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Rivers in the Anthropocene: Global scale modifications of riverine nutrient fluxes by damming

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Abstract

The damming of rivers represents one of the major anthropogenic disturbances of the natural cycles of water and nutrient elements on the continents. Currently, more than 50% of the world's stream and river flow crosses one or more dams before reaching the oceans. This fraction could climb up to 90% by 2030. The associated modifications of both the absolute and relative riverine fluxes of nutrients have far-reaching ecohydrological implications, from individual ecosystems to the global biogeosphere. While dam reservoirs usually act as sinks of macronutrients along the river continuum, their effects on riverine fluxes and chemical speciation differ markedly from one nutrient element to another. Dams can thus fundamentally alter nutrient limitation patterns and water quality in river-floodplain systems and receiving water bodies, including lakes and coastal marine areas. Here, we briefly review recent research addressing the impact of dams on riverine nutrient fluxes and stoichiometry, and identify some of the research challenges ahead.

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Keywords

Damming
Rivers
Nutrients
Retention
Global analyses
Reservoir management

1. Introduction

Rivers and their associated riparian areas, reservoirs and floodplains sustain a plethora of ecological functions and essential ecosystem services. Rivers and streams supply water for drinking, sanitation, irrigation and industrial usage. They support inland fisheries and aquaculture, and account for a substantial fraction of the world's electricity production. Biogeochemical processes in streams and floodplains contribute to water purification, nutrient cycling and waste assimilation. Historically, trade and human settlement often followed the course of rivers, while floodplains yielded fertile lands for agriculture.

River systems are not only central to humanity's water and food security, they also harbor a wide diversity of natural habitats and biological species.

The biodiversity and ecosystem functions of river systems are, in turn, closely linked to the flow regime, which regulates the timing and intensity of exchanges of water and materials between river channel, adjacent floodplains and connected aquifers (Sparks, 1995). Dissolved and suspended materials carried by rivers are ultimately delivered to lakes and sea. The outflow of rivers therefore contributes to maintaining the biological productivity and ecological integrity of inland and coastal marine environments.

Rivers are the great integrators of the freshwater cycle. The flow regime and chemical composition of river water inform us about hydrological connectivity and storage, terrestrial–aquatic interactions, and landscape disturbances in watersheds. Rivers and streams record changes in regional climate, land and water use, and pollutant loadings. Modifications of the natural flow regime and increased inputs of nutrients are among the most significant human drivers of change of riverine ecosystems and connected water bodies (Harrison et al., 2005).

Humans have been building dams for at least 7000 years. The systematic damming of rivers, however, began in earnest after the 1930s. By the end of the 20th century, more than half of the world's surface water was passing through dams prior to reaching the oceans (Vörösmarty et al., 1997). Since then, a new wave of dam construction has started, with the number of large hydroelectric dams projected to nearly double by 2030 (Zarfl et al., 2015). Within the next decades, dams will moderately to severely impact flow conditions in almost all major rivers on earth (Grill et al., 2015). The global scale effects of river damming, however, have received relatively little attention compared to those of other drivers of environmental change, such as energy use, agricultural intensification and urbanization.

River damming generates both risks and opportunities for integrated watershed management. In many of the major grain producing areas of the world, the water storagecapacity created by the construction of dams has enabled spectacular advances in food production, while the ability to control flow conditions in river systems may help to reduce the societal costs of droughts and catastrophic flooding events. The disruption of the natural flow regime by dams, however, has been linked to the decline in biodiversity of river systems (Poff et al., 2007). Furthermore, the construction of dams not only changes the flow of water, but also the associated material flows, in particular those of nutrients. Nutrient fluxes directly affect the trophic state and water quality of rivers and their receiving water bodies.

Understanding how the construction of dams modifies the environmental flows of nutrients within river basins should be taken into consideration in the design and implementation of long-term, ecohydrological strategies aimed at the sustainable utilization of water resources(Zalewski, 2000, Donald et al., 2015). Unfortunately, much of the data needed to address the impacts of dams on riverine nutrient fluxes are either nonexistent or not available in the public domain. In this paper, we review recent research on river damming and its effects on the transport of macronutrients (phosphorus, nitrogen, silicon) along the river continuum. In particular, we address the question of how to scale up the limited number of available elemental budgets for individual reservoirs in order to estimate the regional, and ultimately global, effects of dams on riverine nutrient fluxes. We further highlight that, in addition to modifying the absolute fluxes of nutrients, dams may significantly alter riverine nutrient ratios. The latter finding is important because changes in both the absolute and relative delivery of nutrients by rivers affect the ecological health of receiving lakes and coastal seas.

