and Scheldt continental aquatic systems, as viewed by the Riverstrahler model (drainage network) and NEWS 2 models (basin scale). The grid size shown ($0.5^\circ \times 0.5^\circ$) represents the elemental unit of the NEWS 2 models.

such local-scale errors are inherent to the use of global data set (unless time consuming local-scale manual corrections are made everywhere), our analysis of the Scheldt River system is therefore limited to its southern part, i.e., the upper Scheldt and Leie rivers, and does not include the area drained by the Rupel affluent.

3. Comparison of the Global NEWS and Riverstrahler Models

3.1. NEWS 2 Watershed Models

[12] The Global NEWS group has elaborated several submodels applied to more than 5000 river basins that simulate annual exports to the sea of different nutrient forms, including dissolved, particulate, organic, and inorganic forms of nitrogen and phosphorus [Beusen *et al.*, 2005; Dumont *et al.*, 2005; Harrison *et al.*, 2005a, 2005b]. For dissolved forms, two main sources of nutrients are distinguished: point sources and diffuse sources. Point sources are related to wastewater flows, primarily in urban areas. Diffuse sources are primarily related to agricultural activities, such as livestock production and fertilized cropland, and to disturbances of natural ecosystems (e.g., atmospheric deposition of anthropogenic nitrogen). The models of dissolved forms, originally independently formulated, have been unified in NEWS 2 [Mayorga *et al.*, 2010] in order to

provide a coherent analysis of nutrient sources and exports from watersheds according to the following general yield equation (1):

$$\begin{aligned} \text{Yld} &= \text{FE}_{\text{riv}} \times (\text{RS}_{\text{dif}} + \text{RS}_{\text{pnt}}) \\ \text{Yld} &= \text{FE}_{\text{riv}} \times [(\text{FE}_{\text{land}} \times \text{WS}_{\text{dif}}) + (\text{FE}_{\text{wwt}} \times \text{WS}_{\text{pnt}})] \end{aligned} \quad (1)$$

where WS_{dif} and WS_{pnt} are diffuse and point watershed sources, respectively, partially emitted to river by the use of export coefficients FE_{land} and FE_{wwt} (with “land” referring to landscape and “wwt” to wastewater treatment). The resulting river sources (RS_{dif} and RS_{pnt}) are exported to the basin’s outlet, using the FE_{riv} export fraction. The latter expresses aquatic or in-stream retention and is determined by basin-scale calibrations and empirical parameterizations based on syntheses from the literature.

[13] Nutrient sources are derived from empirical relationships that take into account population density, per capita gross domestic product, and regional sanitation information for point sources and on the basis of the IMAGE 2.4 [MNP, 2006] model output and regional agricultural information for diffuse sources. The gross watershed sources (WS_{dif} and WS_{pnt}) of nitrogen and phosphorus are assumed to be partially retained in the “landscape” before reaching the river network. This retention affects both diffuse ($1 - \text{FE}_{\text{land}}$) and

Table 1. State Variables and Processes Taken Into Account by the Riverstrahler Model^a

State Variables	Processes
Suspended matter	Sedimentation, resuspension
Phytoplankton (diatoms, nonsiliceous algae)	Photosynthesis, growth, respiration, lysis, sedimentation, erosion
Zooplankton	Grazing, growth, respiration, remineralization and excretion, mortality
Heterotrophic bacteria	Respiration, growth, mortality
Dissolved and particulate organic matter	Degradation (rapid or slow hydrolysis), remineralization
Dissolved oxygen	Photosynthesis, respirations, nitrification, benthic consumption
Ammonium, nitrate	Nitrification, denitrification, uptake, benthic recycling
Nitrifying bacteria	Planktonic nitrification
Organic P and adsorbed inorganic P	Algal uptake, benthic recycling, adsorption-desorption
Dissolved and biogenic silica	Diatoms uptake, biogenic silica dissolution
Fecal bacteria	Mortality

^aAfter *Billen et al.* [1994], *Ruelland et al.* [2007], and *Sferratore et al.* [2005].

point ($1 - FE_{\text{wvt}}$) sources and accounts for the “terrestrial” retention of each nutrient form.

[14] By distinguishing between terrestrial and aquatic retention, NEWS 2 models provide an intermediate level with which to assess the net emission of nutrients (RS_{dif} and RS_{pnt}) after their retention within wastewater treatment, soil, groundwater, and riparian areas and are thus highly compatible with a drainage network approach to river systems.

3.2. Riverstrahler Drainage Network Model

[15] The Riverstrahler model [*Billen et al.*, 1994; *Garnier et al.*, 1999] is based on a comprehensive description of processes occurring within the water column and involved in the transfer and retention of nutrients (Table 1). The model is extended to the entire drainage network, with in-stream transformation and retention processes explicitly calculated at the seasonal scale. The model assumes the system to be controlled by hydrological variations (with a 10 day resolution), morphological, and all land-based constraints, while the process kinetics involved in ecological functioning are assumed to be basically the same along the river continuum (see *Garnier et al.* [2002] for a detailed description). Implementation of the model thus relies on databases that include physical information on the drainage network and an accurate description of point and nonpoint sources as they are geographically distributed within the watersheds.

[16] In contrast to NEWS 2 models, the Riverstrahler model only describes aquatic retention of nutrients, and not the processes occurring in watershed landscapes and soils. However, the role played by riparian areas is explicitly taken into account. Also, the consideration of a lower contamination of aquifers than subroot water when defining the contributions of surface and base flows allows the integration of groundwater retention. However, these terms are not mechanistically described, and they can easily be bypassed, enabling a strict “drainage network description” with an aquatic retention term equivalent to the one considered by NEWS 2 model ($1 - FE_{\text{riv}}$) after terrestrial retention.

[17] Another difference between the NEWS 2 and Riverstrahler models is their spatial resolution. While NEWS 2 semiempirical models consider the watershed in its entirety (as a single feature), the elemental spatial unit of the Riverstrahler model is the incremental watershed area drained

by a river reach between two confluences. Accordingly, these units can be described as a set of river branches with a spatial resolution of 1 km, or they can be aggregated to form upstream basins that are idealized as a regular scheme of tributary confluences [*Strahler*, 1957]. This ability to adapt the spatial resolution of the drainage network is an advantage of the Riverstrahler model over the NEWS 2 approach to whole-river systems, especially when point and diffuse sources are not evenly distributed over the river basins under study. A further difference is the temporal scale. NEWS 2 models have an annual time scale, while the Riverstrahler model describes seasonal nutrient variability based on a 10 day resolution.

3.3. Upscaling the Spatial Resolution of the Drainage Network

[18] As previously shown for subcatchments of the Seine River (Oise River [*Ruelland et al.*, 2007]), in this study the sensitivity of Riverstrahler model simulations to spatial resolution is extensively assessed at the outlet of the Seine, Somme, and Scheldt drainage networks. Three different spatial resolutions were chosen. In the finer representation, all second-order subcatchments were considered as individual basins (i.e., 645 subbasins for the Seine, 30 for the Scheldt, and 24 for the Somme), whereas stream orders greater than three were represented as branches (i.e., 6188 km of streams for the Seine, 530 km for the Scheldt, and 229 km for the Somme). Then, the resolution of the drainage network representation was decreased by analyzing every fourth order as an individual subbasin and by considering the different branches for orders 5 (Scheldt), 6, and 7 (Seine). In the third representation, each of the three river systems was treated as a single basin, as in the NEWS approach.

[19] Dissolved inorganic fluxes of nitrogen (DIN) and phosphorus (DIP) were calculated and compared to observed data for the year 2000 (Figure 2) using high-resolution input data (Table 2). Good agreement between the different simulations with respect to the observed fluxes was found, despite an underestimation of DIP fluxes in the Scheldt. The observed seasonal trends were also correctly simulated. Within the Seine, the higher values of the DIN fluxes for a lower-resolution representation of the drainage network can be explained by the fact that reservoirs (conceptually

