Environmental Modelling & Software 25 (2010) 837–853

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

# Global Nutrient Export from WaterSheds 2 (NEWS 2): Model development and implementation

Emilio Mayorga[a,*,1], Sybil P. Seitzinger[a,2], John A. Harrison[b], Egon Dumont[c], Arthur H.W. Beusen[d], A.F. Bouwman[d], Balazs M. Fekete[e], Carolien Kroeze[f,g], Gerard Van Drecht[d]

[a] Rutgers/NOAA CMER Program, Institute of Marine and Coastal Sciences, Rutgers, The State University of New Jersey, 71 Dudley Rd., New Brunswick, NJ 08901-8521, USA
[b] Washington State University, School of Earth and Environmental Sciences, 14204 NE Salmon Creek Avenue, Vancouver, WA 98686, USA
[c] Centre for Ecology & Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB, United Kingdom
[d] Netherlands Environmental Assessment Agency (PBL), P.O. Box 303, 3720 AH Bilthoven, The Netherlands
[e] Global Water Center of the CUNY Environmental Cross-roads Initiative, The City College of New York at the City University of New York, 160 Convent Avenue, New York, NY 10031, USA
[f] Environmental Systems Analysis Group, Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[g] School of Science, Open Univ Netherlands, P.O. Box 2960, 6401 DL Heerlen, The Netherlands

ARTICLE INFO

*Article history:*
Received 31 May 2009
Received in revised form
20 January 2010
Accepted 22 January 2010
Available online 1 March 2010

*Keywords:*
Global NEWS
Nutrients
Millennium ecosystem assessment scenarios
Basin models
Global river exports
Coastal inputs

ABSTRACT

Global NEWS is a global, spatially explicit, multi-element and multi-form model of nutrient exports by rivers. Here we present NEWS 2, the new version of Global NEWS developed as part of a Millennium Ecosystem Assessment scenario implementation from hindcast (1970) to contemporary (2000) and future scenario trajectories (2030 & 2050). We provide a detailed model description and present an overview of enhancements to input datasets, emphasizing an integrated view of nutrient form sub-models and contrasts with previous NEWS models (NEWS 1). An important difference with NEWS 1 is our unified model framework (multi-element, multi-form) that facilitates detailed watershed comparisons regionally and by element or form. NEWS 2 performs approximately as well as NEWS 1 while incorporating previously uncharacterized factors. Although contemporary global river export estimates for dissolved inorganic nitrogen (DIN) and particulates show notable reductions, they are within the range of previous studies; global exports for other nutrient forms are comparable to NEWS 1. NEWS 2 can be used as an effective tool to examine the impact of polices to reduce coastal eutrophication at regional to global scales. Continued enhancements will focus on the incorporation of other forms and sub-basin spatial variability in drivers and retention processes.



## Software availability

The NEWS 2 model was implemented in a Python framework – the Global NEWS modeling Environment (GNE) – developed for the Millennium Ecosystem Assessment scenarios project described here. A description of GNE and user documentation are available at: http://www.marine.rutgers.edu/globalnews/GNE.
NEWS 2 model code consistent with the terminology presented here, together with sample configuration and input and output files, are available at this web site. An earlier version of the model code was used to produce the results described here.

## 1. Introduction

Human activities on land have markedly altered the export of dissolved and particulate nutrients from land to rivers and ultimately to coastal seas. These anthropogenic drivers, which include increased population, food production, sewage emissions and fossil fuel combustion, have led to both increased mobilization of reactive nutrients and alterations to hydrological systems, including rivers (Meybeck and Vörösmarty, 2005). The resulting coastal eutrophication and hypoxia (Diaz and Rosenberg, 2008), perturbation of aquatic community composition due to changing nutrient ratios (Humborg et al., 2000), and alterations in sediment inputs (Syvitski et al., 2005) are now a global-scale challenge. Spatially explicit global models are important tools for characterizing the large-scale

* Corresponding author at: Tel.: +1 206 543 6431; fax: +1 206 543 6785.
*E-mail address:* mayorga@apl.washington.edu (E. Mayorga).
1 Current address: Applied Physics Laboratory, University of Washington, Box 355640, Seattle, WA 98105-6698, USA.
2 Current address: International Geosphere-Biosphere Program, IGBP, The Royal Swedish Academy of Sciences, Lilla Frescativägen 4a, SE-114 18 Stockholm, Sweden.

1364-8152/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envsoft.2010.01.007

impact of these human actions on nutrient inputs to coastal waters (Smith et al., 2003; Van Drecht et al., 2003; Seitzinger et al., 2005; Boyer et al., 2006).

There is growing recognition of the distinct and inter-related impacts on coastal ecosystems caused by multiple nutrient elements and forms (Seitzinger et al., 2005). Phosphorus and silica, rather than nitrogen, can limit primary production. Changes in element ratios may lead to shifts in community composition as a result of contrasting nutrient requirements. Moreover, individual nutrient forms are characterized by different bioavailabilities and retention mechanisms. The Global Nutrient Export from WaterSheds (NEWS) work group of UNESCO-IOC (Intergovernmental Oceanographic Commission) has developed nutrient models to address this challenge. The first generation of NEWS models was used to model river export of dissolved and particulate forms of inorganic and organic nitrogen (N), phosphorus (P) and carbon (C) under contemporary conditions, including human pressures (Beusen et al., 2005; Dumont et al., 2005; Harrison et al., 2005a,b; Seitzinger et al., 2005). Since then, the NEWS models have been further developed. We have re-implemented all element-form sub-models in a common framework within a unified modeling environment, facilitating the application of Global NEWS as an integrated multi-element, multi-form model. In addition to the N, P and C sub-models, a NEWS model for dissolved silica was recently developed, but is described elsewhere (Beusen et al., 2009).

In this paper, we provide a comprehensive and integrated description of NEWS 2, the new generation of the NEWS model encompassing multiple nutrient forms; we leave detailed background discussions and development of individual model components in the 2005 version (NEWS 1) to the original publications. We highlight the representation of sources and sinks on land and rivers, and transfers from land to rivers and ultimately to the coast. NEWS distinguishes point sources, which include wastewater emissions from households and industries, and non-point or diffuse sources, including loading of rivers from agricultural land use and natural ecosystems.

We also describe model updates to NEWS 1. These model enhancements were implemented in support of a project to analyze past and future trajectories of nutrient inputs and river exports based on the Millennium Ecosystem Assessment (MEA) Scenarios (Carpenter et al., 2005). NEWS 2 meets the need for integrated models identified not only by the MEA Scenarios reports, but also by recent assessments of research grand challenges in global earth system and sustainability science (e.g., Reid et al., 2009). It was designed to improve consistency among sub-models, address outstanding issues, and incorporate important anthropogenic drivers that were previously uncharacterized. Scenario results are discussed extensively in a related series of articles (see Seitzinger et al., in press). Here, we present an overview of model inputs used for past, contemporary and scenarios conditions, including recent enhancements to the methods; complete details on inputs are published elsewhere (Bouwman et al., 2009; Van Drecht et al., 2009; Fekete et al., in press). Finally, we will discuss recalibration results, provide a brief assessment of contemporary river exports, and discuss future directions.

## 2. Global NEWS background: from NEWS 1 to NEWS 2

### 2.1. Global NEWS 1 model

NEWS 1 is composed of independently formulated, element-form sub-models that predict steady-state annual exports at the mouth of rivers for dissolved inorganic N (DIN; Dumont et al., 2005); dissolved inorganic P (DIP; Harrison et al., 2005a); dissolved organic forms (DON, DOP, DOC; Harrison et al., 2005b); and particulate N, P and C forms (PN, PP, POC; Beusen et al., 2005). These sub-models were designed to use a consistent set of global input datasets, hydrological and physical factors, and basin definition and hydrography (Seitzinger et al., 2005). Dissolved sub-models incorporate diffuse inputs from anthropogenic activities and natural processes, including fertilizers, manure, biological N fixation, atmospheric N deposition, P weathering, and DOC runoff from wetlands, as a function of specific crop types, land use, animal type, etc.; and point-source emissions of N and P into streams as a function of national and regional socioeconomic and sanitation information. Basins are defined using a consistent global river systems dataset (Vörösmarty et al., 2000). Like other regional to global river nutrient models (e.g., Caraco and Cole, 1999; Seitzinger et al., 2002a; Smith et al., 2003; Green et al., 2004; Boyer et al., 2006), NEWS 1 generally operates on inputs and forcings aggregated to the basin scale; however, most of these inputs are spatially distributed at 0.5° resolutions.

NEWS 1 sub-models represent a hybrid of empirical, statistical and mechanistic model components (Johnes, 1996; Worrall and Burt, 1999; Alexander et al., 2002; Seitzinger et al., 2005; Drewry et al., 2006), and include both natural and anthropogenic influences. Dissolved sub-models are broadly based on a mass-balance approach for the land surface (watershed) and river system, while particulate sub-models are largely statistical and based on a multiple linear regression and several single-regression relationships developed by Global NEWS or taken from the literature. For dissolved forms, inputs into watersheds and rivers are assessed from fluxes (estimated through bottom-up, spatially distributed calculations based on land-use types, regional agronomic and sanitation statistics, and atmospheric transport and deposition models); terrestrial retention parameterizations (based on runoff), and a refinement of the export-coefficient approach (based on modulation by runoff; Johnes, 1996; Worrall and Burt, 1999; Alexander et al., 2002). The dissolved sub-models also enable an apportionment of individual source contributions to total export at the basin mouth; in contrast, the statistical nature of the particulate sub-models prevents an analogous, detailed source attribution.

### 2.2. Towards Global NEWS 2

While NEWS 1 sub-models for dissolved forms were designed to share many common features and input data (Seitzinger et al., 2005), they were formulated and implemented independently. This led to partially inconsistent terminology, unclear elemental mass-balance implications, and some difficulties in jointly analyzing the sources and distribution of nutrient forms within an element or across elements. For NEWS 2, we have developed a unified formulation of the dissolved element-form sub-models. Terms and structures were adopted from all sub-models but primarily from NEWS 1 DIN. As the particulate sub-models are based on statistical and empirical approaches, these cannot be fully reframed into this dissolved formulation; also, the DOC sub-model features pronounced contrasts with dissolved N and P sub-models, particularly in its exclusive reliance on wetland versus non-wetland diffuse source types. Most NEWS 2 components are adopted directly from NEWS 1. NEWS 2 addresses previous shortcomings and inconsistencies, and introduces enhanced or updated inputs. Specific model updates relative to NEWS 1 are summarized in the Supplementary Material.

## 3. Unified sub-model of dissolved forms

The unified formulation for dissolved forms includes explicit sources to the watershed (imports of external origin, recycling, and mobilization or transformation to reactive forms within the watershed); explicit and parameterized land-based sinks from the watershed; inputs to streams from both explicit source-sink watershed accounting and net-source terms based on a refinement of the export-coefficient approach; and retention or loss within the river system (Table 1 and Fig. 1). As in NEWS 1, NEWS 2 generally operates on inputs and forcings aggregated to the basin scale. However, most of these inputs are spatially distributed at resolutions finer than the mean basin area used in global applications (Seitzinger et al., 2005). In addition, some factors – such as basin-wide reservoir retention – are calculated using highly specific within-basin information. Diffuse N and P sources originating in agricultural (anthropogenic) areas of the basin are distinguished from those originating in areas of natural ecosystems in order to facilitate the identification of contributions by each source type to nutrient export at the basin mouth.

Global NEWS assumes that nutrient elements are in steady-state and do not accumulate on land or in the river system; retained nutrients are lost or sequestered permanently. This assumption has been used successfully in regional (Johnes, 1996), continental (Howarth et al., 1996) and global applications (Bouwman et al., 2005; Boyer et al., 2006); Howarth et al. (1996) emphasized that steady-state is a reasonable assumption in areas that have been agricultural for a prolonged period of time. Accounting for interannual memory effects in the soil-groundwater system globally is hampered by limitations in historical nutrient inputs and river output data.

The river export of each dissolved element form is represented by the general yield ($Yld_F$) equation:

$$Yld_F = FE_{riv,F} \cdot (RSpnt_F + RSdif_F), \tag{1}$$

where F (subscript) is the nutrient form, and river sources (RS) are $RSpnt_F$, the export of F from the watershed to streams via point sources (sewage); and $RSdif_F$, the export of F from the watershed to streams via diffuse sources, both natural and anthropogenic. These source and export terms represent basin-scale fluxes and are expressed as kg (of N, P or C) per km$^2$ of basin area ($A$, km$^2$) per year, simplified as kg km$^{-2}$ yr$^{-1}$. $FE_{riv,F}$ is the fraction (0–1) of nutrient form F inputs to rivers (point + diffuse sources) that is exported at the basin mouth, corresponding to retention within the river system ($1 - FE_{riv,F}$). Each term of this high-level equation is expanded and described below, starting with sources. The total mass flux (load) of form F exported by the river, $Ld_F$, is equal to $Yld_F \cdot A$; here, basin load is typically presented in units of Mg yr$^{-1}$.