2. Riverine nutrients

Rising inputs of nutrients are causing long-term shifts in the trophic state and ecosystem functioning of river systems (Garnier and Billen, 2007). For example, over the course of the second half of the 20th century, CO_2 saturation levels in the lower reaches of the Yangtze River (Changjiang) have systematically decreased, a trend that reflects a gradual transition from heterotrophic to autotrophic conditions (Duan et al., 2007). This transition is most likely driven by the increasing supply of anthropogenic nutrients, which stimulates in-stream primary production and, consequently, changes the balance between primary production and respiration. Large shifts in trophic state further imply an evolving role of river-floodplain ecosystems in the global carbon cycle and climate system (Raymond et al., 2013).

Much attention has been devoted to anthropogenic enrichments of rivers by nitrogen (N) and phosphorus (P). A comprehensive assessment of anthropogenic effects on riverine nutrient fluxes, however, needs to take into consideration other essential nutrient elements, such as silicon (Si), sulphur (S) and iron (Fe). Changes in nutrient stoichiometry may lead to changes in nutrient limitation patterns, foodweb structure and trophic status of aquatic environments. The competition between siliceous and non-siliceous algae, for instance, depends on the availability of Si, relative to P and N (Garnier et al., 2010). Because human activities have perturbed loadings of P and N to a greater extent than Si, riverine Si:P and Si:N nutrient ratios may serve as indicators of anthropogenic pressures at the catchment scale.

Time series water quality data for the Yangtze River compiled by Duan et al. (2007) provide a textbook example of historical changes in nutrient stoichiometry within a major river system. From 1960 to 1985, the average molar ratios of dissolved silicate to dissolved inorganic N in the middle and lower reaches of the river dropped from values around 13 to values below 2, primarily as a result of rising concentrations of inorganic N. In contrast, over the same time period, changes in the Si:N ratio within the upper reaches of the river were far less pronounced, due to fewer anthropogenic N sources. Similar trends are observed for the Si:P ratios. The existing data indicate that declining riverine Si:P and Si:N nutrient ratios are a general, worldwide phenomenon, and may be one of the reasons behind the increased incidence of non-siliceous algal blooms in lakes and coastal marine areas (Billen et al., 1991, Humborg et al., 2006, Garnier et al., 2010).

3. Nutrients and river damming

In addition to changes in nutrient loadings (Ver et al., 1999), humans are modifying riverine fluxes of nutrients by building dams. Dam closure turns the upstream stretch of a river channel into a reservoir. The longer hydraulic residence time and the accompanying lowering of flow velocity and turbidity promote primary productivity and nutrient cycling within the reservoir (Fig. 1). Through sediment accumulation, and for N also denitrification, reservoirs usually remove nutrients from the streamflow (Kõiv et al., 2011). Building a dam may thus alleviate eutrophication pressure on downstream ecosystems by reducing the riverine supply of nutrients. However, biogeochemical processes in the reservoir also alter nutrient speciation and stoichiometry, while flow regulation by the dam changes the timing of downstream nutrient delivery by the river. Damming may thus affect watershed nutrient cycles in multiple and complex ways.