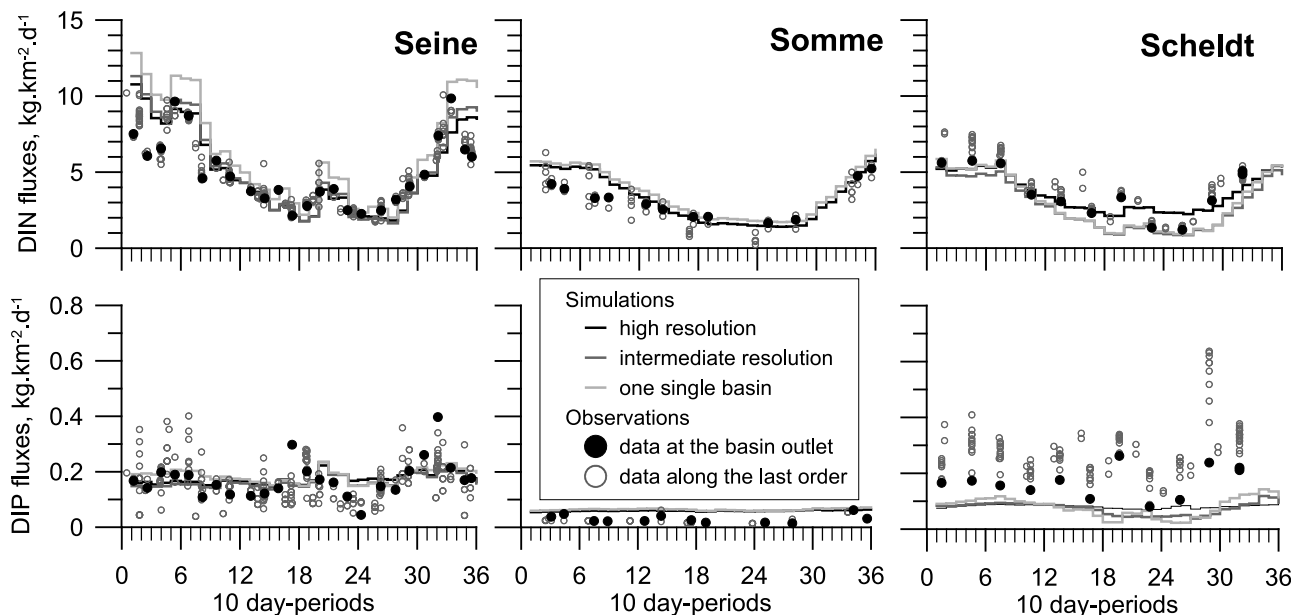


Figure 2. Dissolved inorganic nitrogen (DIN) and phosphorus (DIP) flux exports to the sea, observed (dots) and calculated (line) as determined by the Riverstrahler model according to several representations of the drainage network for the year 2000: (1) high, with the representation of each order 2 subbasin, (2) intermediate, with the representation of each order 4 subbasin, and (3) low, with the representation of the entire drainage network as a single basin.

connected to branches) could not be integrated in a single-basin representation of the drainage network so that their role in nutrient retention cannot be taken into account. Also, both surface and base flows were spatially averaged in the framework of a single-basin representation, thereby eliminating the local disparities and the seasonal variability of the total simulated flows, as observed for DIN and DIP fluxes in the Scheldt.

[20] The reduction in the Riverstrahler model ability to simulate nutrient fluxes with decreasing resolution is relatively small and mainly related to the loss of information subsequent to the generalization of the constraints by order. This degree of resolution is not appropriate to a detailed

exploration of network contamination, but the invariance of the exported fluxes makes this upscaling process robust enough to allow comparison with the annual values provided by the global NEWS 2 models.

4. Consistency of High- and Low-Resolution Input Data

[21] A prerequisite for the subregional use of global input data is the consistency of low- and high-resolution sets of data (Table 2). This aspect was assessed for the three rivers by comparing nutrient exports from the terrestrial part of the watershed to the three river drainage networks, as calculated

Table 2. Detail of the High-Resolution Database Used for the Subregional Assessment of the Seine, Somme, and Scheldt Basins^a

Model Input	Spatial Resolution	Data Sources
Hydrology	8 km (PET and precipitation) Five meteorological stations X, Y location (for gauging stations)	SAFRAN grid, MétéoFrance Belgian Royal Institute of Meteorology Banque hydrologique and Vlaasme Milieu Maatschappij
Morphology	90 m grid cell	Shuttle Radar Topographic Mission (NASA)
Land use	25 ha (minimum surface) Agricultural district (500 km ² in average)	CLC 2000 database (Corine Land Cover, EEA) Farming practices [Mignolet <i>et al.</i> , 2007], Institut National Statistique (Belgian), and Recensement Général Agricole
Population	X, Y location (of sewage release)	Agence de l'Eau Seine Normandie, Agence de l'Eau Artois Picardie, Vlaasme Milieu Maatschappij, and Société Publique Gestion de l'Eau

^aPET, potential evapotranspiration; EEA, European Environmental Agency.

Table 3. Comparison of Nutrient Input to the Seine, Somme, and Scheldt Rivers on the Basis of the High-Resolution Database Integrated Into the Riverstrahler Models and As Provided by the NEWS 2 Models After Landscape Retention for the Years 1970 and 2000^a

	Year	NEWS 2			Riverstrahler		
		Total Sources (kg km ⁻² yr ⁻¹)	Point (%)	Diffuse (%)	Total Sources (kg km ⁻² yr ⁻¹)	Point (%)	Diffuse (%)
Seine							
N	1970	990	47	53	1195	53	47
	2000	1272	35	65	1402	41	59
P	1970	223	90	10	171	83	17
	2000	140	81	19	121	61	39
Somme							
N	1970	-	-	-	-	-	-
	2000	917	26	74	798	23	77
P	1970	-	-	-	-	-	-
	2000	82	74	26	77	31	69
Scheldt							
N	1970	1815	43	57	1448	41	59
	2000	2365	37	63	1976	44	56
P	1970	350	95	5	615	96	4
	2000	236	92	8	184	57	43

^aThe 1970 inputs are derived from *Billen et al.* [2007] for the Seine and from *Billen et al.* [2005] for the Scheldt. For these two rivers, computation of diffuse sources is based on hydrological conditions derived from NEWS 2 (Scheldt) or similar conditions (Seine: 173 mm yr⁻¹ for the dry scenario given by *Billen et al.* [2007]).

on the basis of similar hydrological constraints (see section 5.1). For NEWS 2 models, these fluxes separate diffuse and point sources contribution and represent the gross nutrient input to the river basin multiplied by a calibrated watershed-export coefficient (see equation (1)). For the Riverstrahler model they correspond to the net quantity reaching the river bank, once both riparian and groundwater retention are subtracted, while point sources contribution is directly accounted.

[22] The results for nitrogen and phosphorus are remarkably comparable (Table 3). They reproduce the gradient of anthropogenic inputs from the Scheldt to the Seine and finally the less populated Somme river basin and depict the major changes (increase of N input and decrease of P input) that occurred from 1970 to 2000. Moreover, the respective contributions of point and nonpoint sources are correctly represented for nitrogen. The apportionment of phosphorus source is however not kept with the global data in the 2000s, especially for the Scheldt basin where point emissions of P have rapidly decreased in the last 3 decades, resulting in a balance of point and diffuse sources (Table 3). For the NEWS 2 budget, it has to be noted that models of particulate forms do not allow attribution to point or nonpoint sources [*Mayorga et al.*, 2010], so that particulate forms of nutrient have been entirely attributed to diffuse sources. This is a strong assumption in the assessment of phosphorus sources contribution only, as particulate nitrogen represents a small part of total nitrogen.

[23] These results suggested that, despite different assumptions about the terrestrial retention of nutrients, and the use of a low-resolution database, NEWS 2 models are able to describe consistent inputs to the river system that are highly comparable with those derived from high-resolution databases gathered for their integration into the Riverstrahler model. This finding justifies further work to downscale these

values and to mechanistically assess the nutrients transferred and exported from the river.

5. Downscaling Global Input Data

[24] The translation of the global-scale constraints provided by the Global NEWS data into ones that are appropriate for the Riverstrahler model raises several methodological issues: (1) the state variables themselves differ between the two models; (2) the basin-integrated constraints provided by Global NEWS have to be distributed according to stream orders to be used by the Riverstrahler model implemented to the whole basin (minimum resolution); and (3) the hydrological and climatic (temperature) constraints need to be spatially and temporally distributed. Table 4 provides a synthesis of the downscaling methodologies that concern hydrological and climatic constraints, point sources, and diffuse sources.

5.1. Hydrology and Temperature

[25] NEWS 2 considers annual runoff data derived from worldwide and long-term simulation of the Water Balanced Model, corrected with observed river discharges [*Fekete et al.*, 2002, 2010]. For the year 2000, the values provided at global scale underestimate the hydrological regimes of the three rivers, e.g., 133, 120 and 179 mm yr⁻¹, respectively, for the Seine, Somme and Scheldt river basins against 259, 240 and 328 mm yr⁻¹ as obtained from observations or finer-scale simulations [*Thieu et al.* 2009]. Nevertheless, these values of global runoff stay in the range of values currently observed during dry years and reproduce the differences between the three basins, with higher runoff values for the Scheldt basin.