### 3.1. Sources

#### 3.1.1. Point sources: human waste emission to watershed, retention, and sewage export to streams

Point sources originate in emissions from human excrement and waste from household and industrial activities. These emissions are subsequently attenuated through wastewater treatment in areas connected to sewage systems, and through retention and removal in the landscape in unconnected areas. These watershed source and sink factors vary widely regionally and globally. NEWS 2 point-source calculations encompass N and P and are based on the work of Van Drecht et al. (2003, 2009). Watershed human waste emission of element E from excrement ($WShwExc_E$) is estimated as a function of national gross domestic product (GDP) and population density, while Van Drecht et al. (2009) introduced estimates of phosphorus emissions from laundry and dishwasher detergents ($WShwDet_P$). Emissions in areas not connected to sewage systems (rural and non-sewered urban) occur in a diffuse manner throughout a watershed (Green et al., 2004; Van Drecht et al., 2009), but in NEWS are assumed to be retained or lost from the watershed and therefore do not reach streams. Total, basin area normalized point-source emission (effluent) to streams of element E ($RSpnt_E$) is then calculated as:

$$RSpnt_E = (1 - hw_{frem,E}) \cdot I \cdot WShw_E \tag{2}$$

$WShw_E$ (kg km$^{-2}$ yr$^{-1}$) represents a gross human-waste source to the watershed, where $WShw_N = WShwExc_N$ and $WShw_P = WShwExc_P + WShwDet_P$; $I$ is the fraction of the population

**Table 1**
Types of watershed (land) and river sources, watershed sinks, and aquatic retention, by element form. The conceptual nature of diffuse fluxes is indicated.

| Source or sink term | Anthropogenic/Natural[a] | DIN | DON | DIP | DOP | DOC | PN, PP, POC |
|---|---|---|---|---|---|---|---|
| *Watershed (Land) and river sources* | | | | | | | |
| Diffuse land sources (explicit) | | | | | | | |
| Fertilizers | A | X | X | X | X | | |
| Animal manure | A | X | X | X | X | | |
| Biological fixation | A/N | X | | | | | |
| Atmospheric deposition | A/N | X | | | | | |
| Diffuse river sources (export-coefficient) | A/N | | X | X | X | X | |
| Point sources (human waste) | | | | | | | |
| Human excreta | A | X | X | X | X | | |
| Detergents | A | | | X | X | | |
| Regression-based factors[b] | – | | | | | | X |
| *Watershed (Land) sinks and aquatic retention* | | | | | | | |
| Diffuse | | | | | | | |
| Crop export & grazing (explicit) | A | X | X | X | X | | |
| Runoff-based retention[c] | A/N | X | X | X | X | X | |
| Point (human waste) | | | | | | | |
| Landscape retention | A | X | X | X | X | | |
| Sewage system connectivity and wastewater treatment | A | X | X | X | X | | |
| Aquatic retention | | | | | | | |
| Within channels | – | X | | | | | |
| Consumptive water loss | A | X | X | X | X | X | |
| Reservoirs | A | X | | X | | | X |

[a] Source or sink term is of anthropogenic (A) vs. natural (N) origin, or occurs over agricultural vs. natural areas of the basin or on both areas (A/N); "–" indicates that the term is applied to the entire basin without distinction by sub-area or origin.
[b] Precipitation seasonal intensity (Fournier precipitation), topographic slope (Fournier slope), dominant lithology, and anthropogenic land use (marginal grass and wetland rice percent).
[c] For diffuse sources based on an export-coefficient scheme, the runoff function does not represent a retention term per se.

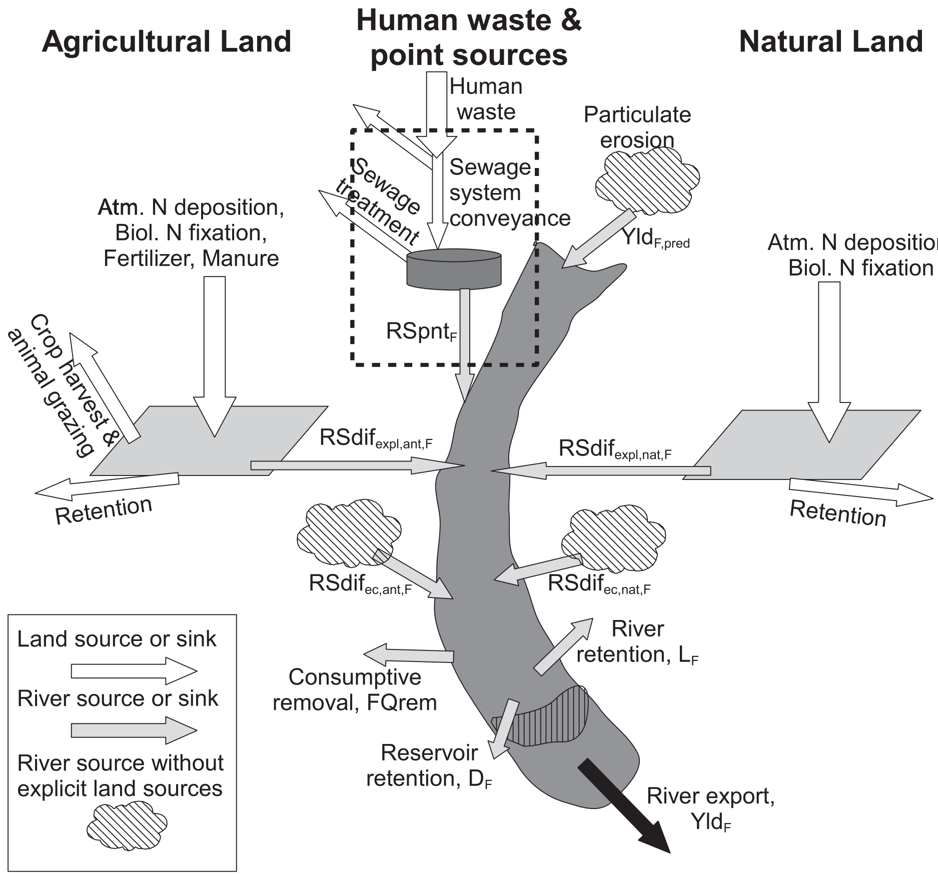


**Fig. 1.** Nutrient sources and sinks from the watershed (land-surface), sources to rivers (RS), and export to the river mouth. River sources and sinks are shown with their NEWS 2 terms, where F is the nutrient form and dissolved diffuse sources (dif) may be calculated explicitly (expl) or based on export coefficients (ec); see Sections 3 and 4, and Table A4. Diffuse sources may originate in agricultural (anthropogenic, ant) or natural (nat) areas. Particulate nutrient input is represented by its pre-dams (pred) yield.

connected to a sewage system; and $hw_{frem,E}$ is the fraction of E in sewage influent removed via wastewater treatment.

NEWS 1 introduced the calculation of point-source watershed export to streams as element-form F (river source $RSpnt_F$) from corresponding total elemental effluent, $RSpnt_E$. In NEWS 2, these schemes are generalized as:

$$RSpnt_F = FE_{pnt,F} \cdot RSpnt_E \tag{3}$$

where $FE_{pnt,F}$ is the fraction of $RSpnt_E$ emitted as form F. $FE_{pnt,F}$ for DIN is a linear, empirical function of $hw_{frem,N}$ (Discussion A3), while for all other N and P forms it is equal to a calibrated or default constant, $c_F$ (see Table A3).

For DOC, Harrison et al. (2005b) found that the inclusion of point sources in river basins did not improve model fit. Therefore, carbon point sources are not estimated.

### 3.1.2. *Diffuse sources: watershed sources and sinks, and export to streams*

Diffuse exports to streams result from both natural and anthropogenic inputs to watersheds and include the net effect of land-based retention or removal (watershed sinks) of nutrients (Fig. 1). In NEWS 2, net watershed diffuse N and P budgets ($WSdif_E$, where E is the element; kg km$^{-2}$ yr$^{-1}$) are constructed for the land-surface source and sink terms that are calculated explicitly, based on the work of Bouwman et al. (2005, 2009). On agricultural (anthropogenic, ant) areas of the watershed, this explicit budget for N is stated as the net N land-surface source, or agricultural surplus:

$$WSdif_{ant,N} = WSdif_{fe,N} + WSdif_{ma,N} + WSdif_{fix,ant,N} + WSdif_{dep,ant,N} - WSdif_{ex,N} \tag{4}$$

where subscripts denote source and sink terms, including synthetic fertilizers (fe), animal manure application (ma), biological N fixation (fix) by crops, atmospheric N deposition as NOy + NHx (dep), and withdrawal in harvested crops and animal grazing (ex, export; a removal or sink term). The explicit, agricultural budget for P is similar, but without biological fixation and atmospheric deposition. Negative $WSdif_{ant,E}$ estimates (i.e, $WSdif_{ex,E}$ exceeds explicit agricultural land-surface sources of element E, resulting in nutrient depletion of soils) are set to zero because negative N or P balances should not result in net decreases in N or P fluxes downstream through watersheds. Negative soil nutrient balances are found in many developing countries.

For natural areas (nat), the explicit land-surface N budget is comprised of ecosystem biological N fixation ($WSdif_{fix,nat,N}$) and atmospheric deposition ($WSdif_{dep,nat,N}$; includes deposition on inland water surfaces) sources only:

$$WSdif_{nat,N} = WSdif_{fix,nat,N} + WSdif_{dep,nat,N} \tag{5}$$

The net N source to the watershed (total N surplus, per Bouwman et al., 2009) is therefore the net balance of land-surface N sources and sinks over anthropogenic and natural areas of the watershed:

$$WSdif_N = WSdif_{ant,N} + WSdif_{nat,N} \tag{6}$$

For P, explicit sources to the watershed are not calculated for natural areas ($WSdif_{nat,P} = 0$). P released through weathering is discussed below. Finally, the DON sub-model relies on a partial accounting of explicit watershed sources that is analogous to the P budget approach:

$$WSdif'_{ant,N} = WSdif_{fe,N} + WSdif_{ma,N} - WSdif_{ex,N} \text{ and } WSdif'_{nat,N} = 0 \quad (7)$$

While this formulation differs from the complete, explicit N source accounting used for DIN (Eq. (4)), it is based on observed relationships between DON river export and fertilizer and animal manure inputs. Inclusion of a sink term ($WSdif_{ex,E}$) for P sub-models and DON is a feature introduced in NEWS 2.

Net inputs to the land-surface are subject to retention within soils, groundwater and riparian areas during transport to streams. While retention may involve permanent loss, transformation to unreactive forms, and temporary accumulation within soils and aquifers, steady-state implies that this watershed retention is treated as a permanent land sink. Export of dissolved N and P from the watershed to rivers has been shown to be positively correlated with water runoff as well as with inputs to the landscape (Caraco and Cole, 1999; Dumont et al., 2005; Harrison et al., 2005a,b; Meybeck and Vörösmarty, 2005; Howarth et al., 2006). The export of element E as dissolved form F originating in explicit (expl), diffuse sources and sinks ($RSdif_{expl,F}$) is estimated using a watershed export fraction term ($FE_{ws,F}$; 0–1):

$$RSdif_{expl,F} = FE_{ws,F} \cdot WSdif_E \quad (8)$$

$FE_{ws,F}$ is a function of mean annual water runoff from land to streams ($R_{nat}$):

$$FE_{ws,F} = e_F \cdot f_F(R_{nat}) \quad (9)$$

where $e_F$ is a calibrated, unitless watershed export constant and $f_F(R_{nat})$ is a runoff modulation function with one or two globally calibrated coefficients and with a shape determined empirically for each nutrient form.

In addition to explicit land sources and sinks, the DIP and dissolved organic matter sub-models include sources representing direct diffuse inputs to rivers from parameterized export processes operating similarly in natural and agricultural areas (see Harrison et al., 2005a,b). These sources are expressed as calibrated terms that may be described as a refinement of the export-coefficient approach (Johnes, 1996; Worrall and Burt, 1999; Alexander et al., 2002), where coefficients are modulated by runoff using the same $f_F(R_{nat})$ runoff function found in the corresponding $FE_{ws,F}$ term for explicit sources. For DIP, DON and DOP:

$$RSdif_{ec,F} = f_F(R_{nat}) \cdot EC_F \quad (10)$$

where $EC_F$ (kg km$^{-2}$ yr$^{-1}$) is a globally constant, calibrated export-coefficient term that is identical over natural and agricultural areas. For DIP, this source represents weathering of phosphorus-containing minerals, while for DON and DOP it corresponds to a net leaching or export of dissolved organic matter from land into streams. The net P weathering term may be equivalent to gross P mobilization by weathering only if the terrestrial ecosystem (natural or agricultural) does not accumulate phosphorus from this source. In contrast, the origin of the DON and DOP leaching export may represent either loss from accumulated organic matter in soils or additional export from the net explicit land source. The steady-state assumption implies that these river sources must be ultimately linked to net watershed sources ($WSdif_E$).

Total diffuse-source watershed export to streams for form F ($RSdif_F$) can now be stated as the sum of explicit and export-coefficient river sources (Fig. 1):

$$RSdif_F = RSdif_{expl,F} + RSdif_{ec,F} \quad (11)$$

$RSdif_F$ can also be described as agricultural and natural-area contributions:

$$RSdif_F = RSdif_{ant,F} + RSdif_{nat,F} = \left[FE_{ws,F} \cdot WSdif_{ant,E} + Ag_{fr} \cdot RSdif_{ec,F}\right] + \left[FE_{ws,nat,F} \cdot WSdif_{nat,E} + (1 - Ag_{fr}) \cdot RSdif_{ec,F}\right] \quad (12)$$

where $Ag_{fr}$ is the fraction of the basin covered by agricultural areas, and $FE_{ws,nat,F} = FE_{ws,F}$ except for DIN (see Section 3.1.3).

