Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Environmental Sustainability

# Modeling phosphorus in rivers at the global scale: recent successes, remaining challenges, and near-term opportunities☆

John A Harrison[1], Arthur HW Beusen[2,3], Gabriel Fink[5], Ting Tang[6], Maryna Strokal[7], Alexander F Bouwman[2,3,4], Geneviève S Metson[8] and Lauriane Vilmin[3]

Understanding and mitigating the effects of phosphorus (P) overenrichment of waters globally, including the evaluation of the global Sustainability Development Goals, requires the use of global models. Such models quantitatively link land use, global population growth and climate to aquatic nutrient loading and biogeochemical cycling. Here we describe, compare, and contrast the existing global models capable of predicting P transport by rivers at a global scale. We highlight important insights gained from the development and application of these models, and identify important near-term opportunities for model improvements as well as additional insight to be gained through new model analysis.

**Addresses**
[1] School of the Environment, Washington State University, Vancouver Campus, Vancouver, WA 98686, USA
[2] PBL, Netherlands Environmental Assessment Agency, P.O. Box 30314, 2500 GH The Hague, The Netherlands
[3] Department of Earth Sciences — Geochemistry, Faculty of Geosciences, Utrecht University, P.O. Box 80021, 3508 TA Utrecht, The Netherlands
[4] Key Laboratory of Marine Chemistry Theory and Technology, Ministry of Education, Ocean University of China, Qingdao 266100, PR China
[5] Landesanstalt für Umwelt Baden-Württemberg (LUBW), Griesbachstraße 1, 76185 Karlsruhe, Germany
[6] International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria
[7] Water Systems and Global Change Group, Wageningen University & Research, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[8] Theoretical Biology, Department of Physics, Chemistry, and Biology, Linköping University, Linköping IFM 581 83, Sweden

Corresponding author: Harrison, John A (john_harrison@wsu.edu)

**Current Opinion in Environmental Sustainability** 2019, **36**:68–77

This review comes from a themed issue on **Environmental change assessment**

Edited by **Nynke Hofstra, Carolien Kroeze, Martina Flörke**, and **Michelle TH van Vliet**

For a complete overview see the Issue and the Editorial

Available online 12th November 2018

Received: 30 May 2018; Accepted: 19 October 2018

https://doi.org/10.1016/j.cosust.2018.10.010

## Introduction

Phosphorus (P) is an essential, often limiting, macronutrient in freshwater systems [1] that, under certain conditions, can also limit primary production in terrestrial and coastal ecosystems [2–4]. By mining phosphorus and using it primarily as a fertilizer, humans have more than doubled the rate at which bioavailable P is supplied to the terrestrial biosphere [5–8]. Widespread mobilization of geologic P in agriculture has been necessary to feed a large and burgeoning global population. However, P runoff and leaching from agricultural fields and animal production facilities [9], and flowing through inadequately treated sewage systems [8], has incurred substantial environmental costs. These include increased frequency and severity of hypoxic events, harmful algal blooms, changes in primary productivity and ecosystem function, often leading to decreased biodiversity, impaired water quality, and increased greenhouse gas emissions [10–13]. Understanding and mitigating the effects of P overenrichment of waters globally, including the evaluation of the global Sustainability Development Goals (SDGs), requires the use of global models that quantitatively link land use, global population growth and climate to aquatic nutrient loading and biogeochemical cycling. Such global P models are useful instruments to evaluate global hotspots and future trends of aquatic P loading under global climate and socioeconomic changes, and can therefore help to provide insight in where and to what extent better management and mitigation measures are needed. A variety of models have been developed for

---

☆ The opinions expressed and arguments employed in this publication are the sole responsibility of the authors and do not necessarily reflect those of the OECD or of the governments of its Member countries.

use at comparatively small (0.01–1000 $km^2$) scales in regions where model input and evaluation data are available, and these are reviewed elsewhere [14–16]. Here we focus exclusively on *global* P loading and transport models, which have emerged just within the past two decades, following early pioneering work [17–19]. Such global models are also useful at local and regional scales for several reasons. They provide context for local observations and modeling efforts, helping people and governments understand where regions fall in terms of the severity of their present-day and potential future P loading problems. Global P models can also provide reasonable estimates of P loading and sources in data-poor regions where applying complex, locally or regionally calibrated models is not possible. Also, when evaluated at the local-regional scale, Global P models provide a mechanism to test, evaluate, and, ultimately, improve understanding of how P sources and transformation control P delivery to and through rivers and watersheds. Finally, global models, when applied in a regional context, can facilitate transboundary analyses that are often not possible using local water quality models.

Below, we: first, briefly describe, compare, and contrast three 'families' of published global total phosphorus (TP) transport models, second, highlight major insights attributable to the development and application of these models, third, discuss important areas for future model enhancement, and fourth, identify important research avenues deserving near-term attention that can be addressed with either existing or somewhat enhanced global P transport models.

## Global P models: key characteristics, similarities and differences

There are currently three peer-reviewed 'families' of global models capable of predicting river total P (TP) loading and transport: IMAGE-GNM, WaterGAP, and Global NEWS. The specific version of each model reviewed here is the most recent one capable of predicting river TP loading and transport: IMAGE-GNM-TP, WaterGAP3.2, and Global NEWS-2-TP for each modeling family, respectively. NEWS-DIP-HD, a high-resolution (half-degree) version of NEWS-2-DIP [20] is also discussed. Each of these models is described in detail elsewhere (See Table 1 and Supplement for primary references), but some key characteristics that are shared across all of these models are as follows. All models include explicit representation of point (i.e. discrete, e.g. sewage outfalls) and nonpoint (diffuse, e.g. fertilizer, manure, and natural weathering) P sources, and all attempt to account for P from both natural and anthropogenic sources. All models also account for in-stream P sinks. All models can be used to estimate in-stream (main-stem) P loads (kg P $basin^{-1}$ $year^{-1}$) and per-area yields (kg P $km^{-2}$ $year^{-1}$) at the mouths of river basins (Table 2). Finally, all models can, in theory, be applied retrospectively and prospectively, although, to-date, only Global NEWS-2-TP has been applied to look at future scenarios (Table 2).The models also differ in some important respects. For example, whereas WaterGAP3.2 and IMAGE-GNM-TP estimate TP transport, and do not estimate the contribution of various P forms (dissolved inorganic P, particulate P, and dissolved organic P) to TP loading,