[26] The Riverstrahler model uses the simulations provided by a simple rainfall-discharge model (see detailed

Table 4. Transposition of the NEWS Model Variables Following the Requirement of the Riverstrahler Model^a

Riverstrahler Requirement	NEWS Forms	Allocation Rules and Downscaling Methodology
Superficial runoff by 10 day periods	Annual runoff, natural value for the basin (mm yr^{-1})	Runoff partitioning and seasonal distribution are based on hydrological model [Fekete et al., 2010] output calibrated on observed data (1996–2000)
Groundwater runoff by 10 day periods	Water consumption	Proportionally distributed as a mean withdrawal on each order
Outflow daily discharge of water	Mean temperature ($^{\circ}\text{C}$)	$T^{\circ}\text{C} = T_{\text{mean}} - T_{\text{amplitude}} \times \cos(\omega(t - 30))$ with $T_{\text{amplitude}} = 6$ to 9°C according to stream order and unchanged across scenarios; $\omega = 2\pi/365$; t in Julian days
T $^{\circ}\text{C}$: mean temperature ($^{\circ}\text{C}$)		
NO_3^- : nitrate concentration	<i>River Diffuse Sources</i> ^b Dissolved inorganic nitrogen (DIN) (tons yr^{-1})	Partitioning of DIN between NO_3^- and NH_4^+ based on a mean ratio by order (derived from high-resolution database; see also Thieu et al. [2009])
NH_4^+ : ammonium concentration		
Total inorganic phosphorus (TIP) concentration	Dissolved inorganic phosphorus (DIP) (tons yr^{-1})	TIP = DIP + ePIP \times SM [Vannery et al., 2005]; ePIP = Pac \times DIP/(DIP + KPods) exchangeable P content of soil; Pac = $0.0055 \text{ g P kg}^{-1}$ (the saturation level); KPods = 0.7 mg P L^{-1} (adsorption half-saturation constant) Constant value: $3.64 \text{ mg Si L}^{-1}$ ($130 \mu\text{mol L}^{-1}$) in agreement with observed values [Billen et al., 2007; Meybeck, 1986]
Dissolved silica concentration (DSi)	-	Use of a mean content of 4.9 mg Si g^{-1} of SM [Sferratore et al., 2006]
Biogenic silica concentration (BSi)	Dissolved organic carbon (DOC) (tons yr^{-1})	Assuming an average partition of the DOC leached from soil: rapidly degradable (2%), slowly degradable (4%), and refractory (94%) [Servais et al., 1987]
Dissolved organic carbon (following three classes of biodegradability) ($\text{DOC}_{1,2,3}$) concentration	Total suspended solids (TSS) concentration (no trapping)	Variable common between the two models Assuming a mean carbon content of 10 g C kg^{-1} with a distribution of 3, 12, and 85% for rapidly degradable, slowly degradable, and refractory, respectively
Suspended matter (SM) concentration		
Particulate organic carbon (following three classes of biodegradability) ($\text{POC}_{1,2,3}$) concentration		
Nitrate (NO_3)	<i>River Point Sources</i> ^c Dissolved inorganic nitrogen (DIN) (tons yr^{-1})	Partitioning of DIN between NO_3^- and NH_4^+ based on a mean ratio by order (derived from the high-resolution database; see also Thieu et al. [2009])
Ammonium (NH_4)		
Phosphate (PO_4)	Dissolved inorganic phosphorus (DIP) (tons yr^{-1})	Variable common between the two models
Suspended matter (SM)	-	On the basis of a theoretical release of $10 \text{ g inhabitant}^{-1} \text{ d}^{-1}$
Total organic carbon (TOC)	-	Theoretical release of $4 \text{ g C inhabitant}^{-1} \text{ d}^{-1}$ [Servais et al., 1999]
Dissolved silica (DSi)	-	Use of a theoretical release $0.3 \text{ mg Si inhabitant}^{-1} \text{ d}^{-1}$ for dissolved silica and $0.5 \text{ mg Si inhabitant}^{-1} \text{ d}^{-1}$ from biogenic silica [Sferratore et al., 2006]
Biogenic silica (BSi)	-	

^aThe downscaling methodology is primarily based on the distribution by order observed throughout the high-resolution database.^bFor river diffuse sources, the transition from nutrient loads (tons yr^{-1}) to nutrient concentration, the annual runoff value for hydrology was used.^cRiver point sources depend on population densities connected to sewage system; this driver is commonly described by the both models.

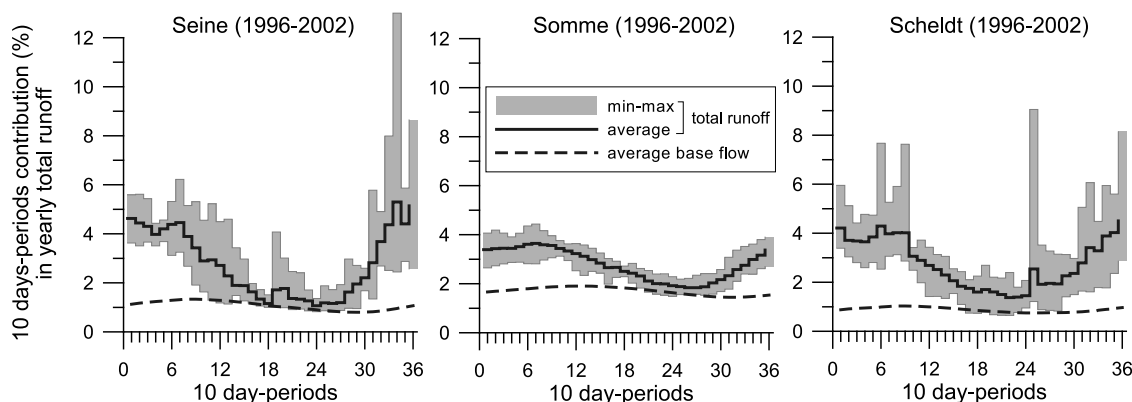


Figure 3. Seasonal distribution of the annual runoff and partitioning between surface and groundwater flow based on hydrological modeling (rainfall-discharge) simulation, calibrated for the period 1996–2002.

description in [Le *et al.*, 2007]) calibrated over several years of observed daily discharge enabling the partitioning of surface water and groundwater runoffs to be correctly reproduced, as an average fraction of the annual total runoff (Figure 3).

[27] Also, a net water abstraction term is considered in the NEWS 2 approach. It is expressed as a fraction of the natural runoff and includes intake for irrigation and other types of human water consumption, both of which imply water loss from the river system. To ensure the consistency of hydrological inputs, this total water withdrawal was distributed by stream order in the Riverstrahler model.

[28] The Riverstrahler model uses a sinusoidal seasonal variation of temperature specifically described by stream order. For the different scenarios which differ in air temperature increase with respect to 1970 (+1.3 to +1.4 in 2030 and from +1.5 to +2.0°C in 2050) [Alcama *et al.*, 2006; Bouwman *et al.*, 2009], the same increase in mean annual water temperature has been imposed (see Table 4).

5.2. Diffuse Sources to the Drainage Network

[29] The diffuse nutrient sources included in NEWS 2 models [Bouwman *et al.*, 2009] are here considered as net river inputs (i.e., after landscape retention), and the simulated dissolved forms of nutrients are inorganic and organic nitrogen (DIN, DON) and phosphorus (DIP, DOP) and organic carbon (DOC). Here, the particulate forms of nitrogen and phosphorus are not directly retrieved, as they are not a true input of the Riverstrahler model that derived particulate nutrient from suspended solid variable (see Table 4). The Riverstrahler model assesses diffuse sources by considering a constant mean composition, assigned to surface and groundwater flows, respectively, according to land use distribution within the watersheds. Accordingly, the variability of nutrient fluxes is entirely supported by the seasonal change in runoff, and the NEWS 2 annual nutrient loads can be easily converted to mean concentrations. Surface and groundwater contamination levels considered by the Riverstrahler model are assumed to be similar in order to

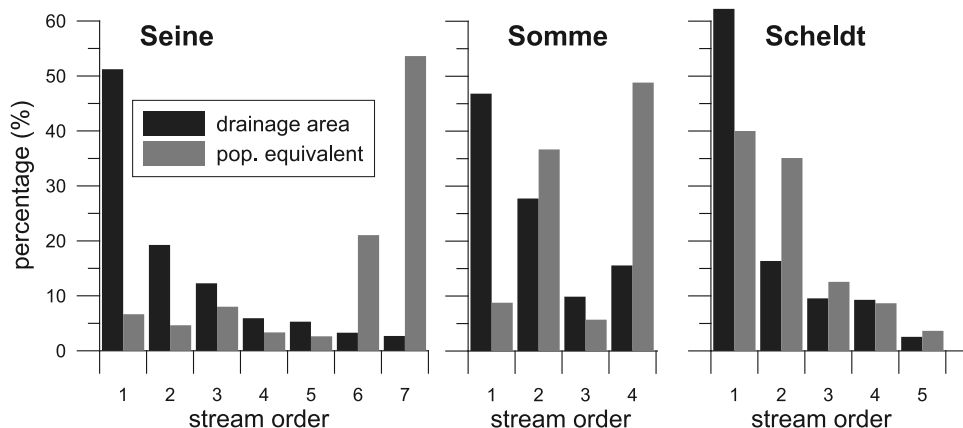


Figure 4. Distribution of drainage area and population equivalents by Strahler order, as two synthetic indicators to describe the distribution of diffuse-source and point-source nutrient loading. This corresponds to the assessment of high-resolution information available for the year 2000.