Finally, for DOC, explicit sources and sinks to the watershed (land ecosystem primary production and respiration, and crop exports) are not estimated. Instead, the sub-model incorporates diffuse sources to the river using only an export-coefficient approach (see Eq. (10) and preceding discussion), dividing the watershed into wetland (wet) and non-wetland (dry) areas, based on extensive observations of higher DOC exports from wetlands (Harrison et al., 2005b):

$$RSdif_{DOC} = RSdif_{ec,DOC} = RSdif_{ec,wet,DOC} + RSdif_{ec,dry,DOC} = \left[f_{DOC}(R_{nat}) \cdot EC_{wet,DOC} \cdot W_{fr}\right] + \left[f_{DOC}(R_{nat}) \cdot EC_{dry,DOC} \cdot (1 - W_{fr})\right] \quad (13)$$

where $W_{fr}$ is the fraction of the basin that is in wetlands, $f_{DOC}(R_{nat})$ is the runoff modulation function, and $EC_{wet,DOC}$ and $EC_{dry,DOC}$ are the export coefficients for wetland and non-wetland areas, respectively.

### 3.1.3. Watershed retention by element form

The watershed runoff function presented in Section 3.1.2 modulates the export of diffuse sources to streams. This function is empirically derived and takes one of two forms for dissolved sub-models. For all element forms except DIP:

$$f_F(R_{nat}) = (R_{nat})^{a_F} \quad (14)$$

while for DIP [Harrison et al., 2005a]:

$$f_F(R_{nat}) = \left[1 + (R_{nat}/a_F)^{-b_F}\right]^{-1} \quad (15)$$

$a_F$ is a calibrated or default constant specific to each nutrient form and $b_F$ is a second calibration constant used only in the DIP runoff function. The calibration of these constants and the runoff export constant $e_F$ is discussed in Section 6, and resulting, unitless values are presented in Table A2. $R_{nat}$ represents mean annual runoff (m yr$^{-1}$) from land to streams before consumptive water abstractions. In NEWS 1, $FE_{ws,F}$ was explicitly constrained to the range 0–1 only for DIN. Nonetheless, for other dissolved N and P forms $FE_{ws,F}$ never exceeds 1 and is effectively constrained to 0–1.

NEWS 2 has an improved representation of DIN watershed retention, developed because NEWS 1 overestimated DIN yields in large, forested, humid tropical basins such as the Amazon. This bias is difficult to address comprehensively as few robust river DIN export values exist for these systems, particularly near the mouth. Nevertheless, field observations strongly suggest that the bias is linked to the occurrence of high rates of N inputs via biological fixation that are largely balanced by correspondingly high N loss rates through denitrification in soils, groundwater and riparian areas (Cleveland et al., 1999, in press; Davidson et al., 2007; Davidson, 2008; Germer et al., 2009; Houlton et al., 2006; Markewitz et al., 2004; McClain and Elsenbeer, 2001; Neill et al., 2006), though pristine tropical rivers are often characterized by relatively elevated DIN yields compared to pristine temperate rivers (Downing et al., 1999; Lewis et al., 1999; Richey and Victoria, 1993). Previous models that have neglected biological N fixation in natural ecosystems (Seitzinger and Kroeze, 1998; Caraco and Cole, 1999; Seitzinger et al., 2002a) or applied a distinct retention term to inputs from N fixation (Green et al., 2004) do not appear to exhibit a tropical DIN bias. We applied a new watershed export constant, $e_{nat,DIN}$ and corresponding export fraction $FE_{ws,nat,DIN}$ to the natural portions of basins that are predominantly in the humid tropics (Section 5). Using the equations developed in Section 3.1.2, the watershed export (river sources) of diffuse nitrogen as DIN in these basins can be described as:

$$\begin{aligned} RSdif_{DIN} &= RSdif_{expl,ant,DIN} + RSdif_{expl,nat,DIN} \\ &= (FE_{ws,DIN} \cdot WSdif_{ant,N}) + (FE_{ws,nat,DIN} \cdot WSdif_{nat,N}) \end{aligned} \quad (16)$$

where, based on Eq. (11), $FE_{ws,DIN} = e_{DIN} \cdot f_{DIN}(R_{nat})$ and $FE_{ws,nat,DIN} = e_{nat,DIN} \cdot f_{DIN}(R_{nat})$.

#### 3.1.4. Export from arid basins

Global analyses of arid regions suggest that basins with $R_{nat} < 0.003$ m yr$^{-1}$ (3 mm yr$^{-1}$) flow to the mouth generally once every ten years (Vörösmarty et al., 2000; Meybeck and Vörösmarty, 2005). We assume that such inactive or arheic basins (Boyer et al., 2006; Meybeck et al., 2006) do not result in export of diffuse sources to the mouth (i.e., $f_F(R_{nat}) = 0$ when $R_{nat} < 0.003$ m yr$^{-1}$). However, as population centers in arid watersheds tend to cluster near the coast, the absence of river flow would typically not prevent the export of point sources to the basin mouth; therefore, in NEWS 2 point sources on arid basins can result in export at the basin mouth in the absence of diffuse exports.

### 3.2. Aquatic retention

Retention of nutrients within the river system can result from both natural and anthropogenic processes (Meybeck and Vörösmarty, 2005; Seitzinger et al., 2006, 2005). As with watershed retention within the landscape, aquatic retention may involve permanent loss, transformation to unreactive forms, and long-term but temporary storage. Following the approach used in NEWS 1 sub-models, this retention can occur in the form of three broad categories (Table 1 and Fig. 1), each expressed as a removal fraction (0–1): 1, retention within the river corridor (channel, river bed sediments, hyporheic areas and floodplains); 2, retention within constructed reservoirs, behind dams; and 3, removal from rivers through net water abstractions for irrigation and other human consumptive water use. For each dissolved element-form F, the aggregate river-system export fraction of F inputs to rivers that is exported at the basin mouth is calculated as the product of these components:

$$FE_{riv,F} = (1 - L_F) \cdot (1 - D_F) \cdot (1 - F\,Qrem) \quad (17)$$

where FQrem is the consumptive water removal fraction (identical for all forms), and $D_F$ and $L_F$ are the retention fractions within reservoirs and along the river network, respectively. The schemes used to estimate these retention components are described below. Implementation details and limitations are specific to the hydrological datasets used.

#### 3.2.1. River network retention

Metabolic processing, biogeochemical transformations and physical retention occurring along river channels and corridors can result in net loss or retention of nutrients exported from the landscape (Seitzinger et al., 2002b; Mulholland et al., 2008). However, model fit to observed river exports in NEWS 1 sub-models was found to improve only for DIN. NEWS 2 preserves those results, setting $L_F = 0$ for all dissolved nutrient forms except DIN (Table 1); for DIN, Dumont et al. (2005) adopted an empirical formulation for denitrification loss as a function of basin area.

#### 3.2.2. Reservoir trapping and retention

Reservoirs can have profound impacts on the transport of biogeochemical constituents by rivers (Humborg et al., 2000; Vörösmarty et al., 2003; Meybeck and Vörösmarty, 2005; Harrison et al., 2009). Detention of water behind dams increases the residence time of water and therefore the opportunities for removal processes to operate; for example, low-oxygen conditions developing at the bottom sediments are conducive to increased removal of reactive nitrogen through denitrification. The reduction of water velocity also promotes settling of particulates, enhancing long-term burial and removal at the bottom; reduced turbidity in the water column can in turn promote autochthonous primary production, leading to additional nutrient removal through settling of algal organic matter.

NEWS 2 preserves the reservoir retention (trapping efficiency) schemes from NEWS 1, which were based on published, empirical parameterizations. For DIN and DIP, retention at each reservoir is estimated as an empirical function of the mean annual change in river water residence time over unimpounded conditions (Vörösmarty et al., 2003), and basin-aggregated retention ($D_F$) is calculated as a discharge-weighted average of the retention within each reservoir. Complete details are found in Discussion A2. For dissolved organic forms, sufficient data or existing retention functions were not available, and we assumed $D_F = 0$ (Harrison et al., 2005b).

#### 3.2.3. Consumptive water use

Water removed from rivers for human consumption in irrigation and domestic and industrial use may be returned to the river or lost (consumed) permanently, primarily through evapotranspiration on irrigated lands and interbasin transfers (Jackson et al., 2001; Fekete et al., in press). In NEWS 2 (as in NEWS 1; e.g., Harrison et al., 2005a), biogeochemical constituents associated with net, consumptive water use are assumed to be permanently removed from the river system. The fraction of river discharge removed consumptively (FQrem) is estimated from total river discharge at the mouth before ($Q_{nat}$) and after ($Q_{act}$) the implementation of large-scale irrigation and other water withdrawal schemes (natural vs. actual discharge, in km$^3$ year$^{-1}$; Harrison et al., 2005a):

$$FQrem = (Q_{nat} - Q_{act})/Q_{nat} = 1 - Q_{act}/Q_{nat} \quad (18)$$

### 3.3. Dissolved yield, summarized and revisited

The NEWS 2 general yield equation for dissolved nutrient forms (Eq. (1)) can now be expanded by organizing river sources into anthropogenic ($RS_{ant,F}$) and natural ($RS_{nat,F}$) sources, where $RS_{ant,F} = RSpnt_F + RSdif_{ant,F}$ and $RS_{nat,F} = RSdif_{nat,F}$:

$$Yld_F = FE_{riv,F} \cdot \left[ (RSpnt_F + RSdif_{ant,F}) + RSdif_{nat,F} \right] \quad (19)$$

The detailed use of this model equation is illustrated for DIN and DOP in Discussion A3.

### 3.4. Source attribution

Multiple natural and anthropogenic sources contribute to the export of nutrients at basin mouths. The utility of river nutrient models like Global NEWS depends to a great extent on their ability to estimate the contribution of each watershed and river source to the export of constituents to the coast, by individual nutrient form as well as total elemental flux (EEA, 2005; Withers and Sharpley, 2008). NEWS 1 sub-models for dissolved forms introduced schemes for separating river export into contributions from individual sources. In NEWS 2, we have harmonized and expanded these approaches for dissolved N and P forms.

NEWS 2 provides dissolved-form source allocation at two levels of detail: a coarse attribution (level-1) that estimates the contribution from three broad source categories, and a detailed attribution (level-2) that subdivides each level-1 source into individual components such as fertilizer and atmospheric deposition. This scheme is adapted from the approach used in the NEWS 1 DON and DOP models (Harrison et al., 2005b). For each of the two attribution levels, the largest source (which may represent <50% of total yield) can be identified and the nature of dominant sources compared across forms.

#### 3.4.1. Coarse attribution (level-1)

The contribution from each broad source category to basin export (kg km$^{-2}$ yr$^{-1}$) of each nutrient form (subscript F) is calculated by applying the river-system export fraction ($FE_{riv,F}$) to each river source term in Eq. (19), resulting in three level-1 yield sources: $YS1pnt_F$, the source contribution from point sources; and $YS1dif_{ant,F}$ and $YS1dif_{nat,F}$, the contribution from all diffuse sources in agricultural and natural areas of the basin, respectively. This approach provides a fully consistent, comparable set of source categories for dissolved N and P forms.

#### 3.4.2. Detailed attribution (level-2)

In level-2 attribution, level-1 sources are subdivided into detailed, individual sources. Human excrement (point source), fertilizer and manure sources are used in all dissolved N and P forms and therefore appear as level-2 source types for all forms. However, other sources – such as P weathering – are specific to one or more forms and cannot be compared across all forms.

For point sources, phosphorus inputs may originate in human excrement and P-based detergents (Section 3.1.1), and their contributions are therefore estimated as two distinct level-2 sources. The river source P contribution from human excrement ($RSpntExc_P$) and detergents ($RSpntDet_P$) can be calculated by replacing $WShw_P$ with $WShwExc_P$ and $WShwDet_P$, respectively, in Eqs. (2) and (3), and applying $FE_{riv,F}$ to each river source term, similar to level-1 attribution calculations. $YS2pntExc_F$ and $YS2pntDet_F$ are then the level-2 yield sources from human excrement and P-based detergents (kg P km$^{-2}$ yr$^{-1}$), respectively, where nutrient form F is DIP or DOP. In contrast, point N inputs originate in human excrement only; therefore, $RSpntDet_F = 0$ for DIN and DON.

For diffuse sources from agricultural areas (anthropogenic), level-2 source attribution is adjusted for crop harvest and grazing nutrient withdrawal by adapting the approach presented by Dumont et al. (2005) for DIN. This approach is based on a proportional allocation of the watershed export (sink) flux to each watershed diffuse source term. For DIN, it is accomplished through the multiplication of each diffuse source term by the fraction $G_{DIN}$ of land-surface diffuse sources remaining after harvest and grazing:

$$\begin{aligned} G_{DIN} &= WSdif_{ant,N}/WSdif_{gross,ant,N} \\ &= 1 - WSdif_{ex,N}/WSdif_{gross,ant,N} \end{aligned} \quad (20)$$

where $WSdif_{gross,ant,N}$ is the sum of all watershed N sources on agricultural areas (gross sources; see Section 3.1.2).