**Table 1**

**Characteristics of global river P transport models**

| | NEWS-DIP-HD | NEWS-2-TP (DIP + PP + DOP) | IMAGE-GNM-TP | WaterGAP3.2 |
|---|---|---|---|---|
| Model characteristics | | | | |
| Input data | Except for hydrology, dams and water residence time, NEWS input data are generated by IMAGE model, see IMAGE-GNM-TP model. | Except for hydrology, dams and water residence time, NEWS input data are generated by IMAGE model, see IMAGE-GNM-TP model. | Hydrology: runoff, water body shapes and volumes, water temperature from PCR-GLOBWB model; nutrient data: sewage, aquaculture P; P fertilizer and manure; crop P harvest and P withdrawal in grass harvest and grazing; P weathering and vegetation P | Input from a hydrological module, protein consumption, population density, treatment level, sanitation practice, fertilizer application by crop and total, soil loss, animal type and density, P in manure, livestock units, chemical weathering, atmospheric P deposition |
| Spatial scale | Half-degree | River basin | Half-degree | 5 arc minutes for P inputs, with P removals estimated at the basin scale |
| Temporal scale | Annual average | Annual average | Monthly | Monthly averages |
| Study region | Global | Global | Global | Global |
| Nutrient forms | Dissolved inorganic | Dissolved inorganic, Dissolved organic, Particulate, and Total | Total | Total |
| Primary reference | Harrison *et al.* [20] | Beusen *et al.* [31], Harrison *et al.* [29,30], Mayorga *et al.* [21] | Beusen *et al.* [24,32••] | Fink *et al.* [22••] |

**Table 2**

**Questions that can be addressed using global river P transport models and the models that have been used to address these questions**

| | NEWS DIP-HD | NEWS-2-TP (DIP + DOP + PP) | IMAGE-GNM-TP | Water-GAP3.2 |
|---|---|---|---|---|
| Questions addressed by global P models | | | | |
| 1. How much P reaches the coastal ocean? | X | X | X | |
| 2. How do nutrient fluxes vary during the year? | | | X, for inputs | X |
| 3. What are the sources of nutrient pollution? | X | X[a] | X | X |
| 3a Where are these sources within watersheds? | | X for DIP | X | |
| 4. What sectors contribute to specific P forms? | X | X[a] | | |
| 5. How much P is retained in soils and sediments within watersheds? | X[b] | X[b] | X | |
| 6. To what extent will P fluxes change in the future due to climate, land use, and socioeconomic changes? | X | X | X | X |
| 7. How much of each form of P (particulate vs. dissolved, organic vs. inorganic) is transported by rivers at global scale? | | X | | |
| 8. How have human activities changed water quality, and what activities within watersheds are likely to improve water quality going forward (SDG 6.3)? | X | X | X | X |
| Questions not currently addressed by global P models | | | | |
| 9. What are some important tradeoffs between SDGs, and how are these likely to work? For example SDGs 2 versus SDGs 6 versus SDGs 11[c]? | | | | |
| 10. How are C, N, P and Si in rivers interacting? | | | | |
| 11. How important is the landscape and sediment P legacy currently and how important will it be in the future? | | | | |
| 12. How do current and future P enrichments translate to freshwater and coastal eutrophication? | | | | |

[a] For DIP and DOP, but not PP.
[b] But limited to steady state.
[c] SDGs 2, 6, and 11 are related to ending hunger, water quality and sanitation, and sustainable cities and communities, respectively.

Global NEWS-2-TP calculates TP as the sum of constituent P forms estimated using Global NEWS-2 submodels: Global NEWS-2 particulate P (PP), Global NEWS-2 dissolved inorganic P (DIP), and Global NEWS-2 dissolved organic P (DOP) [21].

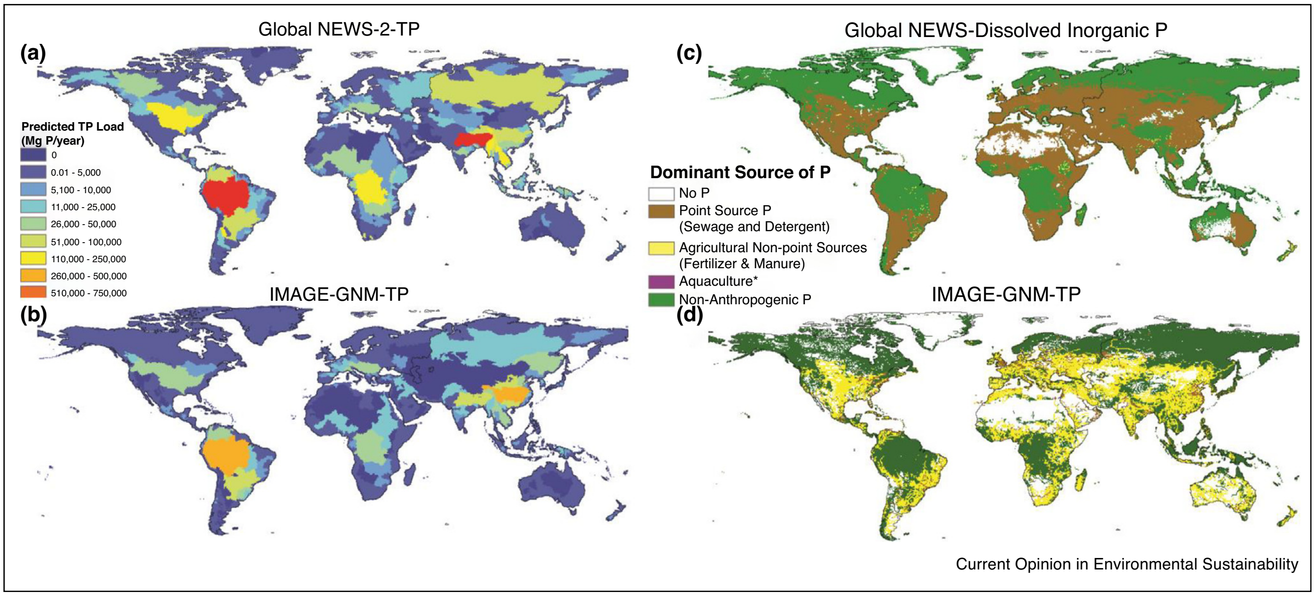
Importantly, the three models differ in spatial scale of output. Whereas Global NEWS-2-TP submodels calculate whole basin export to the sea, NEWS-DIP-HD (a comparatively high-resolution version of NEWS-2-DIP) and IMAGE-GNM-TP produce output resolved at a half-degree scale, and WaterGAP3.2 estimates TP loadings on a 5 arc-minute global grid, although P retention in WaterGAP3.2 is estimated at the watershed scale [22••]. The models also differ in temporal resolution. While IMAGE-GNM-TP, Global NEWS-2-TP, and WaterGAP3.2 all provide predictions of mean annual P export, IMAGE-GNM-TP and WaterGAP3.2 have P delivery models with a monthly time step [23••]. Further, IMAGE-GNM-TP has been applied to estimate TP export annually between 1900 and 2000, whereas Global NEWS-2-TP has only been applied to examine discrete time slices in 1970 and 2000 [24,25]. Global NEWS-2-TP submodels have also been applied to look at scenarios of change to examine trajectories of coastal nutrient delivery between 2000, 2030, and 2050 [25]. Although such an analysis is possible using IMAGE-GNM-TP and WaterGAP3.2, and IMAGE-GNM-TP is formulated to make this relatively convenient due to its relationship with the IMAGE integrated assessment model [26], this work is still in progress. Although work is currently underway to develop a mechanistic instream biogeochemistry model that describes transfers and transformations of the different P forms using the IMAGE-GNM-TP framework [23••], NEWS-2-TP is currently the only global model that can predict export of individual P forms (dissolved inorganic, dissolved organic, and particulate P).