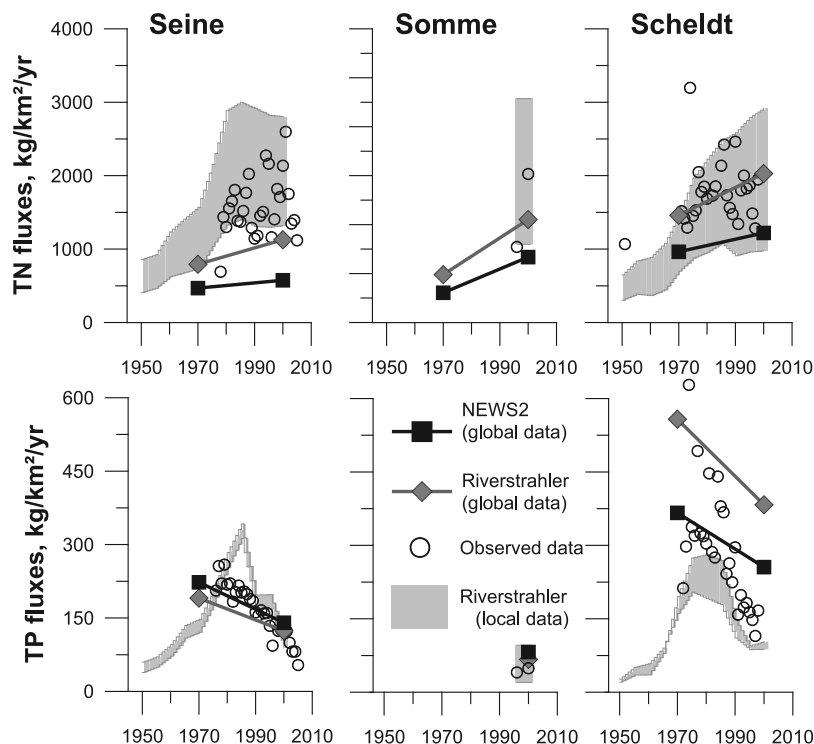


Figure 5. Nutrient (total N (TN) and total P (TP)) fluxes exported to the North Sea by the Seine, Somme, and Scheldt rivers systems, as observed and simulated by (1) the NEWS 2 models on the basis of global inputs (black line); (2) the Riverstrahler model on the basis of downscaled global inputs (gray line); and (3) the Riverstrahler model on the basis of a high-resolution database for two extreme hydrological conditions [Billen *et al.*, 2005, 2007] (gray area). TP fluxes could not be calculated for the year 1970 for the Somme (see also Table 3) because of the lack of correct global-scale point-source data for this period.

avoid any apparent retention of nutrients in the aquifers, while riparian retention terms are ignored.

[30] The spatial apportionment of diffuse sources of nutrients by order is based on the analysis of the high-resolution constraints for the reference year 2000. An analysis of nutrient flux distributions (in their NEWS 2 forms) revealed that nutrient proportions by stream order were very similar, regardless of the nutrient form studied, and strongly correlated with the proportion of watersheds drained by each order, without a clear influence of land use type ($R^2 = 0.99$). Therefore, the surface area of watersheds drained by stream order (Figure 4) was used as a simple descriptor that enabled the downscaling of global diffuse-source values.

5.3. Point Sources to the Drainage Network

[31] The NEWS 2 and Riverstrahler models and databases consider human waste emissions starting from their collection in sewage systems and disregard uncollected rural emissions, which are assumed not to reach the river network [Van Drecht *et al.*, 2009]. On the basis of an approach similar to the one used for diffuse sources, the distribution of point nutrient sources by stream order was analyzed on the basis of the high-resolution constraints for the year 2000. Population equivalents (Figure 4) were used as indicators to distribute point sources provided by the NEWS 2 models.

Indeed, the point sources of nutrient distributed by stream order are highly correlated to population equivalent ($R^2 = 0.88$ to 0.99 for DIN and DIP, respectively).

6. Deterministic Approach of Nutrient Transfer Based on Downscaled-Global Data

6.1. Validation for the Period 1970–2000

[32] The full NEWS 2 data set was downscaled for the recent simulated period (1970–2000), following the previously described methodology, in order to implement the Riverstrahler model and then compare the nutrient transfers and exports simulated by the two models constrained by the same inputs.

[33] The beginning of the period 1970–2000 was characterized by a rapid increase in nitrogen loads in response to the intensification of agricultural production and the construction of sewage systems collecting household effluents. At the end of this period, improvements in wastewater treatment contributed to the slower increase in nitrogen and phosphorus effluents. Of particular relevance was the prohibition of polyphosphates in washing powder, which led to the substantial decrease in phosphorus loading (Table 3).

[34] The simulations by the two models are compared with observations (Figure 5). Finer-scale simulations per-

formed by the Riverstrahler model (Figure 5, gray area) and observed nutrient fluxes gathered over this period are provided to stress the amplitude of change in nutrient export fluxes. Although the two models provide the right trends (e.g., a clear increase in nitrogen and a rapid decrease in phosphorus and flux levels in the same order of magnitude between 1970 and 2000 (Figure 5)), the NEWS2 model tends to underestimate both N and P for the Seine and the Scheldt. This can be explained by the fact that hydrological conditions considered in these flux estimations are generally low for the global input data compared to those provided by the local ones.

[35] For the Seine, Somme, and Scheldt rivers, total phosphorus fluxes exported for the year 2000 were similar: 124, 68, and 383 $\text{kg km}^{-2} \text{yr}^{-1}$, respectively, according to Riverstrahler and 140, 82, and 255 $\text{kg km}^{-2} \text{yr}^{-1}$, respectively, according to NEWS 2. Although greater differences appear for the Scheldt with an impressive decrease in the amount of phosphorus exported to the sea, the two models runs enclose the large variability of observed data over this period.

[36] For total nitrogen, Riverstrahler provided a better fit with the observed data, presuming that NEWS 2 models overestimate aquatic retention. For NEWS 2 models, aquatic retention only concerned the DIN variable [Dumont *et al.*, 2005], as water consumption removed less than 1% of the respective runoff and no reservoir was considered. NEWS 2 estimates for nitrogen retention in the year 2000 were 697 $\text{kg km}^{-2} \text{yr}^{-1}$ for the Seine, 509 $\text{kg km}^{-2} \text{yr}^{-1}$ for the Somme, and 1152 $\text{kg km}^{-2} \text{yr}^{-1}$ for the Scheldt, i.e., half the total nitrogen inputs. The Riverstrahler process-based approach provided much lower aquatic retention values for nitrogen: 126 $\text{kg km}^{-2} \text{yr}^{-1}$ for the Seine, 50 $\text{kg km}^{-2} \text{yr}^{-1}$ for the Somme, and 504 $\text{kg km}^{-2} \text{yr}^{-1}$ for the Scheldt. Most of this retention (from 47 to 78%) was due to benthic denitrification, while losses caused by burial to deeper sediment played only a minor role.

[37] The consistency of the Riverstrahler simulations supports (1) the relevance of using such global input data in assessments of radical changes in nutrient loads and (2) the benefit of the process-based high-resolution approach for calculating the fraction of nutrients exported to the sea.

6.2. Subregional Analysis of the Millennium Ecosystem Assessment Scenarios

[38] The MEA proposed four scenarios of the world future that are structured around theoretical schemes of development, with various degrees of international integration and environmental concerns [Alcamo *et al.*, 2006]. The Global Orchestration (GO) scenario is characterized by high-level globalization, rapid economic growth, and a reactive rather than proactive approach to environmental issues. On the opposite end, the Adapting Mosaic (AM) scenario is based less on the international integration of economies; instead, it actively addresses environmental management at the regional scale, mostly through simple and inexpensive solutions. The Technogarden (TG) scenario is, likewise, deeply involved in environmental issues but it is supported by global improvements in environmental technologies. Last,

the Order from Strength (OS) scenario is less concerned with ecosystem management, focusing primarily on security and regional markets.

[39] The three neighboring basins, those of the Seine, Somme, and Scheldt rivers, are sources of consistent change with respect to the global future dynamics of industrialized countries [Bouwman *et al.*, 2009; Van Drecht *et al.*, 2009]. As an example, population growth in the period 2000–2050 is predicted to increase similarly (14–14.8%) in the GO scenario, to slow down (1–4.3%) in the TG scenario, but decrease slightly (–6 to –10%) in the AM scenario and even more significantly (–14 to –18%) in the OS scenario.

[40] Changes in diffuse nutrient sources can be appraised through the evolution of soil nutrient surpluses resulting from the balance achieved between gross sources (fertilizer, manure, crop fixation, atmospheric deposition) and withdrawal (crop export and animal grazing). These changes reflect the development of human activities and can be linked with the amount of nutrients exported to rivers (Riverstrahler model input), as terrestrial retention remains constant across the four scenarios.