As discussed earlier (Section 3.1.2), the DON, DIP and DOP sub-models also include river sources that cannot be unambiguously formulated as gross fluxes to watersheds and are described in NEWS 2 as a refinement of the export-coefficient approach. We therefore assume that the harvest and grazing export or withdrawal term is only allocated to explicit, anthropogenic watershed sources (fertilizer and manure), maintaining the land and soil system in steady-state. For DIP and DOP:

$$G_{DIP} = G_{DOP} = WSdif_{ant,P}/WSdif_{gross,ant,P} \quad (21)$$

where $WSdif_{gross,ant,P} = WSdif_{fe,P} + WSdif_{ma,P}$. As the DON sub-model relies on a partial diffuse watershed N balance in agricultural areas that, like the P balance, includes only fertilizer and manure inputs ($WSdif'_{ant,N}$; see Section 3.1.2), $G_{DON} \neq G_{DIN}$:

$$G_{DON} = WSdif_{ant,N}/WSdif'_{gross,ant,N} \quad (22)$$

Level-2 contribution by each anthropogenic, explicit diffuse source is then calculated as with other sources above by multiplying the equivalent river source by the export-correction term, $G_F$. For example, the atmospheric N deposition (Dep) source attribution for DIN is:

$$YS2difDep_{ant,DIN} = FE_{riv,DIN} \cdot [(FE_{ws,DIN} \cdot WSdif_{dep,ant,N}) \cdot G_{DIN}] \quad (23)$$

The same approach is used with agricultural N fixation for DIN, and fertilizers and manure for all dissolved N and P forms. For export-coefficient sources, the agricultural river source is used directly; e.g., the DIP source attribution for P weathering (Wth) is:

$$YS2difWth_{ant,DIP} = FE_{riv,DIP} \cdot (RSdif_{ec,DIP} \cdot Ag_{fr}) \quad (24)$$

The same approach is used with agricultural, export-coefficient leaching for DON and DOP.

For diffuse sources from areas of natural ecosystems, level-2 attribution is calculated using the same approach used in agricultural areas. Only DIN includes explicit watershed sources, and no harvest and grazing correction is involved. Attribution for P weathering and N and P export-coefficient leaching is calculated as in Eq. (24), but using the natural fraction ($1 - Ag_{fr}$) of the basin.

#### 3.4.3. DOC attribution

The DOC sub-model includes no point sources and only two diffuse sources, wetlands and drylands. Therefore, the source attribution scheme used for dissolved N and P forms cannot be applied directly. As wetlands and drylands occur within both natural and agricultural areas, the level-1 attribution scheme is not used. Instead, the level-2 attribution simply subdivides total DOC yield into contributions from wetlands ($YS2difWet_{DOC} = RSdif_{ec,wet,DOC}$) and drylands ($YS2difDry_{DOC} = RSdif_{ec,dry,DOC}$).

## 4. Particulates sub-model

The Global NEWS particulate nutrient sub-models previously referred to as NEWS-PNU were presented in Beusen et al. (2005). Each sub-model (POC, PN and PP) is based on a simple statistical regression and is ultimately grounded on a multiple linear regression model for total suspended sediment (TSS) yield also developed by Beusen et al. (2005). For NEWS 2, small but potentially significant changes were introduced (see Discussion A1). Here we present a concise description of model components.

Unlike the dissolved sub-models, the particulate sub-models do not support the attribution of river exports to individual sources.

Nevertheless, the anthropogenic origin of certain independent factors in the TSS model may represent a basis for a separation of anthropogenic from natural contributions to particulate exports.

### 4.1. Total suspended sediments

The TSS model was developed using a large set of river observations that are generally unimpacted by extensive damming (pre-dam), and a wide range of potential independent factors spanning hydrographic, climatic, land use, soil, topographic and lithological basin properties. Each factor was tested using a stepwise regression on log-transformed, pre-dam TSS yield ($Yld_{TSS,pred}$, in Mg km$^{-2}$ yr$^{-1}$), resulting in the selection of five significant factors; three of these (precipitation seasonality, a relief index and dominant lithology) reflect climate and physical conditions while the other two (wetland rice and marginal grassland) reflect specific land-use types that are largely of anthropogenic origin. The model equation is described in Discussion A4.

To limit the occurrence of anomalous TSS yield estimates, the values of each basin factor are truncated to the minimum and maximum values found in the basins used to develop the model (Table A3). For basins dominated by water or ice in the lithology dataset, TSS yield is set to zero. In addition, NEWS 2 introduces a maximum allowable yield of 5000 Mg km$^{-2}$ yr$^{-1}$, equal to approximately twice the maximum TSS yield found in the river dataset. Finally, as done for dissolved forms with diffuse sources, it is assumed that arid basins ($R_{nat} < 0.003$ m yr$^{-1}$) produce no export of particulates.

The impact of sediment trapping by dams is estimated in the same manner as with dissolved nutrient forms:

$$Yld_{TSS} = (1 - D_{TSS}) \cdot Yld_{TSS,pred} \tag{25}$$

where $Yld_{TSS}$ is the actual sediment export yield at the mouth of the basin and $D_{TSS}$ is the basin-aggregated reservoir retention factor. TSS load ($Ld_{TSS,pred}$ and $Ld_{TSS}$, Mg km$^{-2}$ yr$^{-1}$) is the product of yield (pre or post-reservoir) times basin area (km$^2$). Trapping of suspended sediments behind dams is calculated using the approach of Vörösmarty et al. (2003). While this retention scheme is broadly similar to the ones for dissolved nutrients, one important contrast is that retention from sequential reservoirs within a basin is pre-aggregated before calculating the basin-scale retention; details are presented in Discussion A5.

### 4.2. Particulate nutrients

Particulate organic carbon (POC) export is estimated using an empirical relationship with suspended sediment concentration (Ludwig et al., 1996):

$$TSSpc_{POC,pred} = -0.160\left[\log(TSSc_{pred})\right]^3 + 2.83\left[\log(TSSc_{pred})\right]^2 - 13.6\log(TSSc_{pred}) + 20.3 \tag{26}$$

where $TSSpc_{POC,pred}$ is the pre-dam POC content as % of TSS, and $TSSc_{pred}$ (mg L$^{-1}$) is the pre-dam, annually averaged suspended sediment concentration, calculated as $Yld_{TSS,pred}/R_{nat}$ ($R_{nat}$ is in m yr$^{-1}$). This relationship between POC and TSS is consistent with observations that particulate organic carbon content in suspended sediments decreases or is diluted by mineral particles at high sediment loads (Meybeck, 1982). Next, particulate nitrogen (PN) export is estimated using an empirical relationship with POC content (Ittekkot and Zhang, 1989):

$$TSSpc_{PN,pred} = 0.116 \cdot TSSpc_{POC,pred} - 0.019 \tag{27}$$

where $TSSpc_{PN,pred}$ is the pre-dam PN content as % of TSS. Finally, particulate phosphorus (PP) export is estimated using a relationship with POC load developed by Beusen et al. (2005):

$$\ln(1000 \cdot Ld_{PP,pred}) = -3.096 + 1.002 \cdot \ln(1000 \cdot Ld_{POC,pred}) \tag{28}$$

where ln is the natural log, and $Ld_{PP,pred}$ and $Ld_{POC,pred}$ are the pre-dam PP and POC loads (in Mg yr$^{-1}$). $TSSpc_{PP,pred}$ is then calculated from $Ld_{PP,pred}$ and $Ld_{TSS,pred}$.

Yields (kg km$^{-2}$ yr$^{-1}$) for POC, PN and PP before and after reservoir retention can now be calculated, assuming particulates and their associated nutrients are retained at the same rate:

$$Yld_{F,pred} = 1000 \cdot (TSSpc_{F,pred}/100) \cdot Yld_{TSS,pred} \tag{29}$$

$$Yld_F = (1 - D_{TSS}) \cdot Yld_{F,pred} \tag{30}$$

where F is the element form. Corresponding nutrient loads (Mg yr$^{-1}$) are calculated from yields and basin area. Note that although these sub-models provide total particulate N and P (PN and PP) rather than differentiated inorganic and organic particulate forms, PN occurs largely as organic matter while PP is typically dominated by inorganic forms (Meybeck, 1982).

## 5. Model inputs

The Millennium Ecosystem Assessment (MEA) scenario implementation by the Global NEWS working group motivated the development of NEWS 2. This effort involved consistent model application and data development from the recent past (1970) to the present (2000), and two future years (2030 & 2050) for the four MEA scenarios (see Bouwman et al., 2009; Seitzinger et al., in press). It included enhancements to input datasets and uniform application of input pre-processing steps across nutrient forms and model runs. Here we summarize the input data used (Table 2); complete descriptions are published elsewhere (Bouwman et al., 2009; Van Drecht et al., 2009; Fekete et al., in press), and important changes relative to datasets used in NEWS 1 are compiled in Discussion A1. Scenario assumptions on population growth, economic development, protein consumption, urbanization and sanitation trends are used to project future agricultural land use distributions, diffuse and point sources and sinks, and water use.

### 5.1. Hydrography, areas, physical environment and regionalization

NEWS 2 was applied on the STN-30p river system (Vörösmarty et al., 2000), a global 0.5° × 0.5° grid dataset (excluding Antarctica) that delineates flow directions and all major basins draining to the coast. We removed permanently glaciated, northern high-latitude cells (Boyer et al., 2006; Vörösmarty et al., 2000) from version 6.01 to create a non-glaciated version (Fig. 2) containing 6081 basins, including 164 endorheic basins. Basin areas (km$^2$) were recalculated with a global grid of 0.5° cell areas created using a spheroid-based approach (Kimerling, 1984). This grid was also used in area-weighted aggregations to basin scale. While STN-30p treats cells as fully land or sea, diffuse and point source datasets (below) use a land mask specifying the land fraction of each 0.5° cell. Cell areas and land fractions were used jointly, as appropriate. For the particulate sub-models, dominant lithology and Fournier slope are calculated as presented in Beusen et al. (2005); see also Table A3. Finally, we provide aggregations of basins into ocean drainages, continents and latitude bands (Table 2 and Fig. 2a–c) to facilitate consistent regional analyses; these regional groupings are

**Table 2**
Input datasets.

| Dataset | Resolution | Time-varying | DIN | DON | DIP | DOP | DOC | PN, PP, POC | Sources[b] |
|---|---|---|---|---|---|---|---|---|---|
| *Hydrography, areas and regions* | | | | | | | | | |
| Basins and river networks | 0.5° | | X | X | X | X | X | X | 1 |
| Cell and land area | 0.5° | | X | X | X | X | X | X | 1, 2, 3 |
| Continents, oceans[a] | basin | | X | X | X | X | X | X | 1, 4 |
| Latitude bands[a] | basin | | X | X | X | X | X | X | 5 |
| *Geophysical* | | | | | | | | | |
| Lithology | 1° | | | | | | | X | 6, 7 |
| Topography | 0.5° | | | | | | | X | 6, 8 |
| *Climate and hydrology* | | | | | | | | | |
| Precipitation | 0.5° | X | | | | | | X | 2, 9, 10 |
| Runoff & Discharge | 0.5° | X | X | X | X | X | X | X | 9 |
| Consumptive water use | 0.5° & basin | X | X | X | X | X | X | | 9, 11 |
| Reservoirs | 0.5° & dam | X | X | | X | | | X | 9, 12 |
| *Land use and ecosystems* | | | | | | | | | |
| Agriculture & sub-classes | 0.5° | X | X | X | X | X | | | 2 |
| Wetland rice & marginal grassland | 0.5° | X | | | | | | X | 2 |
| Wetlands | 0.5 min | | | | | | X | | 13 |
| Humid Tropical Forests (Köppen-Geiger Climate Zones) | 0.5° | | X | | | | | | 14 |
| *Point sources (socioeconomic and sanitation drivers)* | | | | | | | | | |
| Gross Domestic Product | Nation | X | X | X | X | X | | | 15 |
| Total and urban population density | 0.5° | X | X | X | X | X | | | 15 |
| Sanitation statistics | Nation/region | X | X | X | X | X | | | 15 |
| Detergent emissions | Nation/region | X | | | X | X | | | 15 |
| *Diffuse sources* | | | | | | | | | |
| Fertilizers, manure, crop harvest & animal grazing | 0.5° | X | X | X | X | X | | | 2 |
| Biological N fixation, atmospheric N deposition | 0.5° | X | X | | | | | | 2 |

[a] Used for analysis of results.
[b] Data sources: 1, Vörösmarty et al. (2000); 2, Bouwman et al. (2009); 3, Processed as described in text; 4, With modified continents; 5, Based on mouth cell latitude; 6, Beusen et al. (2005); 7, Amiotte-Suchet et al. (2003); 8, NGDC (2002); 9, Fekete et al. (in press); 10, New et al. (1999); 11, Meybeck and Ragu (1996); 12, Vörösmarty et al. (2003); 13, Lehner and Döll (2004); 14, Kottek et al. (2006); 15, Van Drecht et al. (2009).

also used in the MEA scenario analysis presented elsewhere (see Seitzinger et al., in press).

### 5.2. Climate and hydrology

We make use of HadCM2 GCM climate forcings scaled through the IMAGE model (Bouwman et al., 2009), and hydrological model runs (WBMplus model; Fekete et al., in press) executed largely as unconstrained simulations. While this approach may lead to results (e.g., discharge) that differ from contemporary observations, it provides for comparability of results across all time periods. Hydrological simulations include runs with and without anthropogenic alterations, and schemes implemented to project future conditions. Large contemporary reservoirs are derived from an existing database, and the location and capacity of future large reservoirs are estimated from regional hydropower projections. Nutrient retention (Sections 3.2.2 and 4.1) is then calculated from individual reservoir characteristics as implemented and modeled in WBMplus (Fekete et al., in press). Basin-scale consumptive removal (FQrem) is calculated from Eq. (18) using modeled $Q_{act}$ and $Q_{nat}$. However, discharge from rivers with large consumptive withdrawals or evaporative losses is poorly simulated. For example, only a 5% discharge reduction is modeled for the Nile in year 2000, compared to an observed discharge reduction of >90% since the 1950s (Milliman et al., 2008; Meybeck and Ragu, 1996). Therefore, for 2000 we replace modeled FQrem with observed values from Meybeck and Ragu (1996) where available (121 large basins), following Harrison et al. (2005a, 2005b); past and future FQrem is scaled to observations by applying the difference between 2000 modeled and observed values.