Model input parameters also differ between existing models in important ways. For example, IMAGE GNM-TP includes aquaculture P effluent as a P point source whereas other models do not. In addition, IMAGE-GNM-TP dynamically computes changes in soil P pools and temporary subsoil and groundwater P storage [27]. P from rock weathering is included in IMAGE-GNM-TP following Hartmann *et al.* [28] and vegetation scouring from floodplains is also included as a P source. Importantly, IMAGE GNM-TP takes into account the legacy effect of landscape N and P, which is needed not only for the estimation of soil P storage, but also may be important for better estimation of P export potential over long periods. In contrast, Global NEWS-2-TP and WaterGAP3.2 do not account for long-term P accumulation or depletion from soils, opting instead to calculate P transport as a function of annual or shorter-term (in the case of WaterGAP3.2) P inputs to watersheds. Global NEWS-2-TP, Global NEWS-DIP-HD, IMAGE-GNM-TP, and WaterGAP3.2 also calculate in-stream P retention differently. Whereas Global NEWS-2-TP and Global NEWS-DIP-HD account for P removed in reservoirs and with consumptive water use, IMAGE-GNM-TP estimates in-stream P retention using a nutrient spiraling approach [19], which is in-turn calculated as a function of residence time, depth and a constant uptake velocity, which is the same for all water bodies, but corrected for temperature. WaterGAP3.2 uses river depth, flow velocity, and a TP-specific settling velocity, that includes biodegradation, to calculate in-stream P retention [22••].

Finally, global P transport models differ with respect to both their capacity to attribute river and coastal P loading to land-based activities and sources and the process by which they achieve this attribution. The Global NEWS dissolved P submodels (including NEWS-DIP-HD) can be used to attribute coastal P delivery to a variety of land-based human and natural P sources, including fertilizer, manure, sewage (both detergent and human waste), and natural weathering [29,30] (Figure 1c). In contrast, the statistical nature of the NEWS particulate P submodel prevents detailed source attribution [31]. Hence, it is not currently possible to use NEWS-2-TP to attribute sources of TP to rivers and the sea. In contrast, IMAGE-GNM-TP attributes TP to agricultural runoff, 'natural' (non-agricultural) runoff, weathering, floodplain vegetation, sewage, and aquaculture [24,32••; Figure 1d]. WaterGAP3.2 has also been used to estimate the relative importance of various P sources, including sewered and non-sewered point sources, manufacturing wastewater, domestic non-point sources, inorganic fertilizer, livestock waste, irrigation return flows, urban surface runoff, atmospheric deposition, P weathering, and vegetation and soils [22••] (Table 2).

Differences in assumptions and structures between global TP models have important implications for both source attribution and how the models respond to scenarios. For example, if a process or potential P source is not included in a model, there is no way to evaluate how TP loading will respond to changes in that process or source in a scenario. A specific case-in-point is that IMAGE-GNM-TP is the only model which would show any sensitivity to changes in aquaculture development because it is the only model that includes this P source. Similarly, WaterGAP3.2 is the only model that would show changes in P loading as a response to changing dust deposition rates as it is the only P model with an atmospheric deposition

**Figure 1**



Current Opinion in Environmental Sustainability

Coastal total P delivery (Mg P/basin/year) predicted by Global NEWS-2-TP **(a)** and IMAGE-GNM-TP **(b)** models, and sources of dissolved inorganic P attributed by the NEWS-DIP-HD model **(c)** and sources of TP as estimated by the IMAGE-GNM-TP model **(d)**. TP from Global NEWS 2 is the sum of dissolved inorganic P, dissolved organic P and particulate P. *Aquaculture sources are not considered in the NEWS-DIP-HD model.

term. The models will all respond differently to potential changes in climate as they each implement somewhat different assumptions about the relationship between water runoff and non-point P transport to surface waters, and only IMAGE-GNM-TP contains an explicit link between temperature and natural weathering rates.

## Recent successes

### Understanding where river P fluxes are high (and rapidly changing)

Global NEWS-2-TP and IMAGE-GNM-TP models provided the first global, spatially explicit estimates of global P delivery to coastal zones [21,29–31,32••]; Global NEWS-DIP-HD and IMAGE-GNM-TP provided the first-ever estimates of DIP and TP delivery to (and through) the surface freshwater component of watersheds [20,32••]. WaterGAP3.2 and IMAGE-GNM provided the first-ever estimate of TP loading to the world's largest lakes [22••]. Understanding spatial patterns of P loading to freshwaters and the coastal zone addresses an important knowledge gap, helping to identify regions with high P pollution (hotspots). This understanding has also allowed researchers to identify regions meriting further study (e.g. China [33], Manila Bay, and the Bay of Bengal [34]) and, when used in conjunction with N export models, can highlight where nutrient ratios are changing rapidly [32••], potentially modifying aquatic ecosystems and species composition.

The spatial distributions of high yielding watersheds predicted by Global NEWS-2-TP and IMAGE-GNM-TP show some important similarities (Figure 1a and b), with the Amazon, Yangtze, Ganges, Mekong, and Mississippi rivers showing up among the top-ten exporters of coastal P (kg P basin$^{-1}$ year$^{-1}$) in both models. WaterGAP3.2 indicates these areas are also hotspots for TP loading to large lakes [22••]. There are also some important differences between model predictions for watersheds globally. For example TP loads in large, high-latitude rivers appear to be greater in NEWS-2-TP than in IMAGE-GNM-TP (Figure 1a and b). In all existing global TP loading models, basins with highest predicted P exports have either high water discharge, intensive agriculture, or both.

