Global integrated modeling framework of riverine dissolved inorganic nitrogen with seasonal variation

Yizhou Huang1,2, Daisuke Tokuda2, Xudong Zhou2 and Taikan Oki1,4
1Department of Multidisciplinary Science, Graduate School of Arts and Sciences, The University of Tokyo, Japan
2Institute of Industrial Science, The University of Tokyo, Japan
3Department of Civil Engineering, Graduate School of Engineering, The University of Tokyo, Japan
4Rector’s Office, United Nations University, Japan

Abstract: Understanding patterns and seasonal variations of excessive nutrients in surface water from anthropogenic activities is important for pollution control. In this study, we developed an integrated biogeochemical modeling framework for nitrogen exchanges among the atmosphere, terrestrial, and aquatic ecosystems. A land surface model, a terrestrial nitrogen cycle model, and a riverine hydrodynamics model incorporated with a river temperature model were consolidated and driven by multiple nitrogen sources related to anthropogenic activities. We estimated the global nitrogen loading and transporting in global rivers, with consideration of seasonal variations, and the validation demonstrates the reliability of the proposed model. The total dissolved inorganic nitrogen (DIN) flow rate is accumulated following rivers and it has high total DIN loads even in regions with low population density but large basin area, such as those at high latitudes. This study successfully improves estimation of nitrogen loading on global scale with consideration of seasonal variation. Our results show consistent trends with the observed data of DIN concentrations in global rivers, where all above variables are greatly affected by seasonal variations. The results also reflect the monthly-variant nitrogen inputs help produce closer DIN concentration estimates to observations, which will possibly stress the need for further study on seasonal variability of anthropogenic emissions.

KEYWORDS global rivers; water pollution; nitrogen pollution; biogeochemical modeling; seasonal variation

INTRODUCTION

For many decades, one of the most popular topics in biogeochemical cycle and nutrient transport has been the cycle of nitrogen, which is a requisite and highly demanded element for living organisms on Earth. However, since 1970, the amount of biologically available nutrients entering the terrestrial ecosystem has more than doubled in comparison to preindustrial era levels (Galloway et al., 2008). Excess nitrogen from anthropogenic activities has interfered with the biogeochemical nitrogen cycle of natural ecosystems, resulting in ozone layer depletion, surface water eutrophication, soil acidification, nitrate pollution of water bodies, and even impacts to human health (Ravishankara et al., 2009; Duan et al., 2013; Fowler et al., 2013; Steffen et al., 2015). Specifically, water quality in terms of nitrate (NO\textsubscript{3}\textsuperscript{-}) leaching from point and non-point sources is a relevant environmental issue in the world (Galloway et al., 1995; Galloway and Cowling, 2002; Mena-Rivera et al., 2017). Understanding the connection between anthropogenic nitrogen discharge and changes to nature, and quantifying them in water bodies, are critical for humans in order to secure natural sustainability under further social development (Schlesinger, 2009; Steffen et al., 2015; Best, 2019).

To address the above-mentioned problems, numerical models have recently been widely used to estimate transport of certain chemical substances in rivers and streams (Dumont et al., 2005; Seitzinger et al., 2005; He et al., 2011; Beusen et al., 2015; Liu et al., 2019). At the very beginning, Meybeck (1982) started the questions about carbon, nitrogen, and phosphorus running through world rivers. Then the research on nitrogen cycle, primarily focused on river basin scale, has been brought to attention (Bouwman et al., 2005; Dumont et al., 2005; Seitzinger et al., 2005). The research group of Global Nutrient Export from Watersheds (Global NEWS) established multiform and future prediction models of riverine nutrient export (Seitzinger et al., 2010). However, the methods which treated entire river basins as a basic unit failed to illustrate the spatial variations and leaching and transport of the nitrogen within the basin (Howarth et al., 2002; Bouwman et al., 2005; Harrison et al., 2005). For improving studies in this field, He et al. (2011) used an integrated biogeochemical modeling framework with detailed information on nitrogen leaching or nitrate concentration in individually distributed grids. Beusen et al. (2015) also incorporated Integrated Model to Assess the Global Environment-Global Nutrient Model (IMAGE-GNM) with a distributed hydrological model to simulate global nitrogen and phosphorus transportation. These models and integrated studies have contributed greatly to understanding the spatial distribution of nitrogen within a river basin and have linked calibrated...
model in order. However, the hydrological processes are still missing in water bodies. To overcome these shortages, Nevison et al. (2016) and Liu et al. (2019) used Community Land Model (CLM) with the River Transport Model (RTM) built inside, along with a coupler of the Community Earth System Model (CESM) to simulate riverine nitrogen transport. However, CLM likely underestimates leaching and runoff of all forms of nitrogen because it includes temperate-zone managed crops only (Liu et al., 2019), where manure plays an important role in soil nitrogen budget (Bouwman et al., 2005). In addition to the hydrological processes, thermal process can also play a role in nitrogen transport in rivers. Although considered in certain global model simulations (Liu et al., 2019), nitrogen transport with thermal process was rarely presented with monthly validations or reliable monthly reproductions and predictions.