To assess the impact of bias in pure simulations, Fekete et al. (in press) also performed a more realistic simulation for contemporary conditions using climate observations (New et al., 1999) and the discharge-gage correction approach from Fekete et al. (2002). We will compare predicted nutrients exports from these results with those using baseline, simulated hydrology for the year 2000.

### 5.3. Land use, ecosystems and nutrient sources

Bouwman et al. (2009) provide agricultural land-use class distributions by grid cell, where the land portion of a cell is assumed to be either fully agricultural or natural. Basin-scale agricultural area is calculated from cell values. Wetland distribution is estimated from Lehner and Döll (2004), as described by Harrison et al. (2005b). Using the Kottek et al. (2006) dataset, basins with >50% coverage in Group A (equatorial) Köppen–Geiger climate zones are classified as predominantly humid tropical for the DIN sub-model.

Bouwman et al. (2009) calculate cell-based explicit N and P diffuse sources and sinks to the watershed (Tables 1 and 2), separated into agricultural vs. natural fluxes. These fluxes are calculated by land-use type, crop characteristics, animal type and national or regional agricultural information and projections, using the IMAGE model and other sources.

Watershed urban wastewater emission of N and P is estimated as a function of national GDP, following Van Drecht et al. (2009). Van Drecht et al. introduced estimates of P emissions from laundry and dishwasher detergents. Sewage system connectivity and nutrient removal through wastewater treatment are estimated from national and regional sanitation statistics. Population density is available at the cell scale. Combining this information, cell-scale emissions to land and rivers are calculated before aggregation to the basin.

## 6. Calibrations

In the NEWS sub-models, global-scale calibrations are performed using nutrient export observations at river mouths. For

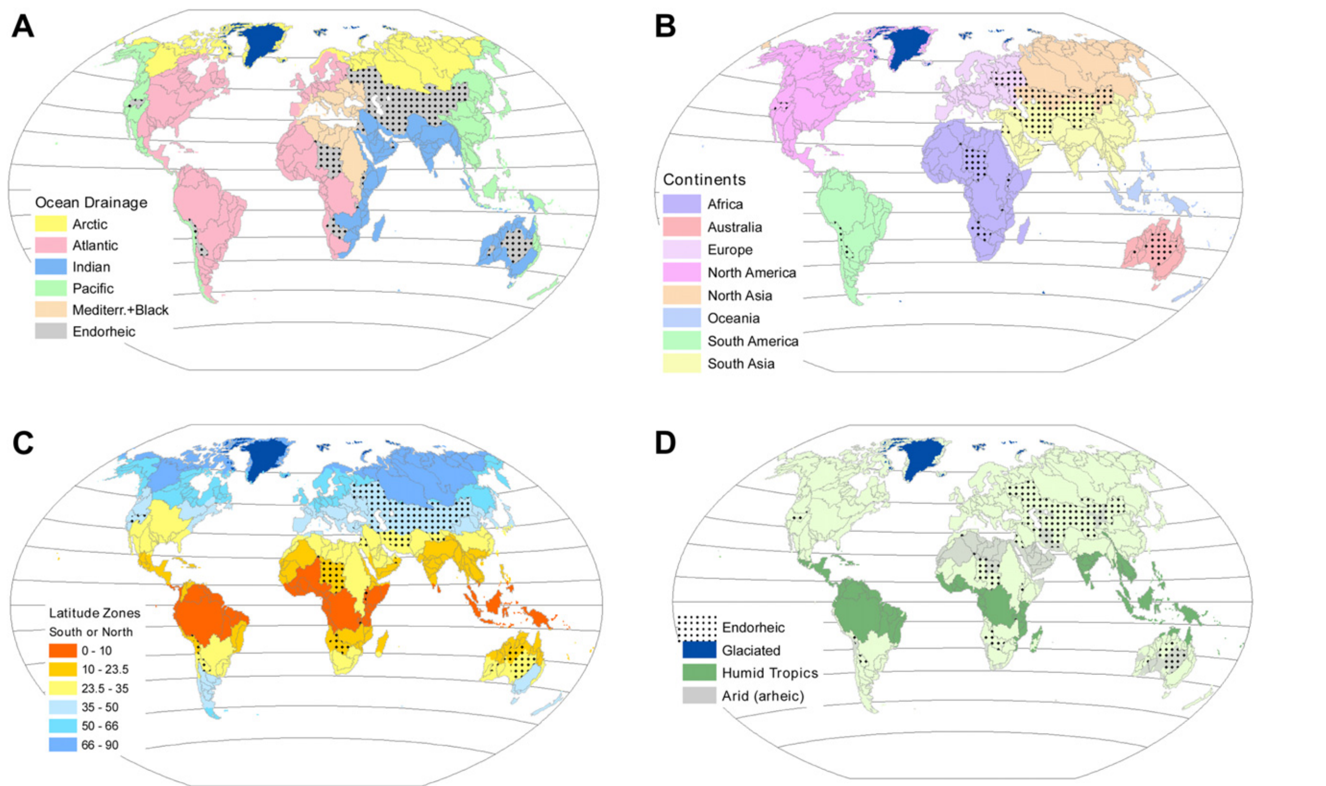


**Fig. 2.** Regions used in NEWS 2, representing aggregations of basins. Every map shows permanently glaciated regions (dark blue), endorheic basins (stippled), major basin boundaries and latitude bands. A. Ocean drainages (Vörösmarty et al., 2000). B. Continents; from Vörösmarty et al. (2000), but with Asia divided into North (latitude of basin mouth cell > 45°N) vs. South Asia. C. Latitude bands based on basin mouth cells (Symmetric N. and S. bands: 0–10°, 10–23.5°, 23.5–35°, 35–50°, 50–66°, and 66–90°). D. Tropical humid basins (dark green), and arid basins for year 2000 simulation (gray). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

NEWS 2, recalibration of dissolved N and P sub-models was necessary in order to account for modified input datasets and model components. DOC and particulate sub-models were not recalibrated, as their inputs and model components were largely unchanged or the modifications did not impact calibration basins or the calibration schemes. Recalibrations were carried out using largely the same procedures described in NEWS 1 (Dumont et al., 2005; Harrison et al., 2005a,b), newly estimated nutrient input sources for the year 2000, observed hydrological factors (Meybeck and Ragu, 1996; Vörösmarty et al., 2003) (but see below for DIN), and small changes to the river observation dataset (Table A5) relative to NEWS 1, particularly for DIN. Parameter values were tested over realistic ranges, selecting the set that maximized the Nash–Sutcliffe model efficiency ($R^2$) (Moriasi et al., 2007) on log-transformed basin yields (natural log for DIN and $\log_{10}$ for other forms). For DON and DOP, all calibration parameters ($a_F$, $c_F$, $e_F$ and $EC_F$) were recalibrated, while for DIP only $e_F$ was recalibrated, as the other three ($a_F$, $b_F$ and $EC_F$) were previously calibrated for pristine conditions where the DIP sub-model is unchanged from NEWS 1.

The calibration approach for the new DIN parameter for natural areas in humid tropical basins ($e_{nat,DIN}$) required the addition of new humid tropical river observations, as only three calibration basins previously met that criteria; 5 such observations and 2 general tropical observations (Meybeck and Ragu, 1996) were added to the calibration set (Table A5). Parameter $e_{DIN}$ was first calibrated by excluding humid tropical basins, and the resulting value was then kept fixed while calibrating $e_{nat,DIN}$ using only humid tropical basins. This two-step calibration was performed to avoid parameter interactions that could negatively impact basins outside the humid tropics. To reduce high bias on actual, untransformed DIN yields, we also constrained average model error (ME) on non-tropical rivers to a maximum absolute value of 15% and evaluated this constraint on humid tropical rivers as well. ME is defined as positive for model overestimates and is defined as $(1/n)\ \Sigma_{i\ =\ 1\ldots n}\ 100\cdot(M_i - O_i)/O_i$, where $n$ is the number of observations and $M_i$ and $O_i$ are the individual modeled and observed yields, respectively (Alexander et al., 2002; Dumont et al., 2005).

Early tests indicated that the DIN sub-model was more sensitive than other sub-models to the hydrological factors used for calibration, particularly runoff (e.g., for DIP, see Harrison et al., 2005a). To minimize artifacts in DIN exports under the MEA scenarios, we also calibrated this sub-model to the pure-simulation hydrological forcings that served as drivers for the MEA model runs, and used only these calibration parameters with the MEA NEWS 2 runs. These two calibrations will be compared below.

For DON, DOP and DIP, we divided river observations into independent calibration and validation sub-sets, as described by Harrison et al. (2005a,b). Only calibration $R^2$ values will be reported here, as previous results and new tests indicated that calibration and validation model fit were similar.

## 7. Results and discussions

### 7.1. Calibration and model assessment

Fig. 3 shows calibration results for export yields from recalibrated nutrient forms (dissolved N and P forms), indicating that NEWS 2 can explain the observed variation to a reasonable extent. The highest model fit occurs with DON and DOP (Nash-Sutcliffe efficiency $R^2 = 0.71$ and 0.90, respectively), the forms that feature the weakest control by nutrient sources. Their calibration $R^2$ values are identical to those from NEWS 1 (Harrison et al., 2005b). DIP displays a comparable model fit relative to NEWS 1 (0.51 vs. 0.62).

Using the simulated hydrology results implemented in the MEA scenarios, DIN calibration model fit is lower than in NEWS 1 ($R^2 = 0.54$ vs. 0.70) but within the range found in the two NEWS 1 validation assessments (0.54 and 0.78). $R^2$ with simulated hydrology is optimal with a calibration procedure that constrains the average model error (ME) to a maximum absolute value of 15% only for basins outside the humid tropics, resulting in a lower absolute ME than the median model error identified in NEWS 1 (6% vs. 20%). Calibration with observed hydrology allowed us to select a more robust model ($R^2 = 0.60$ and absolute ME $= 9\%$) that constrains both non-tropical and humid tropical basins to an absolute value of ME $< 15\%$. NEWS 2 DIN sub-model predictions display a lower bias than in NEWS 1. Nevertheless, calibration tests with either simulated or observed hydrology indicated that the highest model efficiency is obtained when removing the tropical observations added in NEWS 2, highlighting the need for additional, globally representative and better-constrained nutrient export observations. NEWS 2 nutrient sub-models remain approximately as robust as NEWS 1 models while providing additional capabilities and more consistent drivers.

For DON and DOP, the calibrated parameter $a_F$ (Table A2) is lower than in NEWS 1 by 10% and 14%, respectively, while $e_F$ is identical for DON and lower by 50% for DOP; these changes indicate a reduced sensitivity to runoff and diffuse nutrient inputs, particularly for DOP. $c_F$ is lower than in NEWS 1 by 18 and 50% for DON and DOP, respectively, reflecting a lower sensitivity to sewage inputs which in the case of DOP may reflect the increase in P sewage inputs in NEWS 2 due to inclusion of P detergent contributions. $EC_F$ values are similar to those in NEWS 1. In contrast, for DIP the recalibrated parameter (watershed export constant, $e_F$) experienced a large increase (620%), resulting in a much greater sensitivity to runoff and diffuse nutrient inputs. For DIN, the parameter $e_F$ recalibrated with simulated hydrology is lower by 14%, while the new export constant for humid tropical basins ($e_{nat,F}$) was calibrated to 11% the value of $e_F$, reflecting the postulated higher retention in these basins.

### 7.2. NEWS 2 river export of nutrients for the year 2000

Global and regional results from the application of NEWS 2 for the year 1970, 2000 and the MEA scenarios, including source attributions, are discussed extensively in a series of articles (see Seitzinger et al., in press). Here we limit our focus to the year 2000, providing a general overview and assessment of results. Global annual export of total N (TN), P (TP) and organic C (TOC) from rivers is estimated to be 44.9 Tg N, 9.04 Tg P and 317 Tg C, respectively (Fig. 4); corresponding exports to the coast (exorheic basins) are 43.2 Tg N, 8.57 Tg P and 303 Tg C. These values are similar to