Global NEWS-2-TP indicates that globally, particulate P is the most abundant form of P reaching the global coastal zone (6.6 Tg P year$^{-1}$ globally), followed by DIP (1.4 Tg P year$^{-1}$), with somewhat less DOP exported from watersheds (0.6 Tg P year$^{-1}$) [25]. IMAGE-GNM-TP provided first maps of within-basin (0.5° × 0.5°) TP loading to surface waters and Global NEWS-DIP-HD did the same for DIP, showing that P loading hotspots play a disproportionately important role in controlling P loading to surface waters and the global coastal zone [20,32••]. In the case of DIP, cities appear to play a disproportionately important role, with cities of populations >100 000 people (less than 2% of global land area) contributing in excess of 35% of total DIP loading to surface waters globally [20].

### Understanding the human imprint on river P loads

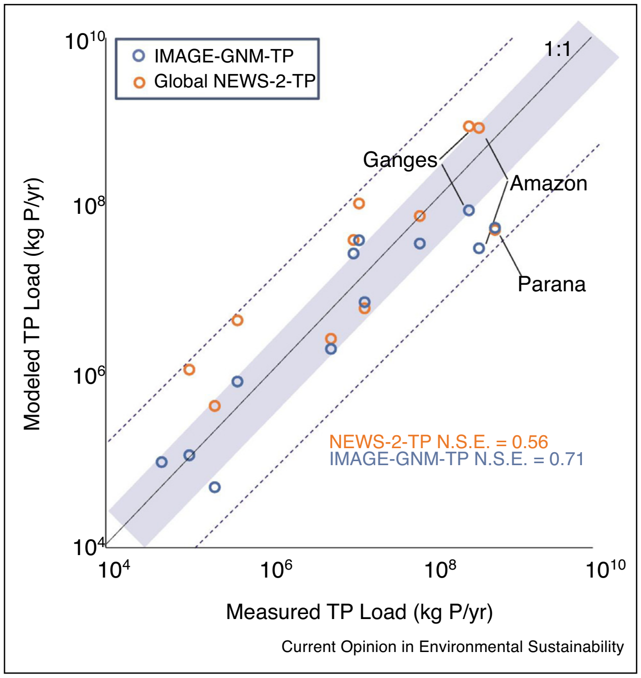
In addition to creating first-ever global maps of P loading and status, global models have also been used to estimate the human impact on global P transport. Based on a comparison of year 1900 and year 2000 output from IMAGE-GNM-TP, humans have tripled P inputs to surface waters, which, in turn, has increased total P export to the global coastal zone by 74% [32••]. Source attribution output from Global NEWS-DIP-HD indicates that humans have more than tripled the rate of coastal DIP delivery [20]. For TP, humans have had their greatest impact globally through agricultural expansion and intensification ([21,22••,32••]; Figure 1c), whereas for DIP, sewage is the single greatest contributor globally (Figure 1d). Such knowledge is essential to effective water quality management. Indeed global models can be used to explore the impact of multiple drivers (i.e. P sources or factors controlling the efficiencies with which such sources are delivered to aquatic ecosystems) on river TP loading and transport, not just TP sources, but also climate, hydrological, societal, and economic drivers.

In addition to hindcasting, these models can also be used to evaluate scenarios of future socioeconomic development, climate, and land-use change. By feeding the models input that is altered to account for a global change element of interest, it is possible to estimate how future P loading is likely to change under different socioeconomic scenarios (e.g. shared socioeconomic pathways (SSPs); [35•,36,37,38•], climate scenarios (e.g. representative concentration pathways (RCPs); [39,40]; nutrient use scenarios, and integrated land use and climate scenarios (e.g. the Millennium Ecosystem Assessment (MEA) scenarios [41]). Such exercises, which have to-date only used MEA storylines [41] (not SSPs and RCPs), have shown that increases in delivery of DIP, the most readily bioavailable P form, to surface waters are almost certain to occur as populations increase, agriculture expands and intensifies, and as sewers are built in developing countries (while accompanying water treatment infrastructure often lags far behind). Estimates of increases in coastal DIP loading range from 37 to 57% globally between 2000 and 2050, depending on the socioeconomic scenario [25]. In contrast, PP loads are projected to decrease due to dam construction over the same time period across a wide variety of scenarios [25]. Because the anticipated changes in DIP and PP loading are of similar magnitude, global TP fluxes could either increase or decrease, depending on the scenario [25]. This suggests that P management is critical in determining whether cultural eutrophication continues to worsen at the global scale. It also highlights a need to better understand PP bioavailability (see below). Further intensifying the need to understand P dynamics is the fact that if nitrogen mobilization continues apace as projected [42,43], P limitation may become more prevalent, and additions of P to ecosystems could have an even greater impact than they do under present conditions.

## Challenges & opportunities

Despite progress over the past two decades in modeling P transport to and through aquatic systems, a number of challenges and opportunities remain. One puzzling outcome (and research opportunity) resulting from the comparison of several P models is that there is substantial uncertainty regarding even the total global rate of P delivery to the coastal zones. Global NEWS-2-TP and IMAGE-GNM-TP produce estimates of global P export that differ by more than a factor of two (9 Tg P year$^{-1}$ for Global NEWS-2-TP versus 4 Tg P year$^{-1}$ for IMAGE-GNM-TP). IMAGE-GNM-TP has a somewhat better model performance than Global NEWS-2-TP on the dataset of large rivers used here as estimated by their Nash-Sutcliffe efficiency coefficients (NSE; Figure 2). However, there is some indication that IMAGE-GNM-TP underestimates P export from high-exporting basins such as the Amazon, Ganges and Yangtze [44] rivers. It is also possible that NEWS-2-TP overestimates TP export from low-load basins (Figure 2). One important difference between Global NEWS-2-TP and IMAGE-GNM-TP that may explain the discrepancy between their estimates of global TP export resides in how the two models treat the relation between agriculture inputs (manure and fertilizer) and delivery to the surface waters. In Global NEWS-2-TP a runoff-dependent fraction of annual agricultural P balance (P inputs minus P removed via harvest and grazing) is delivered to rivers but this load from non-point P sources does not respond to accumulation (or depletion) of TP in soils through time. In IMAGE-GNM-TP the delivery of TP to surface water is dependent upon the soil P content, which is in-turn determined by the local history of P accumulation (or depletion). This is the main reason that IMAGE-GNM-TP estimates much lower delivery of TP to surface waters than Global NEWS-2-TP. Another important difference between Global NEWS-2-TP and IMAGE-GNM-TP that may explain some of the discrepancy between their estimates of global TP export is that IMAGE-GNM-TP includes an explicit in-stream TP uptake and removal process whereas Global NEWS-2-TP does not. In Global NEWS-2-TP, in-stream removal of TP is assumed to occur only in reservoirs and with the removal of water for consumptive use (e.g. irrigation). The global importance of long-term, net TP removal and uptake along large river flow paths is uncertain and an important area for future investigation. More broadly, better understanding all the sources and processes involved in river P export is urgently needed to enhance our capacity to predict P delivery to coastal zones globally. To support the attainment of this understanding, there is a clear need for more and better river TP (and other P form) load data.