[41] Nitrogen surplus rapidly decreases within the more environmentally concerned scenarios (TG and AM), with an average of –57% in 2050, supported by an increase in fertilizer efficiency and an important decrease in atmospheric deposition; by contrast, the surplus is reduced by only –26% in the GO and OS scenarios (Table 5). Gross nitrogen export by agriculture increases in all scenarios; the only exception is the Scheldt, because of the predominance of livestock farming. Phosphorus diffuse sources, which represent only a small part of total phosphorus input to the rivers, follows the same line, with important decreases in the P surplus (–36 to –85%) in the TG and AM scenarios.

[42] Nonetheless, future changes in point sources will deeply modify phosphorus releases as well as those of nitrogen, albeit to a lesser extent. The main differences between the scenarios are related to population and economic growth, both of which are rapid in the TG and GO scenarios. For our three industrialized watersheds, there is no significant difference between the scenarios regarding the level of connection to sewage treatment. The fraction of population connected increased slowly (1–2%) after the major improvements in sanitation that were made between 1970 and 2000. At the 2050 horizons of the TG and GO scenarios, wastewater treatment is improved, thereby removing a mean 70–82% of phosphorus and 61–72% of nitrogen. These efficiencies are lower within the OS and AM scenarios (61–73% for phosphorus removal and 53–63% for nitrogen removal). However, while higher economic growth supports greater improvement of sewage treatment, the concomitant higher population growth is associated with an increase in raw emissions, which ultimately limits the differences between the scenarios. The decrease in nitrogen and phosphorus inputs to rivers is important compared to the levels of these nutrients exported in the year 2000, but there is little variability across the scenarios. Phosphorus exports to the river are 47–64 $\text{kg km}^{-2} \text{yr}^{-1}$ for the Seine; 23–32 $\text{kg km}^{-2} \text{yr}^{-1}$ for the Somme, and 129–163 $\text{kg km}^{-2} \text{yr}^{-1}$ for the Scheldt.

Table 5. Synthesis of the Evolution of the Main Land-Based Drivers and Sources According to the Four Millennium Ecosystem Assessment Scenarios^a

	World Development: Reactive Environmental Management					
	Globalization (GO)			Regionalization (OS)		
	Seine	Somme	Scheldt	Seine	Somme	Scheldt
Socioeconomic						
Population (inhabitants km ⁻²)	242 (15%)	114 (15%)	399 (14%)	180 (-14%)	85 (-14%)	284 (-19%)
GDP (1995 U.S.\$ person ⁻¹ yr ⁻¹)	65,047 (180%)	65,047 (180%)	66,664 (181%)	53,309 (130%)	53,309 (130%)	50,940 (115%)
Urban pop. (% ₀ ,±change)	93.3 (+6%)	100 (+23%)	98.8 (0%)	93.3 (+6%)	100 (+23%)	98.8 (0%)
Sewage connect. (% ₀ ,±change)	96.1 (+7%)	100 (0%)	96.9 (+2%)	96.7 (+8%)	100 (0%)	95.9 (+1%)
Point sources						
Raw N emission (kg km ⁻² yr ⁻¹)	1,864 (46%)	882 (46%)	3,263 (52%)	1,327 (4%)	628 (4%)	2,068 (-3%)
N removed by sewage (%)	71.8	71.8	61.2	62.5	62.5	53.0
Raw P emission (kg km ⁻² yr ⁻¹)	386 (24%)	182 (24%)	686 (50%)	270 (-13%)	128 (-13%)	423 (-8%)
P removed by sewage (%)	81.8	81.8	69.8	72.3	72.3	61.1
Diffuse sources(*)						
Gross N source (kg km ⁻² yr ⁻¹)	9,756 (-12%)	12,170 (-5%)	15,631 (-8%)	9,845 (-12%)	11,638 (-9%)	14,210 (-16%)
N export (kg km ⁻² yr ⁻¹)	5,988 (2%)	8,253 (10%)	9,489 (3%)	6,226 (6%)	7,841 (4%)	8,337 (-10%)
N surplus (kg km ⁻² yr ⁻¹)	3,768 (-29%)	3,917 (-26%)	6,142 (-21%)	3,619 (-31%)	3,797 (-28%)	5,873 (-24%)
Gross P source (kg km ⁻² yr ⁻¹)	1,404 (-4%)	1,950 (13%)	2,488 (5%)	1,474 (1%)	1,793 (3%)	2,220 (-6%)
P export (kg km ⁻² yr ⁻¹)	1,069 (0%)	1,497 (9%)	1,655 (13%)	1,126 (5%)	1,413 (3%)	1,452 (-1%)
P surplus (kg km ⁻² yr ⁻¹)	335 (-13%)	453 (27%)	833 (-8%)	348 (-9%)	380 (6%)	768 (-15%)
World Development: Proactive Environmental Management						
	Globalization (TG)			Regionalization (AM)		
	Seine	Somme	Scheldt	Seine	Somme	Scheldt
Socioeconomic						
Population (inhabitants km ⁻²)	214 (2%)	101 (2%)	354 (1%)	197 (-6%)	93 (-6%)	315 (-10%)
GDP (1995 US\$ person ⁻¹ yr ⁻¹)	58,064 (150%)	58,064 (150%)	59,544 (151%)	52,642 (127%)	52,642 (127%)	53,107 (124%)
Urban pop. (% ₀ ,±change)	93.3 (+6%)	100 (+23%)	98.8 (0%)	93.3 (+6%)	100 (+23%)	98.8 (0%)
Sewage connect. (% ₀ ,±change)	96.1 (+7%)	100 (0%)	96.9 (+2%)	96.1 (+7%)	100 (0%)	95.9 (+1%)
Point sources						
Raw N emission (kg km ⁻² yr ⁻¹)	1,608 (26%)	761 (26%)	2,816 (32%)	1,449 (14%)	685 (14%)	2,348 (10%)
N removed by sewage (%)	71.8	71.8	61.2	62.5	62.5	53.0
Raw P emission (kg km ⁻² yr ⁻¹)	332 (7%)	157 (7%)	591 (29%)	295 (-5%)	140 (-5%)	486 (6%)
P removed by sewage (%)	81.8	81.8	69.8	72.3	72.3	61.1
Diffuse sources (*)						
Gross N source (kg km ⁻² yr ⁻¹)	8,433 (-24%)	9,979 (-22%)	13,760 (-19%)	8,004 (-28%)	10,015 (-22%)	12,567 (-26%)
N export (kg km ⁻² yr ⁻¹)	6,454 (10%)	8,163 (9%)	9,352 (1%)	5,821 (-1%)	7,957 (6%)	8,817 (-5%)
N surplus (kg km ⁻² yr ⁻¹)	1,979 (-62%)	1,817 (-66%)	4,408 (-43%)	2,184 (-59%)	2,058 (-61%)	3,750 (-52%)
Gross P source (kg km ⁻² yr ⁻¹)	1,328 (-9%)	1,611 (-7%)	2,203 (-7%)	1,182 (-19%)	1,487 (-14%)	1,909 (-19%)
P export (kg km ⁻² yr ⁻¹)	1,166 (9%)	1,472 (7%)	1,626 (11%)	1,056 (-2%)	1,434 (4%)	1,536 (5%)
P surplus (kg km ⁻² yr ⁻¹)	162 (-58%)	139 (-61%)	576 (-36%)	126 (-67%)	53 (-85%)	373 (-59%)

^aPercentage values assess change between 2000 and 2050. Asterisk indicates diffuse-source values consider anthropogenic areas only; the “export” term includes crop export and animal grazing. GO, Global Orchestration; OS, Order from Strength; TG, Technogarden. AM, Adapting Mosaic.