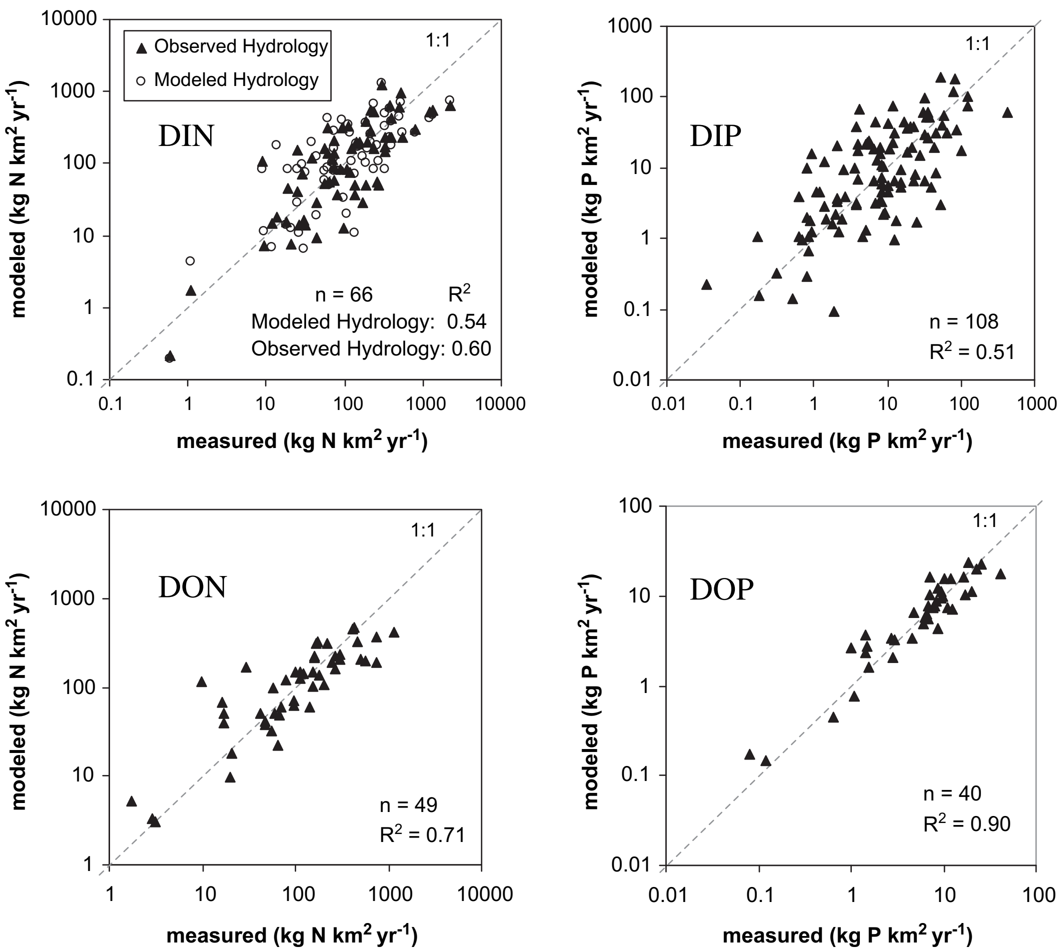


**Fig. 3.** Modeled vs. measured yields (log–log) for nutrient forms recalibrated for NEWS 2. The number of basin observations used ($n$) and the calibration model efficiency ($R^2$, based on log-transformed yields) are shown for each form. Calibration results using observed hydrology data are shown for all forms. An additional calibration result using modeled, uncorrected hydrology is also shown for DIN.

previous estimates, though generally at the lower end of published ranges (Meybeck, 1982; Ludwig et al., 1996; Seitzinger et al., 2005; Boyer et al., 2006). Exorheic TN exports are within the published range (e.g., 38.6 Tg N, Green et al., 2004; 48 Tg N, Boyer et al., 2006; and 66 Tg N, Seitzinger et al., 2005). Few TP export estimates exist, but our exorheic value is also within the published range (e.g., 9 Tg P, Meybeck, 1982; 11 Tg P, Seitzinger et al., 2005). TOC exports are somewhat lower than other estimates (e.g., 367 Tg C, Seitzinger et al., 2005; 380 Tg C, Ludwig et al., 1996). The distribution among forms for global exorheic exports varies by element (Fig. 4), dominated by DIN (43.7%) and PN (31.2%) for nitrogen, PP (76.5%) and to a much lesser extent by DIP (16.7%) for phosphorus, and with slightly higher exports by DOC (53.9%) for organic carbon.

TN exports display a distribution between endorheic and total global exports (3.7%, Fig. 4) that is similar to the 3.5% value of Green et al. (2004), but much lower than the 19% of Boyer et al. (2006). The reason for this contrast with Boyer et al. is unclear, but lower export from endorheic areas relative to their global coverage (13.9% of total global area) is consistent with their more arid and sparsely populated character compared to exorheic basins (Vörösmarty et al., 2000).

Total exports and distribution among forms vary substantially across regions (Figs. 4 and 5), as has been pointed out previously (Ludwig et al., 1996; Green et al., 2004; Seitzinger et al., 2002a, 2005; Boyer et al., 2006). South Asia is a prominent hot spot of export as a result of high runoff, high relief and large human pressures, representing about 28% of global exorheic TN and TP export while covering only 15% of global exorheic area. Large runoff and substantial relief in South America also lead to globally high exports, despite lower human pressures. More generally, the tropics – particularly the humid tropics – represent a zone of high export to the coast, accounting for 55–64% of global TN, TP and TOC exports. However, patterns of distribution among forms vary with multiple regional characteristics. For example, high DIN and DIP yields are indicators of anthropogenic pressures (Smith et al., 2003; Seitzinger et al., 2005), as seen in Europe and at the sub-region or basin scale, as hot spots in the Eastern USA, Japan, Indonesia and large areas of South Asia (Figs. 4 and 5). While the Atlantic Ocean

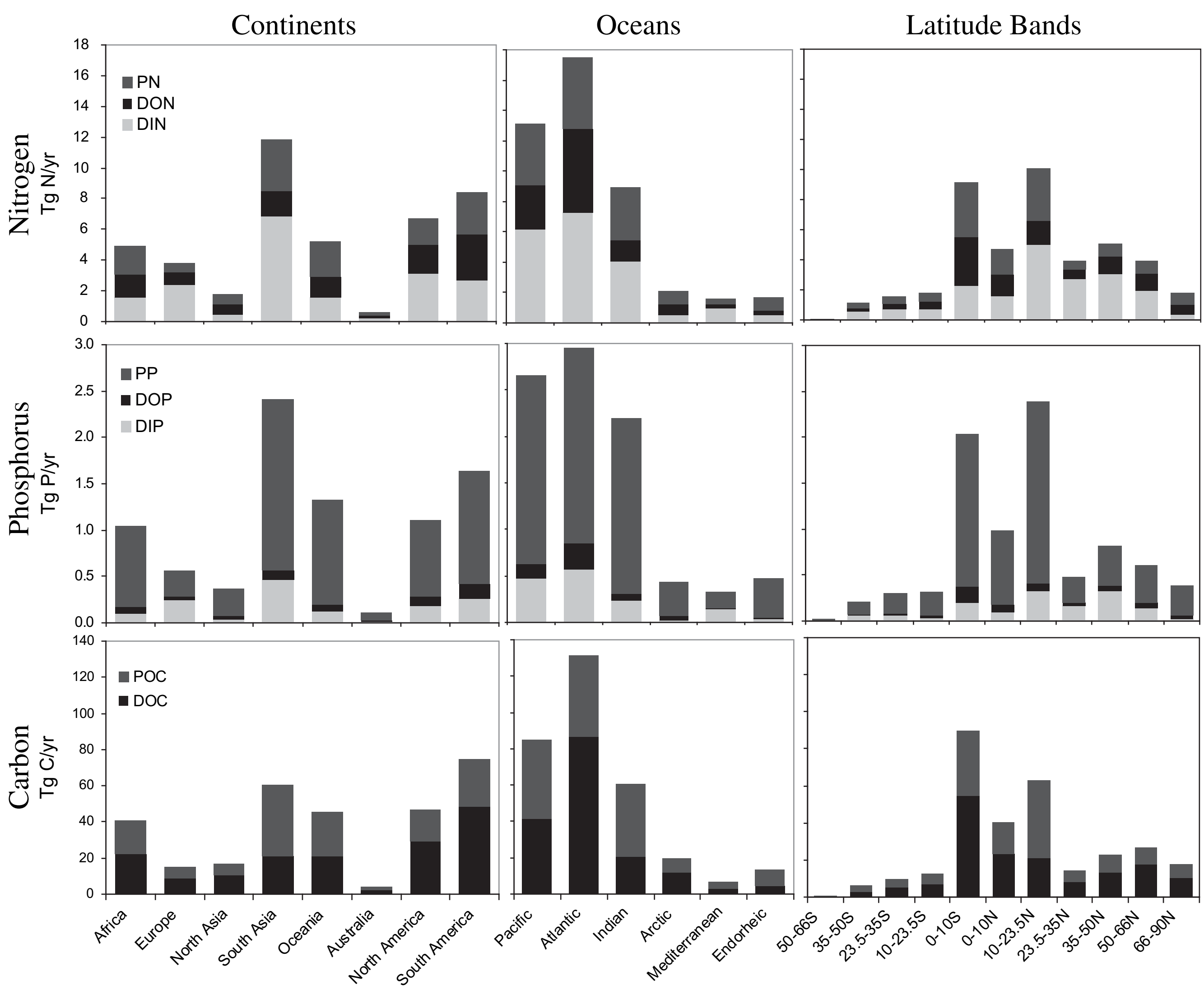


**Fig. 4.** Regional nutrient export for the year 2000. Exports of each N (top), P (middle) and C (bottom) nutrient form (Tg yr$^{-1}$) by continent (left), ocean drainage (center), and latitude band (right). The ocean figures show endorheic exports, while continent and latitude-band figures include only exports to the oceans (exorheic). The Mediterranean includes the Black Sea as well. Regional extents are shown in Fig. 2.

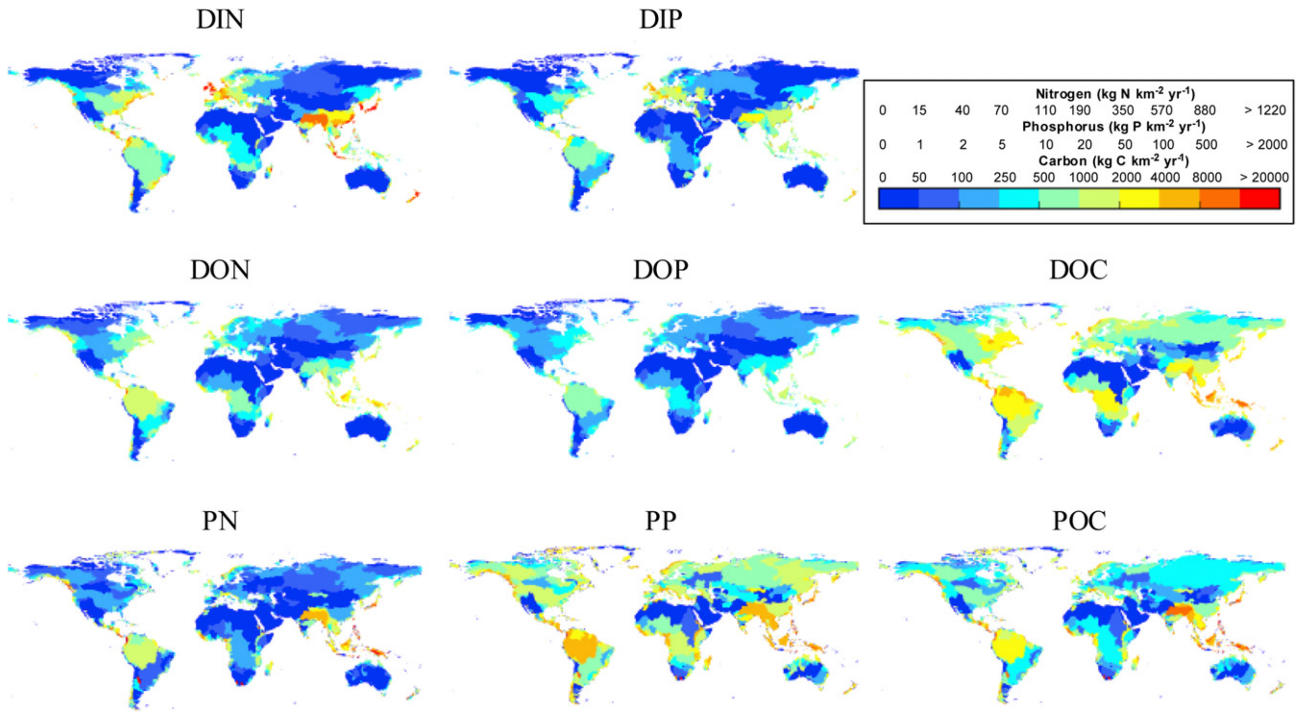


**Fig. 5.** Maps of yields (kg km$^{-2}$ yr$^{-1}$) for the year 2000, for each N (left), P (center) and C (right) nutrient form. A common legend is used for all forms in each element, and the same colour ramp and number of classes are used across all forms.

drainage area (45.7 × 10$^{6}$ km$^{2}$) is more than twice that of the Pacific or Indian oceans, particulate nutrient loads are similar in all three drainages (Fig. 4) as a result of erosion from higher topographic relief in the Pacific and Indian drainages that leads to particulate yields twice as high as in the Atlantic (e.g., for PN, 102, 90 and 46 kg N km$^{-2}$ yr$^{-1}$ in the Pacific, Indian and Atlantic drainage, respectively; Figs. 4 and 5); in contrast, similar dissolved organic yields in the Pacific and Atlantic lead to the Atlantic having exports that are twice as high and a greater contribution by dissolved organic forms to total elemental exports. Finally, although regional comparisons among model results are hampered by differences in inputs and calibrations (Boyer et al., 2006), Oceania (Fig. 2) TN exports in NEWS 2 and Green et al. (2004) provide an interesting contrast. Global exorheic TN exports are similar (see above), but the contribution of Oceania is an order of magnitude higher in NEWS 2 (12% vs. 1%); higher NEWS 2 exports derive in large part (Fig. 4) from the model's form-specific focus that enables it to isolate distinct drivers for particulate exports in this mountainous region.

Differences between year-2000 NEWS 2 results using realistic hydrology (gage-corrected and forced with observed climate) and results using MEA modeled hydrology are relatively small (10–25% or less; not shown). For regional exports to the coast, the most prominent contrast is in DIN from South Asia, which increased with realistic hydrology by 43% (from 6.9 to 9.8 Tg N yr$^{-1}$). This globally significant increase in load is driven by increased runoff, reflected by a 31% increase in discharge to the coast, in a region characterized by high diffuse N inputs from anthropogenic activities and high runoff. While global exorheic export increased from 18.9 to 22.4 Tg N yr$^{-1}$, both estimates remain within the published range (Smith et al., 2003; Green et al., 2004; Dumont et al., 2005).