**Figure 2**



Current Opinion in Environmental Sustainability

Comparison of measured and modeled TP load as predicted by the NEWS-2-TP and IMAGE-GNM-TP models for large (>20 000 km$^2$) basins globally with available TP load data. Nash-Sutcliffe Efficiencies (NSE) values for the two models are shown, and n = 12 for both measurement-model comparisons. Shaded area and dotted lines represent range +/− a factor of two and +/− one order of magnitude, respectively.

At the global scale, P transfers are dominated by particulate P originating from diffuse sources [23••,45], and therefore controlled by hydrological/climatic conditions. It has been shown in many small scale studies that most of the diffuse P delivery occurs during precipitation events [46,47]. Such nutrient flushing from land to surface freshwaters can lead to episodes of severe water quality deterioration [48], which can, in-turn, under certain conditions, affect water scarcity/availability [49]. These dynamics are not yet in global P loading models but are likely to be quite important [23••]. Hence, the impact of hydrology on P transfers at submonthly time scales should be included in future iterations of global P models, and TP loadings during extreme rainfall events should be explicitly accounted for in order to refine the potential of global models to identify periods and locations of increased eutrophication risk.

Finer than annual temporal resolution may also be key in that such time steps allow models to estimate when (and how) nutrient ratios change during the year and therefore when conditions favor harmful algae growth (e.g. during times of P abundance coupled with strong N and Si limitation). Annual models do not capture such dynamics, and thus incorporating seasonality into global P models would help to quantitatively link P loading to P impacts (e.g. HABs, cyanobacteria blooms, global indicators of eutrophication status). Attaining appropriately scaled (subannual) input and validation data presents an important, although ultimately surmountable, challenge.

Given that PP is the dominant form of P export to coastal areas, but is typically less biologically available than DIP, better understanding and modeling the bioavailability of PP is necessary to better interpret the implications of P loading model outputs. In the few regions and studies where PP bioavailability has been assessed in freshwater systems (Northwest and Northeast USA), the bioavailable fraction of PP ranges from <5% to 69% of TP with most between 20%–30% [50–52]. The bioavailability of PP may vary more than this at the global scale as these studies currently represent a limited subset of watershed types and geographies. In the studies that do exist, PP bioavailability is heavily influenced by differences in treatment processes of point sources, and surface runoff and discharge conditions [50,52,53], both further linked to the properties of eroded sediment and climatic conditions. Therefore, linking PP transport modeling with sediment/soil mobilization and transport might improve estimates of P availability and hence P impacts on receiving aquatic ecosystems.

One key process governing both the mobility and bioavailability of PP, which has been demonstrated as important to P cycling at finer scales (e.g. Ref. [54]) but is not yet incorporated into global models, is the sorption/desorption interaction of dissolved P with particles in soil, surface water and ground water. P desorption is likely to be particularly important in estuaries, as seawater anions compete with dissolved $PO_4^{3-}$ for exchange sites on particulates and enhance the availability of formerly adsorbed P. Froelich *et al.* [55] posited that available P could increase by a factor of 2–4.9 as rivers discharge into the marine environment as a result of this mechanism, but little work has been done to test this hypothesis beyond the few systems in which it was originally reported. Linking river P export models to estuarine P processing models remains a key challenge.

Additional model enhancements that could greatly increase the utility of global P models include: first, the broader inclusion of time-lags in P delivery from soils to surface waters that clearly exist in nature (‘P legacy’ effects) [56] but are only present in one of the existing global P models: IMAGE-GNM-TP, and there only at an annual scale, second, explicit representation of interactions between P and other nutrients (and other types of water pollution), and third, explicit feedbacks on P dynamics resulting from ecosystem conditions such as hyoxia, which can increase P solubility and mobility [57]. Finally, enhancing model representation of within-basin spatial heterogeneity of P sources, sinks and predictions allows for better source attribution (e.g. with DIP and urban areas), enhanced quantification of P loading and storage, enhanced model evaluation potential, and facilitates a range of potential model applications (e.g. examining freshwater P loading of wetlands, lakes, reservoirs, and streams or P retention potential). Although care must be taken to evaluate higher-resolution models using appropriately scaled data, rapidly improving computing speeds and global P loading data sets are creating exciting opportunities to apply global P loading models with higher spatial resolution than has been feasible to-date. Increased spatial resolution of Global P models may raise challenges for large-scale scenario analysis efforts, and, in some cases may not represent an improvement over locally developed and tuned models (of which there are many), but increased spatial resolution could also greatly facilitate the use of global models in addressing problems such as algal blooms. For example, determining sources and processes contributing to algal blooms in transboundary watersheds or in coastal zones receiving inputs from rivers draining multiple countries (or continents) will likely require the use of global models. In addition, where water quality measurements are not available, having better integration of terrestrial data in river P loading models, will allow for better predictions based on similar sites that do have data.

In addition to opportunities for model improvement, there are also opportunities to use existing, or slightly improved, version of global P models to address critical questions that have not yet been addressed. One area ripe for progress using existing models is quantitatively linking P inputs to surface waters with lake and river ecosystem functions such as primary (and even secondary) production. Although there is a rich literature linking local and regional P loading to eutrophication of surface waters, global patterns remain poorly understood [58]. The recent advent of satellite products with chlorophyll *a* information along with recent advances in P transport modeling set the stage for exciting progress in this area [59].