The aim of this study is to develop an integrated biogeochemical modeling framework, including materials exchange among the atmosphere, terrestrial and aquatic ecosystems, and to investigate the nitrogen load transport in global rivers, with consideration of seasonal variations. This framework was built to explore the behavior of the anthropogenic released nitrate by incorporating several models. Various point and non-point nitrogen sources such as synthetic fertilizer application, manure production, atmospheric deposition and municipal wastewater were introduced as loading dataset. The seasonal variation which impacts the monthly nitrate transport mechanism in rivers was also discussed for a more comprehensive understanding of nitrogen fate and transport.

**METHODS AND EXPERIMENT DESIGN**

**Overview of integrated model framework**

In this study we proposed an integrated model framework for nitrogen loads from different sources, and the transporting of nitrogen under effects of water temperature in global rivers (Figure 1). A land surface model – MATSIRO (Takata et al., 2003), a terrestrial nitrogen cycle model (TNCM) based on Lin et al. (2000) and Suga et al. (2005), and a riverine hydrodynamic model – CaMa-Flood (Yamazaki et al., 2011) incorporated with a river temperature model – HEAT-LINK (Tokuda et al., 2019), were consolidated for achieving such evaluations. For input datasets (Table 1), the integrated model framework first produced global soil temperature, soil moisture, runoff, and runoff temperature from MATSIRO, which is driven by atmosphere forcing. The nitrogen cycle and the riverine hydrodynamics were built based on MATSIRO outputs. Nitrogen input (Text S1) introduced in this study consists of sources from synthesis fertilizer application (Nishina et al., 2017), manure production (Zhang et al., 2017), external atmospheric deposition (Tian et al., 2018), urban wastes flow (Morée et al., 2013), and aquaculture pollutions (Bouwman et al., 2013). The nitrate leaching from various land types was calculated by TNCM. The riverine hydrodynamic model was aimed to carry nitrogen from anthropogenic and natural sources through riverine network. Each grid cell in the riverine network acquired water containing dissolved inorganic nitrogen (DIN) from grid cells on upstream, as well as the DIN diffused from nearby land and point sources pollution within the grid cell. Meanwhile, the river temperature model controlled freezing and thawing status and affected material transport throughout a year. Lastly, annual total nitrogen amount at river outlets and monthly

![Figure 1. Integrated modelling framework in simulating global terrestrial nitrogen load and riverine nitrogen concentration](image-url)
average nitrogen concentration in streams were collected for validation.

Incorporation of TNCM and HEAT-LINK

The TNCM has been developed to take account of the mass balance of nitrogen in both organic soil and vegetation of the ecosystem. The terrestrial nitrogen cycle partially includes biological processes that rely on a different set of environmental factors. The internal parameters of TNCM, such as storage and fluxes, are the same as the model structure of the nitrogen cycle model by Lin et al. (2000, 2001), and two alternate versions revised by Suga et al. (2005) and He et al. (2009). In addition, this study also introduced the nitrogen source of manure production and atmospheric deposition (Figure S1). The model contains four variables for nitrogen: nitrogen in vegetation ($N_{\text{veg}}$), Mg N km$^{-2}$, organic nitrogen matter in soil ($N_{\text{org}}$, Mg N km$^{-2}$), ammonium ($N_{\text{NH}_4}$, Mg N km$^{-2}$), and nitrate ($N_{\text{NO}_3}$, Mg N km$^{-2}$). The nitrogen balance for each process is shown below:

\[
\frac{\partial N_{\text{veg}}}{\partial t} = \text{hfix} + \text{uptk} - \text{litf} - \text{hvst} \quad (1)
\]

\[
\frac{\partial N_{\text{org}}}{\partial t} = \text{litf} - \text{mnrl} + \text{manu} \quad (2)
\]

\[
\frac{\partial N_{\text{NH}_4}}{\partial t} = \text{mnrl} + \text{depoamm}_{\text{in+ex}} + \text{fertamm} - \text{uptk} \times \frac{N_{\text{org}} + N_{\text{mnrl}}}{N_{\text{NH}_4}} - \text{vola} - \text{ntrf} \quad (3)
\]

\[
\frac{\partial N_{\text{NO}_3}}{\partial t} = \text{ntrf} + \text{deponit}_{\text{in+ex}} + \text{fertnit} - \text{uptk} \times \frac{N_{\text{org}}}{N_{\text{NH}_4} + N_{\text{NO}_3}} - \text{dinit} - \text{lech} \quad (4)
\]

where, $\text{hfix}$ is flux of nitrogen fixation as in nitrogen, $\text{uptk}$ is flux of nitrogen uptake by plant, $\text{litf}$ is flux of litter-fall from leaf, trunk, and root as in nitrogen, $\text{mnrl}$ is flux of soil organic matter mineralization as in nitrogen, $\text{manu}$ is the amount of manure production from livestock, $\text{depoamm}_{\text{in+ex}}$ is flux of internal and external nitrogen deposition as in ammonium, $\text{vola}$ is flux of ammonium volatilization, $\text{ntrf}$ is flux of nitrification, $\text{deponit}_{\text{in+ex}}$ is flux of internal and external nitrogen deposition as in nitrate, $\text{dinit}$ is flux of nitrification and gas emission process, $\text{lech}$ is flux of nitrate leaching, $\text{fertamm}$ is the amount of ammonium in fertilizer, and $\text{fertnit}$ is the amount of nitrate in fertilizer. All of these fluxes are in units of Mg N km$^{-2}$ d$^{-1}$, $\text{hvst}$ is the ratio of harvested crops. For natural ecosystem, all external nitrogen inputs such as $\text{depoamm}_{\text{in+ex}}$, $\text{manu}$, and $\text{fert}$ were set to zero.

The function of coupled riverine hydrodynamic model (Tokuda et al., 2019) in this integrated model is to create a network of river channels and to simulate riverine transport of the nutrients, as well as to simulate seasonal variation under temperature change for global rivers in a more realistic manner. For instance, the freeze-thaw cycle of a river can directly impact river discharge, and thus nitrogen transport. The governing equations in HEAT-LINK follow the one-dimensional mass conservation law, the Saint-Venant equation for momentum conservation, and the conservation law of energy. More detail of the models and data used in this study are specified in the Supplemental Material.

Model setting

Similar research recently performed validations of DIN load in 1995 (He et al., 2011; Liu et al., 2019; Tian et al., 2020). Therefore, the initial database set up in this study was based on the year of 1995. An experimental group of constant nitrogen input was added for discussion. An additional run for 2001–2010 was also implemented for 10-year simulations which can show recent temporal changes of the DIN. The spin-up period of the entire integrated model was set as 20 years. The initial condition for the river water temperature was the air temperature on the first day of 1995, and CaMa-Flood assumes the sea-level elevation for the initial condition.

Data analysis

In addition to $R^2$, the determination of efficiency, to evaluate model performance we also evaluated root mean
square error expressed as a percentage ($pRMSE$) of the results. $pRMSE$ is calculated as follows:

$$pRMSE = 100 \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{n}}$$  \hspace{1cm} (5)

Where $O$ is the mean of observed data, $O_i$ is observed data, $S_i$ is the simulated data, and $n$ is the number of observed data. We consider $pRMSE$ under 50% to be acceptable in perspective of the global scale of the integrated model (Beusen et al., 2015).