### 7.3. NEWS 2 nutrient exports compared to NEWS 1

NEWS 2 sub-models differ from NEWS 1 sub-models in both model formulation and inputs. While they display a similar capacity to explain the observed variation in nutrient export among basins, new features, improved consistency among sub-models, and incorporation of newly characterized anthropogenic drivers represent significant enhancements over NEWS 1. Therefore, insights may be gained by assessing major differences in model output for contemporary conditions between NEWS 2 (year 2000) and NEWS 1 (year 1995; from NEWS 1 publications, including small corrections implemented after publication). The 5-year difference between the baselines for these two versions is considered to be negligible relative to changes resulting from modifications to input methods (Bouwman et al., 2009; Van Drecht et al., 2009).

At regional to global scales, NEWS 2 exports differ from NEWS 1 primarily for particulate forms and DIN (Fig. 6). The largest contrast occurs with export of particulates in Oceania (Fig. 6), a reduction from 9.3 to 2.3 Tg N yr$^{-1}$ from NEWS 1 to NEWS 2, respectively. This is largely the result of a new constraint on maximum yield of total suspended sediment (TSS) imposed to limit the occurrence of very small basins with extremely high, anomalous exports. In more arid regions, the use of a more stringent definition of arid basins with zero export (maximum runoff of 3 rather than 1 mm/yr) also constrained the export of particulates. Global exorheic PN, PP and POC exports were reduced by 53.0, 27.2 and 27.2%, to 13.5 Tg N yr$^{-1}$, 6.56 Tg P yr$^{-1}$and 140 Tg C yr$^{-1}$, respectively. These exports are somewhat lower than published values (Meybeck, 1982; Ludwig et al., 1996; Seitzinger et al., 2002a) discussed in Beusen et al. (2005). However, they are based on an estimate of TSS export to the coast of 14.4 Pg yr$^{-1}$ that is more consistent with the recent, robust assessment of 12.4 Pg yr$^{-1}$ from the QRT model of Syvitski et al. (2005) than is the NEWS 1 estimate of 16.8 Pg yr$^{-1}$. Nonetheless, both estimates are bracketed by the assessments from QRT (above) and 18.1 Pg yr$^{-1}$ from Ludwig et al. (1996).

DIN export was substantially reduced across tropical regions in NEWS 2 (Figs. 6 and 7) as a result of the new humid tropical scheme intended to minimize overestimates in NEWS 1. This is the driver for a reduction in exorheic global DIN export from 25.5 Tg N (NEWS 1) to 18.9 Tg N/yr (NEWS 2). Decreases in DIN yield of more than

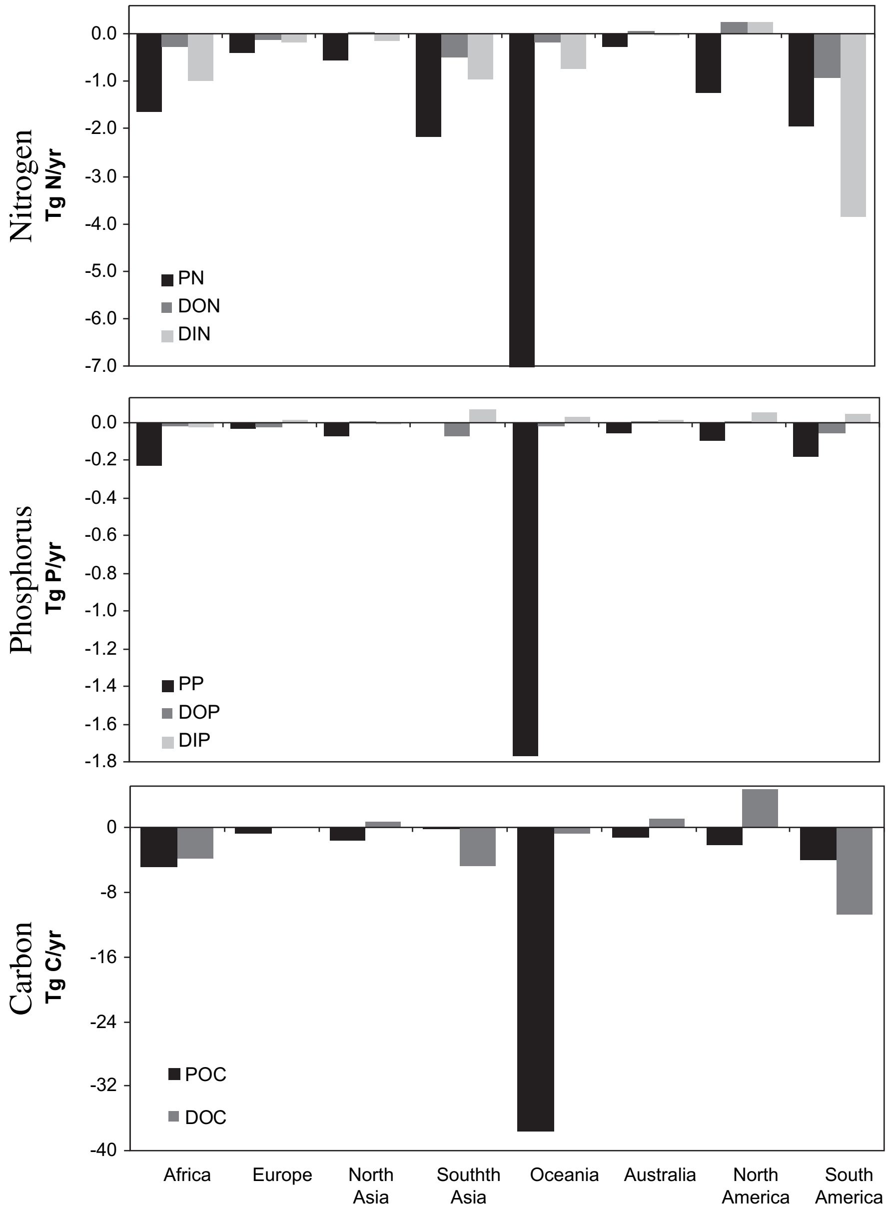


**Fig. 6.** Difference between year 2000 simulated exports and published NEWS 1 exports for 1995 (Seitzinger et al., 2005), aggregated by continent (exorheic exports only). Positive values represent an increase in NEWS 2 exports relative to NEWS 1.

80 kg N km$^{-2}$ yr$^{-1}$ can be seen all across the humid tropics (Fig. 7). Other changes are visible, though their driving factors are less clear. In developed, northern temperate countries, most of Western Europe and some small basins in the Eastern USA, many of which are known to exhibit high DIN yields, show decreased yields due to a combination of factors that include an underestimation of runoff in the MEA simulated hydrology for year 2000. However, this decrease is offset regionally by an increase from other basins, including Scandinavia, Eastern Europe, parts of North America and Japan (Fig. 7).

The combined impact of net reductions in DIN and PN exports is a substantially lower global exorheic TN load compared to NEWS 1 (Fig. 6), from 66 to 43.2 Tg N yr$^{-1}$; however, the NEWS 1 estimate was somewhat higher than other, published estimates (discussed above).

Differences between NEWS 1 and NEWS 2 for other dissolved forms are small to moderate. DIP export shows a small but broad increase (Figs. 6 and 7) as the net effect of multiple model changes, including the addition of P detergent to sewage. Increases are observed from North America to South Asia and parts of Europe, while smaller decreases are seen in Central Africa, parts of Oceania and South Asia, and Germany. A small reduction in global DOC export (<10%) is the combined effect of an updated wetland dataset and simulated runoff. For DOM sub-models, common regional contrasts for DON, DOP and DOC reflect the preeminent role of runoff (Fig. 6; see Harrison et al., 2005b).

### 7.4. Future directions

NEWS 2 is the first global, spatially explicit model to assess river export of multiple nutrients in a consistent way. It includes improved and unified representation of river basins, model formulations and model inputs. A strength of NEWS 2 is that nutrient form sub-models have been implemented in a fully integrated fashion to analyze past and future trends, ensuring consistency in model inputs and calculations. Nutrient sub-models

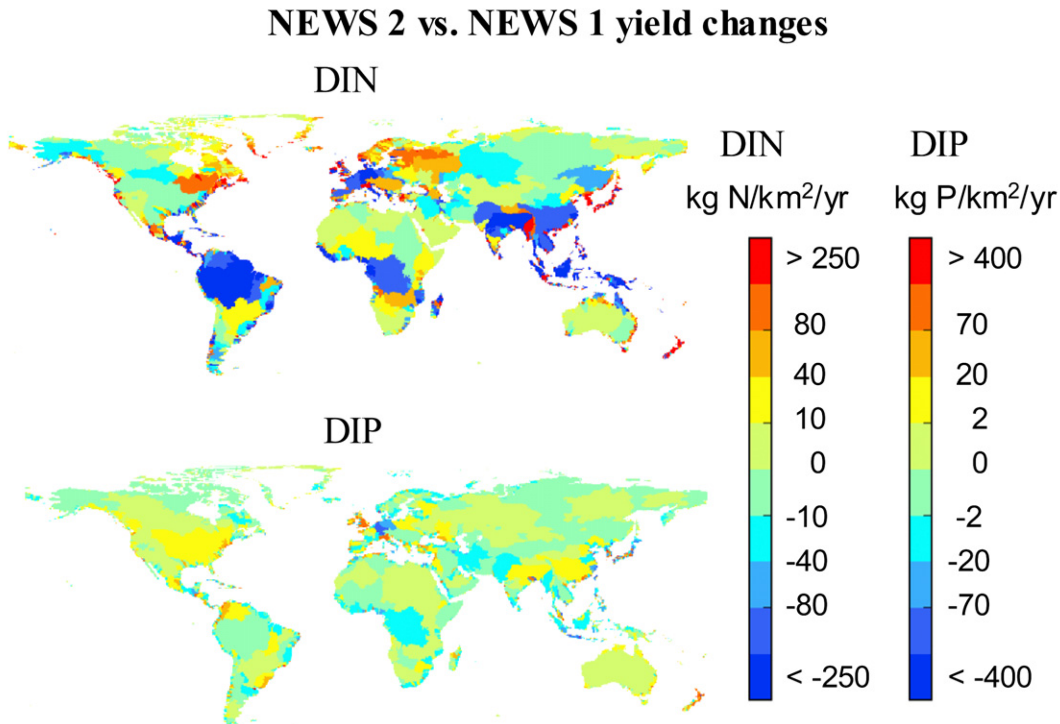


**Fig. 7.** Maps comparing NEWS 2 modeled DIN and DIP yields for the year 2000 to NEWS 1 results for 1995 (Dumont et al., 2005; Harrison et al., 2005a). This contrast is shown as the difference between NEWS 2 and NEWS 1 basin yields (kg $km^{-2}$ $yr^{-1}$), where positive values represent an increase in NEWS 2 basin yield relative to NEWS 2.

remain approximately as robust as NEWS 1 sub-models while providing additional capabilities and more consistent drivers. NEWS 2 can serve as an effective tool to analyze the effects of policies to reduce negative coastal impacts at regional from basin nutrient exports at regional to global scales. Here, we discuss ongoing and potential future enhancements.

Existing gaps in element forms are currently being closed. A multiple linear regression sub-model analogous to the existing TSS sub-model was recently developed for dissolved silica (DSi) (Beusen et al., 2009); ongoing improvements are focusing on reservoir retention parameterizations. This addition will greatly enhance our ability to address coastal perturbations such as eutrophication and shifts in phytoplankton community composition driven by changing ratios of exported nutrients (Humborg et al., 2000; Diaz and Rosenberg, 2008). We are also implementing a dissolved inorganic carbon (DIC) sub-model that will enable NEWS 2 to address the coupling of carbon and nutrient cycling, from weathering of multiple bioactive elements to metabolism and fixation of organic matter.

Some ambiguities remain in the separation of diffuse sources into anthropogenic versus natural contributions. For instance, atmospheric N deposition on natural areas may originate from distant anthropogenic sources. A similar uncertainty occurs in the calculation contributions from some additional anthropogenic diffuse sources. However, improving these attribution features would require a more detailed assessment of natural and anthropogenic sources.

The Global NEWS model evolved from a focus on basin-scale inputs and export of nutrients to the coast. However, improvements in the representation of spatially distributed watershed inputs and retention mechanisms along the path from terrestrial sources to the river mouth are enabling more complex analyses of the large-scale, coupled transformations and fate of nutrient forms. Constraining the generation and retention of nutrients forms from land to river systems to the coast at regional to continental scales remains a significant challenge. NEWS 2 represents an important contribution in this regard. Further enhancements will likely require addressing spatial heterogeneities within basins. We are currently pursuing this approach by downscaling important model equations for DIP to the scale of 0.5-degree cells, with promising initial results (Harrison et al., 2010).

Many of these future enhancements depend strongly on observations along river systems. The wide availability of river measurements that are extensive, representative of multiple watershed scales and conditions across the world, and with a better assessment of uncertainties, is a fundamental requirement for improving the robustness of model predictions; Harrison et al. (2010) illustrate the value of tributary observations for global nutrient modeling.

## Acknowledgments

We are grateful to UNESCO-IOC for supporting this work and to Charles Vörösmarty, Dominik Wisser, Rosalynn Lee, Gilles Billen, Josette Garnier and the rest of the Global NEWS working group for useful discussion and feedback. We thank Cory Cleveland and Chris Neill for discussions on tropical nitrogen cycling. NASA supported the work of E. M., S. P. S., J. A. H. and B. M. F. NOAA additionally supported the work of S. P. S. The work of A. H. W. B., A. F. B. and G. V. was part of the project Integrated Terrestrial Modeling of the Netherlands Environmental Assessment Agency (PBL).