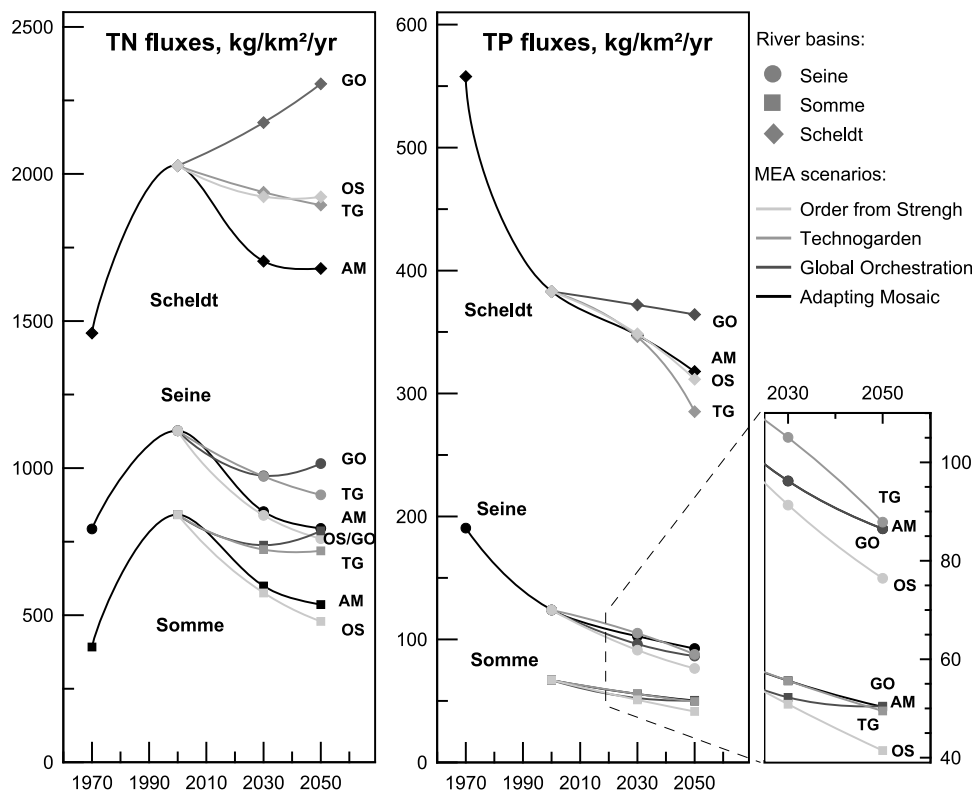


Figure 6. Total N and total P deliveries calculated by the Riverstrahler model according to the MEA global inputs (GO, Global Orchestration; OS, Order from Strength; TG, Technogarden; AM, Adapting Mosaic) downscaled to the Seine, Somme, and Scheldt drainage network.

[43] Despite a higher aquatic retention in the Scheldt, estimated to 52% by the Riverstrahler model (compared to about 30% each for the Seine and the Somme), phosphorus levels at the outlet of the Scheldt remain twofold to threefold higher than the Seine and Somme deliveries (Figures 5 and 6). Indeed, water treatment is less advanced in the Scheldt, in agreement with the treatment efficiencies reported for the current period [Billen *et al.*, 2005; Thieu *et al.*, 2009]. For example, phosphorus removal by sewage treatment increases from 50 to 61% between 2000 and 2050 in the Scheldt versus 59–72% for the other two basins during the same period. Also, the processes involved in aquatic retention and simulated by the model are not significantly affected across the scenarios, such that variations of fluxes at the outlets of the three basins reflect the changes influencing river inputs.

[44] Table 5 provides an overview of the MEA’s perspective of the impact of changes in “driving forces,” and shows that these changes do not seem to be followed by a spatial rearrangement of human activities. For example, the fractions of urban population remain unchanged across the scenarios, there is no evident modification of the total areas of grassland or wetland, and even agricultural areas remain rather stable. Indeed, these subregional MEA storylines are translated into changes in the intensity of human disturbances, while spatial distributions within the catchment areas are similar across the scenarios.

6.3. Integrating the Potential Impact of the Inner Basin Dynamics

[45] The downscaling of the NEWS 2 constraints relies on the spatial distribution by stream order of synthetic indicators, namely, the watershed surface for diffuse sources and the population for point sources. Both were defined for the year 2000, and the distribution rules were assumed to remain constant for future scenarios. One benefit of a mechanistic, spatially distributed approach lies in its ability to take into account changes in the spatial organization of human activities.

[46] The example of population distribution is used here to illustrate the contrasts between the GO and AM scenarios. In accordance with their storylines, we assumed a redistribution of population between small and large towns. Thus, in the AM scenario, 25% of the population living in large agglomerations (over 100,000 inhabitants) moved to medium (between 20,000 and 100,000 inhabitants) and small (below 20,000 inhabitants) towns. In the GO scenario, the populations of large agglomerations increased by 25% at the expense of medium and small towns.

[47] When transposed to the different orders of each of the three basins, these new distributions are determined by the proportion and the size of the respective urban centers, as well as their location along the stream order. In the AM scenario, the population is less concentrated and is relocated

downstream along the Scheldt and to the upstream parts of the Seine. By contrast, in the GO scenario, there are greater disparities in population distribution. The case of the Seine is particularly impressive with respect to the growth of the Paris conurbation along the last order of the basin.

[48] The responses of the three river systems to these changes in the distribution of point sources in the AM and GO scenarios were assessed with the Riverstrahler model. The trend to more uniform distribution of point sources in the AM scenario translated into an increase in the aquatic retention of nitrogen and phosphorus. Phosphorus was more sensitive, with the calculated retention increasing from 22 to 26 kg km⁻² yr⁻¹ for the Seine and from 5.7 to 6.2 kg km⁻² yr⁻¹ for the Somme. In the GO scenario for the Seine and Somme basins, our assumption resulted in an increase in the population in the downstream part of the basins, thus decreasing aquatic retention with respect to the similar scenario with no spatial redistribution. For example, phosphorus retention decreased from 22 to 19 kg km⁻² yr⁻¹ in the Seine and from 6 to 5.5 kg km⁻² yr⁻¹ in the Somme. As the reference distribution of population within the Scheldt is opposite to that of the other two rivers, with a higher population upstream, the effect of the population reallocation was also different from that of the two other basins: aquatic retention of both N and P increased by 2% in the GO scenario and decreased by 1% in the AM scenario.

7. Discussions and Conclusions

[49] Despite their four highly contrasting views of how the world will evolve over the next few decades, the scenarios provided in the framework of the MEA are based on consistent and plausible assumptions. Subregional use of global input data has provided a useful assessment of nutrient sources and successfully reproduced the contrasts observed between the Seine, Somme, and Scheldt rivers. These rivers differ strongly in their population densities and agricultural orientations. However, the proximity and similar level of development of these three industrialized basins contributed to limit the differences in the final assessment of the scenarios in terms of nutrient delivery at the outlets. In addition, the low water discharge values used from global data set also tend to minimize these differences.

[50] The methodology proposed here for downscaling global inputs does not introduce further assumptions about regional changes in the main driving forces, thus allowing a comparison of the results by the two models. However, in the present work, the impact of future climate change on hydrology was possibly largely underestimated. Changing annual runoff values in the MEA scenarios (−2% and 2%) were not accompanied by changes in the seasonal distribution of the surface and groundwater contributions (Figure 3). These potential changes in the seasonal variability of river discharge include an increase in diffuse sources contribution during winter and a decrease of precipitation in summertime that might concentrate point sources inputs and also influence water residence times. For the Seine River, *Ducharne et al.* [2007] have demonstrated that these seasonal changes in discharge might have a negligible impact under climate

change scenario, while higher impact should be expected from the warming of the water column. The Riverstrahler model includes temperature as an important process driver acting mainly on the dynamics of bacteria, phytoplankton, and zooplankton communities (nutrient uptake, growth, and mortality) [*Garnier et al.*, 1995]. This controlling factor is not considered in the application of the global NEWS 2 models to the different prospective scenarios; it is taken into account in the Riverstrahler application, although the sensitivity of the annual total nitrogen and phosphorus delivery is very low (less 2%).

[51] Another key factor affecting the impact of the MEA scenarios on river nutrient export is the internal changes expected to occur within the basins and their impact on nutrient retention. We have demonstrated the necessity of a spatially distributed approach to describe the transfer of human wastewater release within a basin. The change in river nutrient retention is directly linked with the increased residence time of the water mass [*Seitzinger et al.*, 2002b]. However, several other aspects of proactive environmental management, such as restoration of natural stream morphology (enlargement of the river bed, connection of lateral arms) and flow regime [*Muhar et al.*, 1995; *Poudevigne et al.*, 2002], could supply the AM or TG scenarios with additional features.

[52] The Riverstrahler mechanistic approach is better adapted than the NEWS 2 models to integrate the link between biogeochemical processes and morphological constraints, or the spatial organization of the landscape at the basin scale. However, the use of global-scale models remains essential for integrating the development of socioeconomic driving forces acting at the global scale and the major dynamics transcending the limits of river basins.

[53] Starting from the ability of the Riverstrahler model to be upscaled to a single-basin representation, we demonstrated that the NEWS 2 estimates of nutrient loads transferred to the river network are consistent and that the data can be downscaled on the basis of simple descriptors (population distribution and watershed area by stream order). The comparison of the simulated fluxes over the period 1970–2000 has emphasized the benefit of an approach linking “global-empirical” modeling of nutrient transfer from the source to the river with a “subregional, spatially distributed and process-based” approach of in-stream retention.

[54] Here, the purpose was not only to provide a subregional assessment of the MEA or to compare the models’ performances for the three sample watersheds; rather, a further aim was to analyze the suitability of this global information with respect to the requirements of modeling approaches at more detailed scale levels. The scalable Riverstrahler model has already been successfully applied to the analysis of several river systems across the world: the Red River (Vietnam [*Le et al.*, 2005, 2010]), the Kalix subarctic basin (Sweden [*Sferratore et al.*, 2008]), and the Danube [*Garnier et al.*, 2002]. The methodology presented here could be transposed to these or other basins in the world, supporting the idea that a mechanistic approach can be applied at the global scale, provided that adequate information is available.