Additionally, as noted previously, much useful insight could be gained from additional scenario analyses, especially ones employing a model inter-comparison approach [60]. Simply using the latest RCPs and SSPs to drive existing P transport models would yield novel understanding of how global changes are likely to affect P transport in the future. Even greater insight would result if these analyses also encompassed interactions with other nutrients (e.g. nitrogen and silica) and aquatic pollutants (e.g. pesticides, pathogens) [61]. Such scenario analyses have the potential to inform large-scale policy agendas (e.g. both water quality sustainability development goals (SDGs) and other SDGs). For example, increased access to sanitation in conjunction with P recovery technologies could advance human health, food security (i.e. by increasing access to recyclable nutrients like P), and energy SDGs [62•], but these types of scenarios have not yet been integrated with water quality models and thus environmental SDGs. Similarly, use of legacy P has been put forth as a way to meet global food security goals with less dependence on newly mined mineral P [63], and could be used in conjunction with IMAGE-GNM-TP to explore how effective such P mitigation strategies are likely to be in attaining freshwater and coastal water quality SDGs. Finally, scenario analyses can be coupled with source attribution and economic cost-benefit analysis to examine the environmental and economic costs associated with potential P mitigation strategies. Work is ongoing to develop a theoretical approach for such analyses [64]. Such efforts would essentially seek to find effective, low-cost solutions to P overenrichment that could help guide national and regional efforts to maintain or restore aquatic ecosystems. Using global scenarios for such analyses may be particularly important to inform international agreements and proposed interventions (e.g. with the Baltic Sea [65]). Addressing such questions will require enhanced global P models and experts working across disciplines (e.g. biophysical scientists and modelers working in teams with economists and social scientists).

## Conclusion

Within the past two decades, global P loading and transport models have granted useful insight into: P loading hotspots, P sources, and drivers of P delivery to surface waters historically, currently, and under future scenarios. However, there is still much room for improvement in model performance and representativeness, and key questions remain to be answered. Opportunities to achieve model improvements include: first, increased temporal resolution, including representation of 'event' fluxes, second, improved representation of sorption/desorption dynamics in groundwater, rivers, and (especially) the coastal zone, and third, the incorporation of interactions between P and other nutrients, ecosystem conditions, and non-nutrient pollutants. Efforts to achieve all of these model enhancements would be greatly facilitated by the collection of more river P flux data. Key research opportunities that could be achieved using either existing or enhanced global P models include: first, quantitatively linking P delivery to aquatic ecosystem function (e.g. primary production), and second, examining and evaluating potential costs, benefits, and efficacy of P mitigation strategies, and how well nations are meeting water quality targets, including water quality SDGs.

## Acknowledgements

This paper evolved from a workshop titled 'Water Quality: a new challenge for global scale modelling' held at Wageningen University 18–21 September 2017. Funding for this workshop came from the OECD-CRP, the support of which is gratefully acknowledged. Harrison received support from an NSF INFEWS grant (NSF EAR1639458). A.F.B. and A.H.W.B. received support from PBL Netherlands Environmental Assessment Agency through in-kind contributions to The New Delta 2014 ALW projects no. 869.15.015 and 869.15.014. L.V. benefited from a grant financed by the Netherlands Organisation for Scientific Research (Earth and life sciences Open Programme 2016, project no. ALWOP.230). G.S.M was supported by a FORMAS, the Swedish research council for sustainable development, grant (Grant: 992023 Wennergren. FORMAS 942-2016-69). M.S. was supported by the Sustainable Resource Management for Adequate and Safe Food Provision project (KNAW-MOST SURE: PSA-SA-E-01) and by the Multi Pollutant Modelling project (5160957330-DEELPRJ_1).

## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.cosust.2018.10.010.

## References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Elser JJ, Bracken MES, Cleland EE, Gruner DS, Harpole WS, Hillebrand H, Ngai JT, Seabloom EW, Shurin JB, Smith JE: **Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems**. *Ecol Lett* 2007, **10**:1135-1142.
2. Vitousek PM, Porder S, Houlton BZ, Chadwick OA: **Terrestrial phosphorus limitation: mechanisms, implications, and nitrogen-phosphorus interactions**. *Ecol Appl* 2010, **20**:5-15.
3. Sylvan JB, Dortch Q, Nelson DM, Brown AFM, Morrison W, Ammerman JW: **Phosphorus limits phytoplankton growth on the Louisiana shelf during the period of hypoxia formation**. *Environ Sci Technol* 2006, **40**:7548-7553.
4. Street LE, Mielke N, Woodin SJ: **Phosphorus availability determines the response of tundra ecosystem carbon stocks to nitrogen enrichment**. *Ecosystems* 2018, **21**:1155 http://dx.doi.org/10.1007/s10021-017-0209-x.
5. Bennett EM, Carpenter SR, Caraco NF: **Human impact on erodable phosphorus and eutrophication: a global perspective**. *Bioscience* 2001, **51**:227-234.
6. Carpenter SR, Bennett EM: **Reconsideration of the planetary boundary for phosphorus**. *Environ Res Lett* 2011, **6**.
7. Cordell D, Drangert JO, White S: **The story of phosphorus: global food security and food for thought**. *Glob Environ Change-Hum Policy Dimens* 2009, **19**:292-305.
8. Van Drecht G, Bouwman AF, Harrison J, Knoop JM: **Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050**. *Glob Biogeochem Cycles* 2009, **23**.
9. Bouwman AF, Beusen AHW, Billen G: **Human alteration of the global nitrogen and phosphorus soil balances for the period 1970-2050**. *Glob Biogeochem Cycles* 2009, **23**.
10. Deemer BR, Harrison JA, Li S, Beaulieu JJ, DelSontro T, Barros N, Bezerra-Neto JF, Powers SM, Santos MAd, Vonk JA: **Greenhouse gas emissions from reservoir water surfaces: a new global synthesis**. *BioScience* 2016, **66(11)**:949-964 http://dx.doi.org/10.1093/biosci/biw117.
11. Ho JC, Michalak AM: **Phytoplankton blooms in Lake Erie impacted by both long-term and springtime phosphorus loading**. *J Great Lakes Res* 2017, **43**:221-228.
12. Schindler DW: **Eutrophication and recovery in experimental lakes implications for lake management**. *Science (Washington D C)* 1974, **184**:897-899.
13. Macdonald GK, Jarvie HP, Withers PJA, Doody DG, Keeler BL, Haygarth PM, Johnson LT, McDowell RW, Miyittah MK, Powers SM *et al.*: **Guiding phosphorus stewardship for multiple ecosystem services**. *Ecosyst Health Sustain* 2016, **2** e01251.

14. Borah DK, Bera M: **Watershed-scale hydrologic and nonpoint-source pollution models: review of mathematical bases**. *Trans ASAE* 2003, **46**:1553-1566.

15. Borah DK, Bera M: **Watershed scale hydrologic and nonpoint source pollution models for long-term continuous and storm event simulations**. In *Total Maximum Daily Load (Tmdl): Environmental Regulations II, Proceedings*. 2003:161-167.

16. Programme U.N.E: *A Snapshot of the World's Water Quality: Towards a global Assessment*. Nairobi, Kenya: United Nations Environment Programme; 2016, 162.