## Appendix. Supplementary material

Supplementary material for this article is available in the online version at doi:10.1016/j.envsoft.2010.01.007.

## References


Alexander, R.B., Johnes, P.J., Boyer, E.W., Smith, R.A., 2002. A comparison of models for estimating the riverine export of nitrogen from large watersheds. Biogeochemistry 57/58, 295–339.

Amiotte-Suchet, P., Probst, J.-P., Ludwig, W., 2003. Worldwide distribution of continental rock lithology: implications for the atmospheric/soil $CO_2$ uptake by continental weathering and alkalinity river transport to the oceans. Global Biogeochemical Cycles 17, 1038. doi:10.1029/2002GB001891.

Beusen, A.H.W., Dekkers, A.L.M., Bouwman, A.F., Ludwig, W., Harrison, J., 2005. Estimation of global river transport of sediments and associated particulate C, N, and P. Global Biogeochemical Cycles 19, GB4S05. doi:10.1029/2005 GB002453.

Beusen, A.H.W., Bouwman, A.F., Dürr, H.H., Dekkers, A.L.M., Hartmann, J., 2009. Global patterns of dissolved silica export to the coastal zone: results from a spatially explicit global model. Global Biogeochemical Cycles 23, GB0A02. doi:10.1029/2008GB003281.

Bouwman, A.F., Van Drecht, G., Van der Hoek, K.W., 2005. Surface N balances and reactive N loss to the environment from global intensive agricultural production systems for the period 1970–2030. Pedosphere 15, 137–155.

Bouwman, A.F., Beusen, A.H.W., Billen, G., 2009. Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050. Global Biogeochemical Cycles 23, GB0A04. doi:10.1029/2009GB003576.

Boyer, E.W., Howarth, R.W., Galloway, J.N., Dentener, F.J., Green, P.A., Vörösmarty, C.J., 2006. Riverine nitrogen export from the continents to the coasts. Global Biogeochemical Cycles 20, GB1S91. doi:10.1029/2005GB002537.

Caraco, N.F., Cole, J.J., 1999. Human impact on nitrate export: an analysis using major world rivers. Ambio 28, 167–170.

Carpenter, S., Pingali, P., Bennett, E., Zurek, M. (Eds.), 2005. Ecosystems and Human Well-being. Scenarios: Findings of the Scenarios Working Group, vol. 2. Island Press.

Cleveland, C.C., et al., 1999. Global patterns of terrestrial biological nitrogen ($N_2$) fixation in natural ecosystems. Global Biogeochemical Cycles 13, 623–645.

Cleveland, C.C., Houlton, B.Z., Neill, C., Reed, S.C., Townsend, A.R., Wang, Y. Using indirect methods to constrain symbiotic nitrogen fixation rates: a case study from an Amazonian rain forest. Biogeochemistry, in press. doi:10.1007/s10533-009-9392-y.

Davidson, E.A., et al., 2007. Recuperation of nitrogen cycling in Amazonian forests following agricultural abandonment. Nature 447, 995–998.

Davidson, E.A., 2008. Biogeochemistry: fixing forests. Nature Geoscience 1, 421–422.

Diaz, R.J., Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. Science 321, 926–929.

Downing, J.A., et al., 1999. The impact of accelerating land-use change on the N-cycle of tropical aquatic ecosystems: current conditions and projected changes. Biogeochemistry 46, 109–148.

Drewry, J.J., Newham, L.T.H., Greene, R.S.B., Jakeman, A.J., Croke, B.F.W., 2006. A review of nitrogen and phosphorus export to waterways: context for catchment modelling. Marine and Freshwater Research 57, 757–774.

Dumont, E., Harrison, J.A., Kroeze, C., Bakker, E.J., Seitzinger, S.P., 2005. Global distribution and sources of dissolved inorganic nitrogen export to the coastal zone: results from a spatially explicit, global model. Global Biogeochemical Cycles 19, GB4S02. doi:10.1029/2005GB002488.

EEA, 2005. Source Apportionment of Nitrogen and Phosphorus Inputs into the Aquatic Environment. European Environment Agency.

Fekete, B.M., Vörösmarty, C.J., Grabs, W., 2002. High-resolution fields of global runoff combining observed river discharge and simulated water balances. Global Biogeochemical Cycles 16, 1042. doi:10.1029/1999GB001254.

Fekete, B.M., Wisser, D., Kroeze, C., Mayorga, E., Bouwman, A., Wollheim, W.M., Vörösmarty, C.J. Millennium ecosystem assessment scenario drivers (1970–2050): climate and hydrological alterations. Global Biogeochemical Cycles, in press.

Germer, S., Neill, C., Vetter, T., Chaves, J., Krusche, A.V., Elsenbeer, H., 2009. Implications of long-term land-use change for the hydrology and solute budgets of small catchments in Amazonia. Journal of Hydrology 364, 349–363.

Green, P.A., Vörösmarty, C.J., Meybeck, M., Galloway, J.N., Peterson, B.J., Boyer, E.W., 2004. Pre-industrial and contemporary fluxes of nitrogen through rivers: a global assessment based on typology. Biogeochemistry 68, 71–105.

Harrison, J., et al., 2009. The regional and global significance of nitrogen removal in lakes and reservoirs. Biogeochemistry 93, 143–157.

Harrison, J.A., Bouwman, A.F., Mayorga, E., Seitzinger, S.P., et al., 2010. Magnitudes and sources of dissolved inorganic phosphorus inputs to surface fresh waters and the coastal zone: a new global model. Global Biogeochemical Cycles 24, GB1003, doi:10.1029/2009GB003590.

Harrison, J.A., Caraco, N.F., Seitzinger, S.P., 2005a. Global patterns and sources of dissolved organic matter export to the coastal zone: results from a spatially explicit, global model. Global Biogeochemical Cycles 19, GB4S04. doi:10.1029/2005GB002480.

Harrison, J.A., Seitzinger, S.P., Bouwman, A.F., Caraco, N.F., Beusen, A.H.W., Vörösmarty, C.J., 2005b. Dissolved inorganic phosphorus export to the coastal zone: results from a spatially explicit, global model. Global Biogeochemical Cycles 19, GB4S03. doi:10.1029/2004GB002357.

Houlton, B.Z., Sigman, D.M., Hedin, L.O., 2006. Isotopic evidence for large gaseous nitrogen losses from tropical rainforests. Proceedings of the National Academy of Sciences 103, 8745–8750.

Howarth, R.W., Swaney, D.P., Boyer, E.W., Marino, R., Jaworski, N., Goodale, C., 2006. The influence of climate on average nitrogen export from large watersheds in the Northeastern United States. Biogeochemistry 79, 163–186.

Howarth, R.W., et al., 1996. Regional nitrogen budgets and riverine N & P fluxes for the drainages to the North Atlantic Ocean: natural and human influences. Biogeochemistry 35, 75–139.

Humborg, C., Conley, D.J., Rahm, L., Wulff, F., Cociasu, A., Ittekkot, V., 2000. Silicon retention in river basins: far-reaching effects on biogeochemistry and aquatic food webs in coastal marine environments. Ambio 29, 45–50.

Ittekkot, V., Zhang, S., 1989. Pattern of particulate nitrogen transport in world rivers. Global Biogeochemical Cycles 3, 383–391.

Jackson, R.B., et al., 2001. Water in a changing world. Ecological Applications 11, 1027–1045.

Johnes, P.J., 1996. Evaluation and management of the impact of land use change on the nitrogen and phosphorus load delivered to surface waters: the export coefficient modelling approach. Journal of Hydrology 183, 323–349.

Kimerling, A.J., 1984. Area computation from geodetic coordinates on the spheroid. Surveying and Mapping 44, 343–351.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World Map of the Köppen–Geiger climate classification updated. Meteorologische Zeitschrift 15, 259–263.

Lehner, B., Döll, P., 2004. Development and validation of a global database of lakes, reservoirs and wetlands. Journal of Hydrology 296, 1–22.

Lewis Jr., W.M., Melack, J.M., McDowell, W.H., McClain, M., Richey, J.E., 1999. Nitrogen yields from undisturbed watersheds in the Americas. Biogeochemistry 46, 149–162.

Ludwig, W., Probst, J.L., Kempe, S., 1996. Predicting the oceanic input of organic carbon by continental erosion. Global Biogeochemical Cycles 10, 23–41.

Markewitz, D., Davidson, E., Moutinho, P., Nepstad, D., 2004. Nutrient loss and redistribution after forest clearing on a highly weathered soil in Amazonia. Ecological Applications 14, S177–S199.

McClain, M.E., Elsenbeer, H., 2001. Terrestrial inputs to Amazon streams and internal biogeochemical processing. In: McClain, M.E., Victoria, R.L., Richey, J.E. (Eds.), The Biogeochemistry of the Amazon Basin. Oxford University Press, pp. 185–208.

Meybeck, M., 1982. Carbon, nitrogen, and phosphorus transport by world rives. American Journal of Science 282, 401–450.

Meybeck, M., Dürr, H.H., Vörösmarty, C.J., 2006. Global coastal segmentation and its river catchment contributors: a new look at land-ocean linkage. Global Biogeochemical Cycles 20, GB1S90. doi:10.1029/2005GB002540.

Meybeck, M., Ragu, A., 1996. River discharges to the oceans: an assessment of suspended solids, major ions, and nutrients. In: Environment Information and Assessment. U.N. Environment Programme, pp. 1–245.

Meybeck, M., Vörösmarty, C.J., 2005. Fluvial filtering of land-to-ocean fluxes: from natural Holocene variations to anthropocene. Comptes Rendus Geoscience 337, 107–123.

Milliman, J.D., Farnsworth, K.L., Jones, P.D., Xu, K.H., Smith, L.C., 2008. Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951–2000. Global and Planetary Change 62, 187–194.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE 50, 885–900.

Mulholland, P.J., et al., 2008. Stream denitrification across biomes and its response to anthropogenic nitrate loading. Nature 452, 202–205.

Neill, C., Elsenbeer, H., Krusche, A.V., Lehmann, J., Markewitz, D., Figueiredo, R.D.O., 2006. Hydrological and biogeochemical processes in a changing Amazon: results from small watershed studies and the large-scale biosphere-atmosphere experiment. Hydrological Processes 20, 2467–2476.

New, M., Hulme, M., Jones, P., 1999. Representing twentieth-century space-time climate variability. Part I: Development of a 1961–90 mean monthly terrestrial climatology. Journal of Climate 12, 829–856.

NGDC, 2002. NGDC 5-minute Gridded Elevation Data (ETOPO5). National Geophysical Data Center.

Richey, J.E., Victoria, R.L., 1993. C, N, and P export dynamics in the Amazon River. In: Wollast, R., Mackenzie, F.T., Chou, L. (Eds.), Interactions of C, N, P and S Biogeochemical Cycles and Global Change. Springer-Verlag, pp. 123–139.

Reid, W.V., Bréchignac, C., Lee, Y.T., 2009. Earth system research priorities. Science 325, 245.

Seitzinger, S., et al., 2006. Denitrification across landscapes and waterscapes: a synthesis. Ecological Applications 16, 2064–2090.

Seitzinger, S.P., Harrison, J.A., Dumont, E., Beusen, A.H., Bouwman, A.F., 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 Biogeochemical Cycles 19, GB4S01. doi:10.1029/2005GB002606.

Seitzinger, S.P., Kroeze, C., 1998. Global distribution of nitrous oxide production and N inputs in freshwater and coastal marine ecosystems. Global Biogeochemical Cycles 12, 93–113.

Seitzinger, S.P., Kroeze, C., Bouwman, A.F., Caraco, N., Dentener, F., Styles, R.V., 2002a. Global patterns of dissolved inorganic and particulate nitrogen inputs to coastal systems: recent conditions and future projections. Estuaries 25, 640–655.

Seitzinger, S.P., et al. Global river nutrient export: a scenario analysis of past and future trends. Global Biogeochemical Cycles, in press. doi:10.1029/2009GB003587.

Seitzinger, S.P., et al., 2002b. Nitrogen retention in rivers: model development and application to watersheds in the northeastern U.S.A. Biogeochemistry 57/58, 199–237.
Smith, S.V., et al., 2003. Humans, hydrology, and the distribution of inorganic nutrient loading to the ocean. BioScience 53, 235–245.
Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., Green, P., 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308, 376–380.
Van Drecht, G., Bouwman, A.F., Harrison, J., Knoop, J.M., 2009. Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050. Global Biogeochemical Cycles 23, GB0A03. doi:10.1029/2009GB003458.
Van Drecht, G., Bouwman, A.F., Knoop, J.M., Beusen, A.H.W., Meinardi, C.R., 2003. Global modeling of the fate of nitrogen from point and nonpoint sources in soils, groundwater, and surface water. Global Biogeochemical Cycles 17, 1115. doi:10.1029/2003GB002060.
Vörösmarty, C.J., Fekete, B.M., Meybeck, M., Lammers, R.B., 2000. Global system of rivers: its role in organizing continental land mass and defining land-to-ocean linkages. Global Biogeochemical Cycles 14, 599–621.
Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P., Syvitski, J.P.M., 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. Global and Planetary Change 39, 169–190.
Withers, P.J.A., Sharpley, A.N., 2008. Characterization and apportionment of nutrient and sediment sources in catchments. Journal of Hydrology 350, 127–130.
Worrall, F., Burt, T.P., 1999. The impact of land-use change on water quality at the catchment scale: the use of export coefficient and structural models. Journal of Hydrology 221, 75–90.