RESULTS

Model validation with annual DIN load

We validated the integrated model in terms of the annual DIN load and yield (load per area) for the year of 1995. Figure 2 shows the comparisons between simulated results and observations for 30 major rivers in different continents (10 in Asia, 7 in Europe, 8 in North America, 3 in South America, 1 in Africa, and 1 in Australia; also see Figure 3). The bar graphs are sorted in terms of the basin size from the largest to the smallest in Figure 2a and 2b. Results show that the basin size is one of the factors for DIN load, as higher DIN load is observed for larger rivers. However, higher average DIN yield can also lead to larger DIN load at river outlets, even though the basin size is smaller (e.g. Pearl River and Rhine River). Low DIN loads are observed in Murray and Rio Grande due to the low yields there, however the low load in Tornionjoki is probably due to its small size.

The scatter plots in Figure 2c and 2d indicate a linear relationship between the simulated and observed DIN load and yield, respectively. The regression lines between simulated and observed DIN load and yield are very close to the 1:1 line. The coefficient of determination $R^2$ is 0.86 and 0.96 for the two variables, respectively. The $pRMSE$ for DIN load was 20.4% and 13.5% for the DIN yield. From here it can be said the integrated model reproduced annual

![Figure 2](image-url)
DIN load in selected rivers with acceptable precision. Since these rivers have different basin sizes and are located broadly around the world, we can expect the integrated model to be capable of simulating global DIN load fairly well.

Result of global spatial distribution

The global spatial distribution of total DIN flow rates in 1995 is illustrated in Figure 3. The DIN flow rate is generally high for rivers with large annual discharge including Amazon River, Mississippi River and Yangtze River. Besides the large river basins selected for validation, rivers in Western Europe, Northern China and South Asia also have high values in annual DIN flow rates. Thanks to the integration of riverine models, the total DIN flow rate is accumulative along the rivers, from upstream to the downstream. Additionally, the major rivers in higher latitude, where seasonal variations play a larger role than regions in lower latitude, contribute much higher DIN flow rates compared with nearby rivers.

River discharge and temperature

The river temperature directly affects the freeze-thaw cycle and thus leads to impact on the seasonality of river discharges, and further affects the concentration and transport of nutrients. Here we selected 4 major rivers (i.e. Ob, Mackenzie, Lena, and Yukon) with sufficient observed nutrient data to evaluate the model’s ability in reproducing the temperature and discharge. Figure S2 compares the estimated monthly river temperature with the observations. In these high-latitude regions, rivers are covered with ice on the surface and the water temperature decreased to zero degrees during winter periods. Despite the cold season, the model can simulate the river temperature and show the general seasonal variations with the observed water temperature fairly well.

Discharge simulation is more difficult than temperature simulation because the bias in discharge is propagated from precipitation, runoff generation and river routing. It has been observed that the discharge simulation in the high latitudes remains challenging in many studies. We also compared the monthly river discharge with observations and the simulation at the selected rivers (Figure S3). However, there is some shift between observed and simulated results. Also, the discharge is overestimated in the month when river thawing begins. This is because the current method of river ice processes and snow melting in the model is comparatively simple. When runoff increases at the beginning of the ice breaking season, the ice is pushed up and crashes. The floating ice flows downstream, and temporary ice jams are formed when some of the floating ice forms a cluster, especially in narrow sections. The model ignores such processes and instead considers the removal of surface ice in mechanisms related only to heat budget (Tokuda et al., 2019).

The coefficient of determination $R^2$ has been tested for discharge and temperature. The estimated river temperature works very well on this model with 0.98, 0.94, 0.95 and 0.99 for Ob, Mackenzie, Lena, and Yukon rivers, respectively. The estimated river discharge also works well for Ob and Lean rivers, with 0.87 and 0.64, respectively. The model does not predict well for Mackenzie and Yukon, with $R^2$ of 0.17 and 0.28, respectively. Despite this, they still show a suitable seasonal trend to DIN simulations.