17. Smith SV, Swaney DP, Talaue-McManus L, Bartley JD, Sandhei PT, McLaughlin CJ, Dupra VC, Crossland CJ, Buddemeier RW, Maxwell BA *et al.*: **Humans, hydrology, and the distribution of inorganic nutrient loading to the ocean**. *Bioscience* 2003, **53**:235-245.

18. Caraco NF: **Influence of human populations on P transfers to aquatic systems: a regional scale study using large rivers**. In *Phosphorus in the Global Environment*, vol. 54. Edited by Tiessen H. Wiley; 1995:235-244 SCOPE.

19. Newbold JD, Elwood JW, Oneill RV, Vanwinkle W: **Measuring nutrient spiralling in streams**. *Can J Fish Aquat Sci* 1981, **38**: 860-863.

20. Harrison JA, Bouwman AF, Mayorga E, Seitzinger S: **Magnitudes and sources of dissolved inorganic phosphorus inputs to surface fresh waters and the coastal zone: a new global model**. *Glob Biogeochem Cycles* 2010, **24**.

21. Mayorga E, Seitzinger SP, Harrison JA, Dumont E, Beusen AHW, Bouwman AF, Fekete BM, Kroeze C, Van Drecht G: **Global nutrient export from WaterSheds 2 (NEWS 2): model development and implementation**. *Environ Model Softw* 2010, **25**:837-853.

22. Fink G, Alcamo J, Florke M, Reder K: **Phosphorus loadings to the world's largest lakes: sources and trends**. *Glob Biogeochem Cycles* 2018, **32**:617-634.
••

This recent study describes and applies the WaterGAP 3 modeling framework to estimate present-day phosphorus loading to the world's largest 100 lakes. It also examines recent trends in P loading to these lakes as well as sources of this P.

23. Vilmin L, Mogollon JM, Beusen AHW, Bouwman AF: **Forms and subannual variability of nitrogen and phosphorus loading to global river networks over the 20th century**. *Glob Planet Change* 2018, **163**:67085.
••

This recent study provides a first-ever half-degree resolution estimate of P inputs to rivers by form for all major P forms. As such it provides an approach and data that could be useful in driving a version of IMAGE-GNM that disaggregates TP into its constituent forms.

24. Beusen AHW, Van Beek LPH, Bouwman AF, Mogollon JM, Middelburg JJ: **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**. *Geosci Model Dev* 2015, **8**:4045-4067.

25. Seitzinger SP, Mayorga E, Bouwman AF, Kroeze C, Beusen AHW, Billen G, Van Drecht G, Dumont E, Fekete BM, Garnier J *et al.*: **Global river nutrient export: a scenario analysis of past and future trends**. *Glob Biogeochem Cycles* 2010, **24**.

26. Stehfest E, van Vuuren D, Kram T, Bouwman L, Alkemade R, Bakkenes M, Biemans H, Bouwman AF, den Elzen M, Janse J *et al.*: In *Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications.* Edited by Agency PNEA. Bilthoven, Netherlands: Netherlands Environmental Assessment Agency; 2014.

27. Zhang J, Beusen AHW, Van Apeldoorn DF, Mogollón JM, Yu C, Bouwman AF: **Spatiotemporal dynamics of soil phosphorus and crop uptake in global cropland during the 20th century**. *Biogeosciences* 2017, **14**:2055-2068.

28. Hartmann J, Moosdorf N, Lauerwald R, Hinderer M, West AJ: **Global chemical weathering and associated P-release — the role of lithology, temperature and soil properties**. *Chem Geol* 2014, **363**:145-163.

29. Harrison JA, Caraco N, Seitzinger SP: **Global patterns and sources of dissolved organic matter export to the coastal zone: results from a spatially explicit, global model**. *Glob Biogeochem Cycles* 2005, **19**.

30. Harrison JA, Seitzinger SP, Bouwman AF, Caraco NF, Beusen AHW, Vorosmarty CJ: **Dissolved inorganic phosphorus export to the coastal zone: results from a spatially explicit, global model**. *Glob Biogeochem Cycles* 2005, **19**.

31. Beusen AHW, Dekkers ALM, Bouwman AF, Ludwig W, Harrison J: **Estimation of global river transport of sediments and associated particulate C, N, and P**. *Glob Biogeochem Cycles* 2005, **19**.

32. Beusen AHW, Bouwman AF, Van Beek LPH, Mogollon JM, Middelburg JJ: **Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum**. *Biogeosciences* 2016, **13**:2441-2451.
••

This paper applies the IMAGE-GNM model globally over the 20th century, elucidating uneven spatial patterns and major increases in river TP loading and transport over this period. It also documents a major shirt in P sources to freshwaters and the coastal zone during the 20th century.

33. Strokal M, Kroeze C, Wang MR, Bai ZH, Ma L: **The MARINA model (Model to Assess River Inputs of Nutrients to seAs): model description and results for China**. *Sci Total Environ* 2016, **562**:869-888.

34. Pedde S, Kroeze C, Mayorga E, Seitzinger SP: **Modeling sources of nutrients in rivers draining into the Bay of Bengal-a scenario analysis**. *Reg Environ Change* 2017, **17**:2495-2506.

35. Mogollón JM, Beusen AHW, van Grinsven HJM, Westhoek H, Bouwman AF: **Future agricultural phosphorus demand according to the shared socioeconomic pathways**. *Glob Environ Change* 2018, **50**:149-163.
•

This paper presents a recent effort to use the Shared Socioeconomic Pathway (SSP) framework to enhance understanding of future trends in agricultural P demand and use. In doing so it highlights major upcoming changes in P use, essentially a doubling of crop P requirements between 2005 and 2050, regardless of the scenario applied.

36. Mogollon JM, Lassaletta L, Beusen AHW, van Grinsven HJM, Westhoek H, Bouwman AF: **Assessing future reactive nitrogen inputs into global croplands based on the shared socioeconomic pathways**. *Environ Res Lett* 2018, **13**.

37. Riahi K, van Vuuren DP, Kriegler E, Edmonds J, O'Neill BC, Fujimori S, Bauer N, Calvin K, Dellink R, Fricko O *et al.*: **The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview**. *Glob Environ Change-Hum Policy Dimens* 2017, **42**:153-168.

38. O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, van Ruijven BJ, van Vuuren DP, Birkmann J, Kok K *et al.*: **The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century**. *Glob Environ Change-Hum Policy Dimens* 2017, **42**:169-180.
•

This recent paper introduces and discusses the Shared Socioeconomic Pathway narratives, thereby establishing a roadmap to novel scenario analyses using global river P transport models.