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References

- Alcamo, J., D. Van Vuuren, and W. Cramer (2006), Changes in ecosystem services and their drivers across scenarios, in *Ecosystem and Human Well-Being*, vol. 2, *Scenarios*, edited by S. R. Carpenter et al., pp. 279–354, Island Press, Washington, D. C.
- Alexander, R. B., P. J. Johnes, E. W. Boyer, and R. A. Smith (2002), A comparison of models for estimating the riverine export of nitrogen from large watersheds, *Biogeochemistry*, 57/58, 295–339, doi:10.1023/A:1015752801818.
- Beusen, A. H. W., A. L. M. Dekkers, A. F. Bouwman, W. Ludwig, and J. Harrison (2005), Estimation of global river transport of sediments and associated particulate C, N, and P, *Global Biogeochem. Cycles*, 19, GB4S05, doi:10.1029/2005GB002453.
- Billen, G., and J. Garnier (2007), River basin nutrient delivery to the coastal sea: Assessing its potential to sustain new production of non siliceous algae, *Mar. Chem.*, 106, 148–160, doi:10.1016/j.marchem.2006.12.017.
- Billen, G., J. Garnier, and P. Hanset (1994), Modelling phytoplankton development in whole drainage networks: The RIVERSTRAHLER model applied to the Seine river system, *Hydrobiologia*, 289, 119–137, doi:10.1007/BF00007414.
- Billen, G., J. Garnier, and V. Rousseau (2005), Nutrient fluxes and water quality in the drainage network of the Scheldt basin over the last 50 years, *Hydrobiologia*, 540, 47–67, doi:10.1007/s10750-004-7103-1.
- Billen, G., J. Garnier, J. Nemery, M. Sebilo, A. Sferratore, P. Benoit, S. Barles, and M. Benoit (2007), A long term view of nutrient transfers through the Seine river continuum, *Sci. Total Environ.*, 375, 80–97, doi:10.1016/j.scitotenv.2006.12.005.
- Bouwman, A. F., A. H. W. Beusen, and G. Billen (2009), Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050, *Global Biogeochem. Cycles*, 23, GB0A04, doi:10.1029/2009GB003576.
- Boyer, E. W., C. L. Goodale, N. A. Jaworski, and R. W. Howarth (2002), Anthropogenic nitrogen sources and relationships to riverine nitrogen export in the northeastern USA, *Biogeochemistry*, 57/58, 137–169, doi:10.1023/A:1015709302073.
- Cloern, J. E. (1996), Phytoplankton bloom dynamics in coastal ecosystems: A review with some general lessons from sustained investigation of San Francisco Bay, California, *Rev. Geophys.*, 34(2), 127–168, doi:10.1029/96RG00986.
- Cugier, P., G. Billen, J.-F. Guillaud, J. Garnier, and A. Ménesguen (2005), Modelling the eutrophication of the Seine Bight (France) under historical, present and future nutrient loading, *J. Hydrol.*, 304, 381–396, doi:10.1016/j.jhydrol.2004.07.049.
- de Wit, M., and G. Bendoricchio (2001), Nutrient fluxes in the Po basin, *Sci. Total Environ.*, 273(1–3), 147–161, doi:10.1016/S0048-9697(00)00851-2.
- Ducharne, A., et al. (2007), Long term prospective of the Seine river system: Confronting climatic and direct anthropogenic changes, *Sci. Total Environ.*, 375, 292–311, doi:10.1016/j.scitotenv.2006.12.011.
- Dumont, E., J. A. Harrison, C. Kroeze, E. J. Bakker, and S. P. Seitzinger (2005), Global distribution and sources of dissolved inorganic nitrogen export to the coastal zone: Results from a spatially explicit, global model, *Global Biogeochem. Cycles*, 19, GB4S02, doi:10.1029/2005GB002488.
- Everbecq, E., V. Gosselain, L. Viroux, and J.-P. Descy (2001), Potamon: A dynamic model for predicting phytoplankton composition and biomass in lowland rivers, *Water Res.*, 35(4), 901–912, doi:10.1016/S0043-1354(00)00360-2.
- Fekete, B. M., C. J. Vörösmarty, and W. Grabs (2002), High-resolution fields of global runoff combining observed river discharge and simulated water balances, *Global Biogeochem. Cycles*, 16(3), 1042, doi:10.1029/1999GB001254.
- Fekete, B. M., D. Wisser, C. Kroeze, E. Mayorga, A. F. Bouwman, and W. M. Wollheim (2010), Scenario drivers (1970–2050), Climate and hydrological alterations, *Global Biogeochem. Cycles*, doi:10.1029/2009GB003593, in press.
- Galloway, J. N., J. Aber, J. Erisman, S. Seitzinger, R. Howarth, E. Cowling, and B. Cosby (2003), The nitrogen cascade, *BioScience*, 53(4), 341–356, doi:10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2.
- Garnier, J., G. Billen, and M. Coste (1995), Seasonal succession of diatoms and Chlorophyceae in the drainage network of the Seine River: Observations and modelling, *Limnol. Oceanogr.*, 40(4), 750–765.
- Garnier, J., G. Billen, and L. Palfner (1999), Understanding the oxygen budget and related ecological processes in the river Mosel: The RIVERSTRAHLER approach, *Hydrobiologia*, 410, 151–166, doi:10.1023/A:1003894200796.
- Garnier, J., G. Billen, E. Hannon, S. Fonbonne, Y. Videnina, and M. Soulie (2002), Modeling transfer and retention of nutrients in the drainage network of the Danube River, *Estuarine Coastal Shelf Sci.*, 54, 285–308, doi:10.1006/ecs.2000.0648.
- Green, P., C. J. Vörösmarty, M. Meybeck, J. Galloway, and B. Peterson (2004), Pre-industrial and contemporary fluxes of nitrogen through rivers: A global assessment based on typology, *Biogeochemistry*, 68, 71–105, doi:10.1023/B:BI0G.0000025742.82155.92.
- Harrison, J. A., N. Caraco, and S. P. Seitzinger (2005a), Global patterns and sources of dissolved organic matter export to the coastal zone: Results from a spatially explicit, global model, *Global Biogeochem. Cycles*, 19, GB4S04, doi:10.1029/2005GB002480.
- Harrison, J. A., S. P. Seitzinger, A. F. Bouwman, N. F. Caraco, A. H. W. Beusen, and C. J. Vörösmarty (2005b), Dissolved inorganic phosphorus export to the coastal zone: Results from a spatially explicit, global model, *Global Biogeochem. Cycles*, 19, GB4S03, doi:10.1029/2004GB002357.
- Howarth, R. W., G. Billen, D. Swaney, A. Townsend, N. Jaworski, K. Lajtha, J. A. Downing, R. Elmgren, N. Caraco, and T. Jordan (1996), Regional nitrogen budgets and riverine N & P fluxes for the drainages to the North Atlantic Ocean: Natural and human influences, *Biogeochemistry*, 35(1), 75–139, doi:10.1007/BF02179825.
- Intergovernmental Panel on Climate Change (IPCC) (2000), *Special Report on Emissions Scenarios: A special report of Working Group III of the Intergovernmental Panel on Climate Change*, Cambridge Univ. Press, Cambridge, U. K.
- Jaworski, N. A., P. M. Groffman, A. A. Keller, and J. C. Prager (1992), A watershed nitrogen and phosphorus balance: The upper Potomac River basin, *Estuaries Coasts*, 15(1), 83–95, doi:10.2307/1352713.
- Kronvang, B., L. M. Svendsen, J. P. Jensen, and J. Dørgé (1999), Scenario analysis of nutrient management at the river basin scale, *Hydrobiologia*, 410, 207–212, doi:10.1023/A:1003846317634.
- Lacroix, G., K. Ruddick, N. Gypens, and C. Lancelot (2007), Modelling the relative impact of rivers (Scheldt/Rhine/Seine) and Western Channel waters on the nutrient and diatoms/Phaeocystis distributions in Belgian waters (southern North Sea), *Cont. Shelf Res.*, 27(10–11), 1422–1446, doi:10.1016/j.csr.2007.01.013.
- Lancelot, C., Y. Spitz, N. Gypens, K. Ruddick, S. Becquevort, V. Rousseau, G. Lacroix, and G. Billen (2005), Modelling diatom and Phaeocystis blooms and nutrient cycles in the Southern Bight of the North Sea: The MIRO model, *Mar. Ecol. Prog. Ser.*, 289, 63–78, doi:10.3354/meps289063.
- Lancelot, C., N. Gypens, G. Billen, J. Garnier, and V. Roubexis (2007), Testing an integrated river-ocean mathematical tool for linking marine eutrophication to land use: The Phaeocystis-dominated Belgian coastal zone (southern North Sea) over the past 50 years, *J. Mar. Syst.*, 64, 216–228, doi:10.1016/j.jmarsys.2006.03.010.
- Le, T. P. Q., G. Billen, J. Garnier, S. Théry, C. Fézard, and C. Van Minh (2005), Nutrient (N, P) budgets for the Red River basin (Vietnam and China), *Global Biogeochem. Cycles*, 19, GB2022, doi:10.1029/2004GB002405.
- Le, T. P. Q., J. Garnier, B. Gilles, T. Sylvain, and C. Van Minh (2007), The changing flow regime and sediment load of the Red River, Viet Nam, *J. Hydrol.*, 334(1–2), 199–214, doi:10.1016/j.jhydrol.2006.10.020.
- Le, T. P. Q., B. Gilles, J. Garnier, T. Sylvain, R. Denis, N. X. Anh, and C. V. Minh (2010), Nutrient (N, P, Si) transfers in the subtropical Red River system (China and Vietnam): Modelling and budget of nutrient sources and sinks, *J. Asian Earth Sci.*, 37(3), 259–274, doi:10.1016/j.jseas.2009.08.010.
- Mayorga, E., S. P. Seitzinger, J. A. Harrison, E. Dumont, A. H. W. Beusen, A. F. Bouwman, B. Fekete, C. Kroeze, and G. Van Drecht (2010), Global Nutrient Export from Watersheds 2 (NEWS 2), Model development and implementation, *Environ. Model. Softw.*, 25, 837–853, doi:10.1016/j.envsoft.2010.01.007.
- Meybeck, M. (1986), Composition chimique des ruisseaux non pollués de France, *Sci. Geol. Bull.*, 39, 3–77.
- Meybeck, M. (2003), Global analysis of river systems: From earth system controls to Anthropocene controls, *Philos. Trans. R. Soc. London, Ser. B*, 354, 1440, doi:10.1098/rstb.2003.1379.
- Meybeck, M., and A. Ragu (1996), River discharges to the oceans: An assessment of suspended solids, major ions and nutrients, U.N. Environ. Programme, Nairobi.