Monthly average DIN concentration

We further assessed monthly average river DIN concentration against observations in selected rivers (Figure 4). The average concentration has an inverted seasonal variation compared to the river discharge, as the concentration usually reaches the highest level during the freezing season and has a lower level after ice breaking. Ob River had an acceptable result, except for a time shift when the lowest concentration occurs. Beside slight overestimation of concentration, Lena River had a one-month shift of the lowest concentration. The reason may be the uncertainty of river discharge estimation, which is mentioned above. Mackenzie River had a fairly close match in DIN concentration. Yukon River had an overall underestimation in DIN transport, but still had a shape that corresponds to the seasonal variation. Overall, the $pRMSE$ for DIN concentration in rivers mentioned above are 27.0%, 9.2%, 47.3%, and 24.0%, respectively. Extra uncertainties and shortcomings of the model will be discussed in the Discussion section. From the perspective of monthly time series simulation, the model reproduced a reasonable seasonal variation of monthly average DIN concentration in major rivers.

We also demonstrate the impact of temporal resolutions
of N inputs to the DIN concentration by driving our model with constant N fertilizer and deposition as shown by the blue line in Figure 4. Except the Mackenzie River, the monthly variation had changed a lot compared to the time-variant N inputs (red line). The \( pRMSE \) for the simulation of the four rivers are 20.5%, 28.9%, 56.6%, and 27.0%, respectively. Although the \( pRMSE \) does not show a great increase, the monthly-variant N inputs produce closer DIN concentration estimates to the observations, comparing to the constant nitrogen inputs. The differences indicate that the time-variant inputs will to some degree benefit the DIN estimations. The improvement should work together with the introduced temperature model as the impact of temperature is different in nitrogen concentration and transport.

For assessing the model performance for more recent conditions, we ran the simulation for a further 10 years (2001–2010) for Mackenzie and Yukon rivers (due to data availability, Figure 5). In general, the simulated DIN concentration is in the similar degree of the observations and the \( pRMSE \) are 48.8% and 46.6% for Mackenzie and Yukon. The average simulated DIN concentration is around 0.03 mg L\(^{-1}\) in summer and 0.10 mg L\(^{-1}\) in winter, showing the importance of seasonal variations and the confidence of long-term simulations of this model.

**DISCUSSION**

There are still several aspects to be discussed about uncertainties of the integrated model framework, including the datasets and the integrated model.

Regarding the nitrogen input, several uncertainties could be pointed out. GDP, population, and crop area are used to estimate the global fertilizer distribution. However, even in the existing activity data, the national census has inherent spatial distribution (Winiwarter and Muik, 2010). For the global manure data, the livestock distribution was generated by using one-phase static GLIMS (Zhang et al., 2017) without variations in time. Moreover, the manure, municipal waste and aquaculture pollution datasets are in yearly resolution, which makes precise seasonal variation study difficult. Hence, adjustments of all inputs with spatial distribution at the subnational level and temporal variations at monthly resolution would be perfect.

As we know, the river hydrodynamic model governs nutrient transport in rivers, and the uncertainties that occur...
in-stream will also create uncertainties in estimating material transport. First, the uncertainty of runoff generated from the land surface model can lead to biases in river discharge resulting in very different DIN concentration results. Second, human activities such as irrigation abstraction and dam regulation can also change the DIN concentration in rivers. Moreover, the river temperature will affect chemical changes in rivers (Duan et al., 2016) but it is not considered. Nutrient reaction with other components including other nutrients, chemicals, microbes, and other pollutants is also yet to be included.

CONCLUSIONS

It is very important to understand in-stream dynamics with nitrogen transport for future related studies. In this study, a fully coupled biogeochemical model with land surface model and river dynamic model was proposed and has been proven with data consistency and efficiency in terms of the temperature, river discharge, DIN concentration, and nitrogen load. This study successfully improves the estimation of nitrogen loading on a global scale with consideration of seasonal variation. Additionally, the results of monthly-variant nitrogen input suggests the need for further study on the seasonal variability of the anthropogenic emissions. This model framework provides a chance of incorporating future prediction information, in order to understand the consequences of climate change and anthropogenic activities to global nitrogen cycle over the long term.