39. van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque JF *et al.*: **The representative concentration pathways: an overview**. *Clim Change* 2011, **109**:5-31.

40. Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T *et al.*: **The next generation of scenarios for climate change research and assessment**. *Nature* 2010, **463**:747-756.

41. Alcamo J, van Vuuren D, Cramer W, Alder J, Bennett EM, Carpenter SR, Christiensen J, Foley JA, Maerker M, Masui T *et al.*: **Changes in ecosystem services and their drivers across the scenarios**. *Ecosyst Hum Well-Being* 2005, **2**:297-373.

42. Galloway JN, Dentener FJ, Capone DG, Boyer EW, Howarth RW, Seitzinger SP, Asner GP, Cleveland CC, Green PA, Holland EA *et al.*: **Nitrogen cycles: past, present, and future**. *Biogeochemistry* 2004, **70**:153-226.

43. Galloway JN, Townsend AR, Erisman JW, Bekunda M, Cai Z, Freney JR, Martinelli LA, Seitzinger SP, Sutton MA: **Transformation of the nitrogen cycle: recent trends, questions, and potential solutions**. *Science* 2008, **320**:889-892.

44. Liu XC, Beusen AHW, Van Beek LPH, Mogollon JM, Ran XB, Bouwman AF: **Exploring spatiotemporal changes of the Yangtze River (Changjiang) nitrogen and phosphorus sources, retention and export to the East China Sea and Yellow Sea**. *Water Res* 2018, **142**:246-255.

45. Seitzinger SP, Harrison JA, Dumont E, Beusen AHW, Bouwman AF: **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**. *Glob Biogeochem Cycles* 2005, **19**.

46. Fraser AI, Harrod TR, Haygarth PM: **The effect of rainfall intensity on soil erosion and particulate phosphorus transfer from arable soils**. *Water Sci Technol* 1999, **39**:41-45.

47. Edwards AC, Withers PJA: **Linking phosphorus sources to impacts in different types of water body**. *Soil Use Manage* 2007, **23**:133-143.

48. Michalak AM: **Study role of climate change in extreme threats to water quality**. *Nature* 2016, **535**:349-350.

49. van Vliet MTH, Florke M, Wada Y: **Quality matters for water scarcity**. *Nat Geosci* 2017, **10**:800-802.

50. Ellison ME, Brett MT: **Particulate phosphorus bioavailability as a function of stream flow and land cover**. *Water Res* 2006, **40**:1258-1268.

51. Baker DB, Confesor R, Ewing DE, Johnson LT, Kramer JW, Merryfield BJ: **Phosphorus loading to Lake Erie from the Maumee, Sandusky and Cuyahoga rivers: the importance of bioavailability**. *J Great Lakes Res* 2014, **40**:502-517.

52. Prestigiacomo AR, Effler SW, Gelda RK, Matthews DA, Auer MT, Downer BE, Kuczynski A, Walter MT: **Apportionment of bioavailable phosphorus loads entering Cayuga Lake, New York**. *J Am Water Resour Assoc* 2016, **52**:31-47.

53. Effler SW, Auer MT, Peng F, Perkins M, O'Donnell SM, Prestigiacomo AR, Matthews DA, DePetro PA, Lambert RS, Minott NM: **Factors diminishing the effectiveness of phosphorus loading from municipal effluent: critical information for TMDL analyses**. *Water Environ Res* 2012, **84**:254-264.

54. Kerr JG, Burford M, Olley J, Udy J: **Phosphorus sorption in soils and sediments: implications for phosphate supply to a subtropical river in southeast Queensland, Australia**. *Biogeochemistry* 2011, **102**:73-85.

55. Froelich PN: **Kinetic control of dissolved phosphate in natural rivers and estuaries - a primer on the phosphate buffer mechanism**. *Limnol Oceanogr* 1988, **33**:649-668.

56. Jarvie HP, Sharpley AN, Spears B, Buda AR, May L, Kleinman PJA: **Water quality remediation faces unprecedented challenges from "legacy phosphorus"**. *Environ Sci Technol* 2013, **47**:8997-8998.

57. Nürnberg GK: **Prediction of phosphorus release rates from total and reductant-soluble phosphorus in Anoxic Lake sediments**. *Can J Fish Aquat Sci* 1988, **45**:453-462.

58. Janssen ABG, Janse JH, Beusen AHW, Chang M, Harrison JA, Huttunen I, Kong X, Rost J, Teurlincx S, Troost TA *et al.*: **How to model algal blooms in any lake on earth**. *Curr Opin Environ Sustain* 2019, **36**:1-10.

59. Sayers MJ, Grimm AG, Shuchman RA, Deines AM, Bunnell DB, Raymer ZB, Rogers MW, Woelmer W, Bennion DH, Brooks CN *et al.*: **A new method to generate a high-resolution global distribution map of lake chlorophyll**. *Int J Remote Sens* 2015, **36**:1942-1964.

60. Van Vliet MTH, Florke M, Harrison JA, Hofstra N, Keller V, Fulco L, Kroeze C, Spanier JE, Strokal M, Wada Y *et al.*: **Model inter-comparison design for large-scale water quality models**. *COSUST* 2018. (in press), This Volume.

61. Strokal M, Spanier JE, Kroeze C, Koelmans AA, Flörke M, Franssen W, Hofstra N, Langan S, Tang T, van Vliet MTH *et al.*: **Global multi-pollutant modelling of water quality: scientific challenges and future directions**. *COSUST* 2018 http://dx.doi.org/10.1016/j.cosust.2018.10.013.

62. • Trimmer JT, Cusick RD, Guest JS: **Amplifying progress toward multiple development goals through resource recovery from sanitation**. *Environ Sci Technol* 2017, **51**:10765-10776.

This recent study evaluates the potential for wastewater resource recovery to offset needs for other sources of nutrients (including phosphorus) and energy. It finds that wastewater P recovery could offset the need for P fertilizer from other sources by more than 100% in many parts of the world, and particularly in least-developed countries.

63. Sattari SZ, Bouwman AF, Giller KE, van Ittersum MK: **Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle**. *Proc Natl Acad Sci U S A* 2012, **109**:6348-6353.

64. Macintosh KA, Mayer BK, McDowell RW, Powers SM, Baker LA, Boyer TH, Rittman BE: **Managing diffuse phosphorus at the source versus at the sink**. *Environ Sci Technol* 2018 http://dx.doi.org/10.1021/acs.est.8b01143.

65. Gren IM, Elofsson K: **Credit stacking in nutrient trading markets for the Baltic Sea**. *Mar Policy* 2017, **79**:1-7.