- Mignolet, C., C. Schott, and M. Benoît (2007), Spatial dynamics of farming practices in the Seine basin: Methods for agronomic approaches on a regional scale, *Sci. Total Environ.*, 375, 13–32, doi:10.1016/j.scitotenv.2006.12.004.
- Millennium Ecosystem Assessment (MEA) (2005), *Ecosystems and Human Well-Being: Synthesis*, Island Press, Washington, D. C.
- Muhar, S., S. Schmutz, and M. Jungwirth (1995), River restoration concepts: Goals and perspectives, *Hydrobiologia*, 303(1), 183–194, doi:10.1007/BF00034055.
- Némery, J., J. Garnier, and C. Morel (2005), Phosphorus budget in the Marne Watershed (France): Urban vs. diffuse sources, dissolved vs. particulate forms, *Biogeochemistry*, 72, 35–56, doi:10.1007/s10533-004-0078-1.
- Netherlands Environmental Assessment Agency (MNP) (2006), *Integrated Modelling of Global Environmental Change. An Overview of IMAGE 2.4*, edited by A. F. Bouwman, T. Kram, and K. Klein Goldewijk, Neth. Environ. Assess. Agency, Bilthoven, Netherlands.
- Officer, C. B., and J. H. Ryther (1980), The possible importance of silicon in marine eutrophication, *Mar. Ecol. Prog. Ser.*, 3, 83–91, doi:10.3354/meps003083.
- Poudevigne, I., D. Alard, R. Leuven, and P. H. Nienhuis (2002), A systems approach to river restoration: A case study in the lower Seine valley, France, *River Res. Appl.*, 18(3), 239–247, doi:10.1002/rra.667.
- Ruelland, D., G. Billen, D. Brunstein, and J. Garnier (2007), SENEQUE 3: A GIS interface to the RIVERSTRAHLER model of the biogeochemical functioning of river systems, *Sci. Total Environ.*, 375, 257–273, doi:10.1016/j.scitotenv.2006.12.014.
- Seitzinger, S. P., C. Kroeze, A. F. Bouwman, N. Caraco, F. Dentener, and R. V. Styles (2002a), Global patterns of dissolved inorganic and particulate nitrogen inputs to coastal systems: Recent conditions and future projections, *Estuaries Coasts*, 25(4), 640–655, doi:10.1007/BF02804897.
- Seitzinger, S. P., R. V. Styles, E. W. Boyer, R. B. Alexander, G. Billen, R. W. Howarth, B. Mayer, and N. Van Breemen (2002b), Nitrogen retention in rivers: Model development and application to watersheds in the northeastern USA, *Biogeochemistry*, 57(1), 199–237, doi:10.1023/A:1015745629794.
- Seitzinger, S. P., J. A. Harrison, E. Dumont, A. H. W. Beusen, and A. F. Bouwman (2005), Sources and delivery of carbon, nitrogen, and phosphorus to the coastal zone: An overview of Global Nutrient Export from Watersheds (NEWS) models and their application, *Global Biogeochem. Cycles*, 19, GB4S01, doi:10.1029/2005GB002606.
- Seitzinger, S. P., et al. (2010), Global nutrient river export trajectories 1970–2050: A Millennium Ecosystem Assessment scenario analysis, *Global Biogeochem. Cycles*, 24, GB0A08, doi:10.1029/2009GB003587.
- Servais, P., G. Billen, and M.-C. Hascoet (1987), Determination of the biodegradable fraction of dissolved organic matter in waters, *Water Res.*, 21(4), 445–450, doi:10.1016/0043-1354(87)90192-8.
- Servais, P., J. Garnier, N. Demarteau, N. Brion, and G. Billen (1999), Supply of organic matter and bacteria to aquatic ecosystems through waste water effluents, *Water Res.*, 33(16), 3521–3531, doi:10.1016/S0043-1354(99)00056-1.
- Sferratore, A., G. Billen, J. Garnier, and S. Théry (2005), Modeling nutrient (N, P, Si) budget in the Seine watershed: Application of the Riverstrahler model using data from local to global scale resolution, *Global Biogeochem. Cycles*, 19, GB4S07, doi:10.1029/2005GB002496.
- Sferratore, A., J. Garnier, G. Billen, D. J. Conley, and S. Pinault (2006), Diffuse and point sources of silica in the Seine River watershed, *Environ. Sci. Technol.*, 40(21), 6630–6635, doi:10.1021/es060710q.
- Sferratore, A., G. Billen, J. Garnier, E. Smedberg, C. Humborg, and L. Rahm (2008), Modelling nutrient fluxes from sub-arctic basins: Comparison of pristine vs. dammed rivers, *J. Mar. Syst.*, 73(3–4), 236–249, doi:10.1016/j.jmarsys.2007.10.012.
- Strahler, A. H. (1957), Quantitative analysis of watershed geomorphology, *Eos Trans. AGU*, 38, 1290–1299.
- Thieu, V., G. Billen, and J. Garnier (2009), Nutrient transfer in three contrasting NW European watersheds: The Seine, Somme, and Scheldt rivers. A comparative application of the Senèque/Riverstrahler model, *Water Res.*, 43(6), 1740, doi:10.1016/j.watres.2009.01.014.
- Turner, R. E., and N. N. Rabalais (1994), Coastal eutrophication near the Mississippi river delta, *Nature*, 368(6472), 619–621, doi:10.1038/368619a0.
- Van Drecht, G., A. F. Bouwman, J. Harrison, and J. M. Knoop (2009), Global nitrogen and phosphate in urban waste water for the period 1970–2050, *Global Biogeochem. Cycles*, 23, GB0A03, doi:10.1029/2009GB003458.
- Verburg, P. H., M. D. A. Rounsevell, and A. Veldkamp (2006), Scenario-based studies of future land use in Europe, *Agric. Ecosyst. Environ.*, 114(1), 1–6, doi:10.1016/j.agee.2005.11.023.
- Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo (1997), Human domination of Earth's ecosystems, *Science*, 277(5325), 494, doi:10.1126/science.277.5325.494.
- Vörösmarty, C. J., B. M. Fekete, M. Meybeck, and R. B. Lammers (2000), Geomorphometric attributes of the global system of rivers at 30-minute spatial resolution, *J. Hydrol.*, 237(1–2), 17–39, doi:10.1016/S0022-1694(00)00282-1.
- Whitehead, P. G., E. J. Wilson, and D. Butterfield (1998), A semi-distributed integrated nitrogen model for multiple source assessments in catchments (INCA): Part 1. Model structure and process equations, *Sci. Total Environ.*, 210(211), 547–558, doi:10.1016/S0048-9697(98)00037-0.
- Wolf, J., R. Rötter, and O. Oenema (2005), Nutrient emission models in environmental policy evaluation at different scales: Experience from the Netherlands, *Agric. Ecosyst. Environ.*, 105(1–2), 291–306, doi:10.1016/j.agee.2004.02.005.

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