ACKNOWLEDGMENTS

The authors are grateful for a MEXT scholarship by The Ministry of Education, Culture, Sports, Science, and Technology of JAPAN and acknowledge the support from the Japan Society for the Promotion of Science [KAKENHI:16H06291] and the Environment Research and Technology Development Fund [JPMEERF20202005] of the Environmental Restoration and Conservation Agency of Japan. We also gratefully acknowledge the United Nations Environment Programme Global Environment Monitoring System (GEMS) for providing us with monthly observed data of river water temperature and nutrients concentration, and the Global Runoff Data Centre (GRDC) for the daily observed discharge data.

SUPPLEMENTS

Text S1. Detail of the models and data used
Figure S1. Flow chart for the terrestrial nitrogen cycle model, orange boxes represent added parts of fluxes (Based on Suga et al., 2005)
Figure S2. Comparison of monthly simulated (red line) and observed (black dots) river temperature (°C) for selected rivers at specific stations
Figure S3. Comparison of monthly simulated (red line) and observed (black line) river discharge (m³ s⁻¹) for selected rivers at specific stations

REFERENCES

Best J. 2019. Anthropogenic stresses on the world’s big rivers. Nature Geoscience 12: 7–21. DOI: 10.1038/s41561-018-0262-x.

Beusen AHW. 2016. Global riverine nitrogen (N) and phosphorus (P) input, retention and export during the 20th century. Data Archiving and Networked Services (DANS). DOI: 10.17026/dans-zgs-9k9m.

Beusen AHW, Van Beek LPH, Bouwman AF, Mogollón JM, Middelburg JJ. 2015. Coupling global models for hydrology and nutrient loading to simulate nitrogen and phosphorus retention in surface water – description of IMAGE–GNM and analysis of performance. Geoscientific Model Development 8: 4045–4067. DOI: 10.5194/gmd-8-4045-2015.

Bouwman AF, Van Dreuch G, Knoop JM, Beusen AHW, Meinardi CR. 2005. Exploring changes in river nitrogen export to the world’s oceans. Global Biogeochemical Cycles 19: GB1002. DOI: 10.1029/2004GB002314.

Bouwman AF, Beusen AHW, Overbeek CC, Bureau DP, Pawlowski M, Gilbert PM. 2013. Hindcasts and future projections of global inland and coastal nitrogen and phosphorus loads due to finfish aquaculture. Reviews in Fisheries Science 21: 112–156. DOI: 10.1080/10641262.2013.790340.

Duan W, Takara K, He B, Luo P, Nover D, Yamashiki Y. 2013. Spatial and temporal trends in estimates of nutrient and suspended sediment loads in the Ishikari River, Japan, 1985 to 2010. Science of The Total Environment 461–462: 499–508. DOI: 10.1016/j.scitotenv.2013.05.022.

Duan W, He B, Nover D, Yang G, Chen W, Meng H, Zou S, Liu C. 2016. Water Quality Assessment and Pollution Source Identification of the Eastern Poyang Lake Basin Using Multivariate Statistical Methods. Sustainability 8: 133. DOI: 10.3390/su8020133.

Dumont E, Harrison JA, Kroeze C, Bakker EJ, Seitzinger SP. 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.

Fowler D, Coyle M, Skiba U, Sutton MA, Cape JN, Reis S, Sheppard LJ, Jenkins A, Grizzetti B, Galloway JN, Vitousek P, Leach A, Bouwman AF, Butterbach-Bahl K, Dentener F, Stevenson D, Amann M, Voss M. 2013. The global nitrogen cycle in the twenty-first century. Philosophical Transactions of the Royal Society B: Biological Sciences 368: 20130164. DOI: 10.1098/rstb.2013.0164.

Galloway JN, Cowling EB. 2002. Reactive nitrogen and the world: 200 years of change. AMBIO: A Journal of the Human Environment 31: 64–71. DOI: 10.1579/0044-7447-31.2.64.

Galloway JN, Schlesinger WH, Levy II H, Michaels A, Schnoor JL. 1995. Nitrogen fixation: Anthropogenic enhancement-environmental response. Global Biogeochemical Cycles 9: 235–252. DOI: 10.1029/95GB00158.

Galloway JN, Townsend AR, Erismann JW, Bekunda M, Cai Z, Freney JR, Martinelli LA, Seitzinger SP, Sutton MA. 2008. Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. Science 320: 889–892. DOI: 10.1126/science.1136674.

Harrison JA, Caraco N, Seitzinger SP. 2005. 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.

He B, Oki T, Kanae S, Mouri G, Kodama K, Komori D, Seto S. 2009. Integrated biogeochemical modelling of nitrogen load from anthropogenic and natural sources in Japan. *Ecological Modelling* 220: 2325–2334. DOI: 10.1016/j.ecolmodel.2009.05.018.

He B, Kanae S, Oki T, Hirabayashi Y, Yamashiki Y, Takara K. 2011. Assessment of global nitrogen pollution in rivers using an integrated biogeochemical modeling framework. *Water Research* 45: 2573–2586. DOI: 10.1016/j.watres.2011.02.011.

Hirabayashi Y, Kanae S, Struthers I, Oki T. 2005. A 100-year (1901–2000) global retrospective estimation of the terrestrial water cycle. *Journal of Geophysical Research: Atmospheres* 110: D19101. DOI: 10.1029/2004JD005492.

Howarth RW, Sharphey A, Walker D. 2002. Sources of nutrient pollution to coastal waters in the United States: Implications for achieving coastal water quality goals. *Estuaries* 25: 656–676. DOI: 10.1007/BF02804898.

Kim H. 2017. Global soil wetness project phase 3 atmospheric boundary conditions (Experiment 1). *Data Integration and Analysis System (DIAS).* DOI: 10.20783/DIAS.501.

Lin BL, Sakoda A, Shibasaki R, Goto N, Suzuki M. 2000. Modelling a global biogeochemical nitrogen cycle in terrestrial ecosystems. *Ecological Modelling* 135: 89–110. DOI: 10.1016/S0304-3800(00)00372-0.

Lin BL, Sakoda A, Shibasaki R, Suzuki M. 2001. A modelling approach to global nitrate leaching caused by anthropogenic fertilisation. *Water Research* 35: 1961–1968. DOI: 10.1016/S0043-1354(01)00484-X.

Liu S, Xie Z, Zeng Y, Liu B, Li R, Wang Y, Wang L, Qin P, Jia B, Xie J. 2019. Effects of anthropogenic nitrogen discharge on dissolved inorganic nitrogen transport in global rivers. *Global Change Biology* 25: 1493–1513. DOI: 10.1111/gcb.14570.

Mena-Rivera L, Salgado-Silva V, Benavides-Benavides C, Coto-Campos JM, Swisscoe THA. 2017. Spatial and seasonal surface water quality assessment in a tropical urban catchment: Burio River, Costa Rica. *Water* 9: 558. DOI: 10.3390/w9080558.

Meybeck M. 1982. Carbon, nitrogen, and phosphorus transport by world rivers. *American Journal of Science* 282: 401–450. DOI: 10.2475/ajs.282.4.401.

Möreé AL, Beusen AHW, Bouwman AF, Willems WJ. 2013. Exploring global nitrogen and phosphorus flows in urban wastes during the twentieth century. *Global Biogeochemical Cycles* 27: 836–846. DOI: 10.1002/gbc.20072.

Nevison C, Hess P, Riddick S, Ward D. 2016. Denitrification, leaching, and river nitrogen export in the Community Earth System Model. *Journal of Advances in Modeling Earth Systems* 8: 272–291. DOI: 10.1002/2015MS000573.

Nishina K, Ito A, Hanasaki N, Hayashi S. 2017. Reconstruction of spatially detailed global map of NH₃ and NOₓ application in synthetic nitrogen fertilizer. *Earth System Science Data* 9: 149–162. DOI: 10.5194/essd-9-149-2017.

Ravishankara AR, Daniel JS, Portmann RW. 2009. Nitrous oxide (N₂O): The dominant Ozone-Depleting substance emitted in the 21st century. *Science* 326: 123–125. DOI: 10.1126/science.1176985.

Schlesinger WH. 2009. On the fate of anthropogenic nitrogen. *Proceedings of the National Academy of Sciences* 106: 203–208. DOI: 10.1073/pnas.0810193105.

Seitzinger SP, Harrison JA, Dumont E, Beusen AHW, Bouwman AF. 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: 10.1029/2005GB002660.

Seitzinger SP, Mayorga E, Bouwman AF, Kroeze C, Beusen AHW, Billen G, Van Drecht G, Dumont E, Fekete BM, Garnier J, Harrison JA. 2010. Global river nutrient export: A scenario analysis of past and future trends. *Global Biogeochemical Cycles* 24: GB0A08. DOI: 10.1029/2009GB003587.

Steffen W, Richardson K, Rockström J, Cornell SE, Fietzer I, Bennett EM, Biggs R, Carpenter SR, de Vries W, de Wit CA, Folke C, Gerten D, Heinke J, Mace GM, Persson LM, Ramanathan V, Reyer B, Sörlin S. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347: 1259855. DOI: 10.1126/science.1259855.

Suga Y, Hirabayashi Y, Kanae S, Oki T. 2005. Changes in river nitrate transport of the world resulted from increase in fertilizer use. *Proceedings of Hydraulic Engineering* 49: 1495–1500. DOI: 10.2208/prohe.49.1495.

Takata K, Emori S, Watanabe T. 2003. Development of the minimal advanced treatments of surface interaction and runoff. *Global and Planetary Change* 38: 209–222. DOI: 10.1016/S0921-8181(03)00030-4.

Tian H, Yang J, Lu C, Xu R, Canadell JG, Jackson RB, Arnhet A, Chang J, Chen G, Ciais P, Gerber S, Ito A, Huang Y, Joos F, Lienert S, Messina P, Olin S, Pan S, Peng C, Saikawa E, Thompson RL, Vuichard N, Winiwarter W, Zaehe S, Zhang B, Zhang K, Zhu Q. 2018. The Global N₂O Model Inter-comparison Project. *Bulletin of the American Meteorological Society* 99: 1231–1251. DOI: 10.1175/BAMS-D-17-0212.1.

Tian H, Xu R, Pan S, Yao Y, Bian Z, Cai WJ, Hopkinson CS, Justic D, Lohrenz S, Lu C, Ren W, Yang J. 2020. Long-term trajectory of nitrogen loading and delivery from Mississippi River basin to the Gulf of Mexico. *Global Biogeochemical Cycles* 34: e2019GB006475. DOI: 10.1029/2019GB006475.

Tokuda D, Kim H, Yamazaki D, Oki T. 2019. Development of a global river water temperature model considering fluvial dynamics and seasonal Freeze-Thaw cycle. *Water Resources Research* 55: 1366–1383. DOI: 10.1002/2018WR023083.

Winiwarter W, Muik B. 2010. Statistical dependence in input data of national greenhouse gas inventories: effects on the overall inventory uncertainty. *Climatic Change* 103: 19–36. DOI: 10.1007/s10584-010-9921-7.

Yamazaki D, Oki T, Kanae S. 2009. Deriving a global river network map and its sub-grid topographic characteristics from a fine-resolution flow direction map. *Hydrology and Earth System Sciences* 13: 2241–2251. DOI: 10.5194/hess-13-2241-2009.

Yamazaki D, Kanae S, Kim H, Oki T. 2011. A physically based description of floodplain inundation dynamics in a global river routing model. *Water Resources Research* 47: W04501. DOI: 10.1029/2010WR009726.

Zhang B, Tian H, Lu C, Dangal SRS, Yang J, Pan S. 2017. Global manure nitrogen production and application in cropland during 1860–2014: a 5 arcmin gridded global dataset for Earth system modeling. *Earth System Sciences Data* 9: 667–678. DOI: 10.5194/essd-9-667-2017.