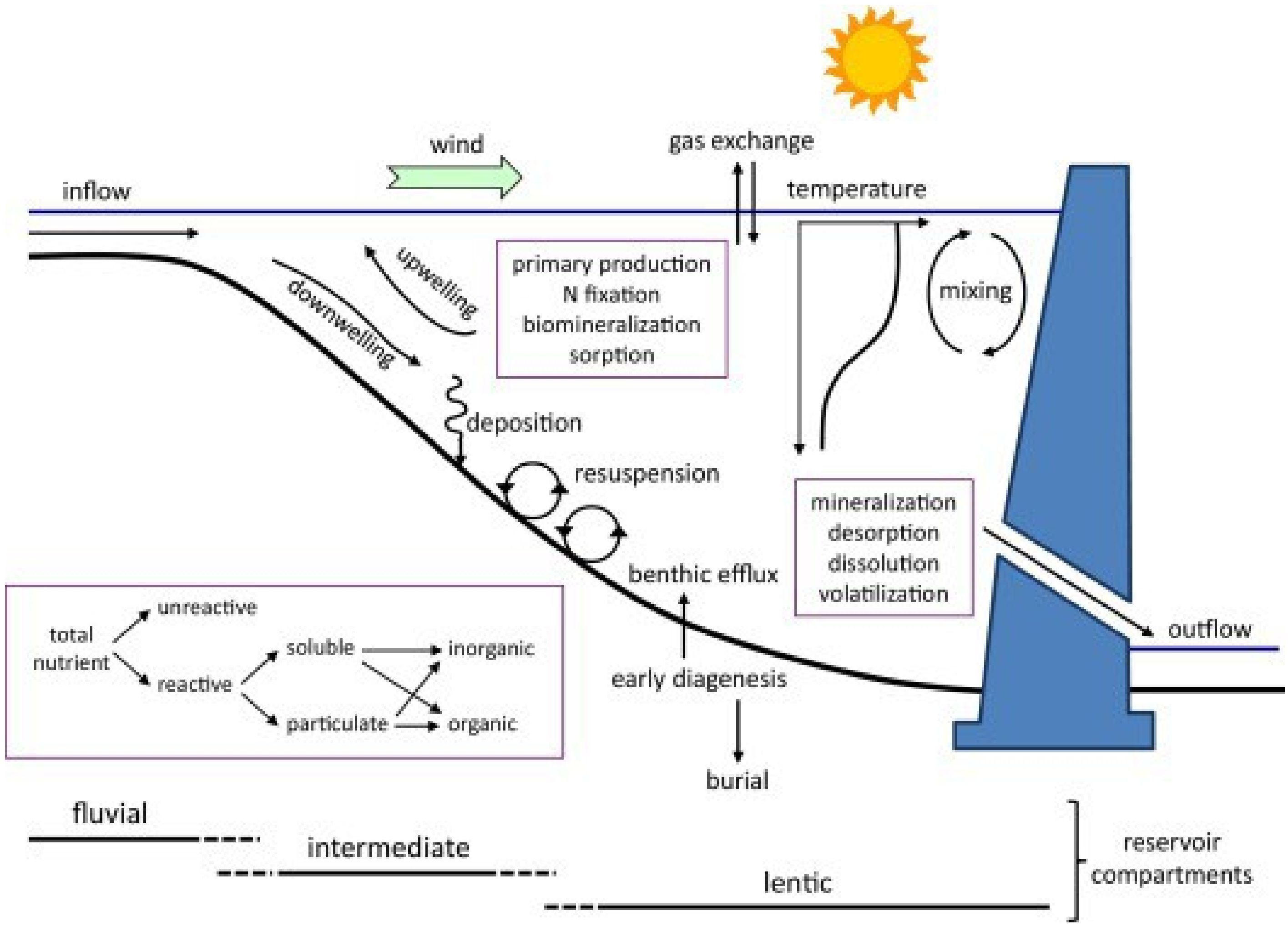

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Fig. 1. Schematic representation of in-reservoir processes controlling the cycling and retention of nutrients in a dam reservoir.

Nutrient retention (or elimination) by a dam is defined as the relative difference between the dam outflow flux of a given nutrient element, or a given chemical form of that element, and the combined inputs to the reservoir via river inflow, groundwater discharge, runoff and atmospheric deposition. In what follows, we first review some recent work addressing nutrient retention in a single reservoir, followed by a presentation of our ongoing efforts to produce global scale estimates of nutrient elimination from river flows due to damming.

3.1. Lake Diefenbaker: a case study

Lake Diefenbaker, a 400 km^2 reservoir on the South Saskatchewan River in Canada, was completed in 1967. The reservoir is an essential regional source of water for irrigation and domestic use. The main dam also provides flood and ice control to downstream communities. Nutrient budgets for Lake Diefenbaker were derived from nutrient concentrations measured in river inflow, dam outflow and the reservoir's water column, as well as data obtained from sediment cores (Maavara et al., 2015a, North et al., 2015).

Lake Diefenbaker efficiently traps P: the annual retention of reactive soluble P is on the order of 60% (North et al., 2015, Donald et al., 2015). In comparison, the reservoir retains only about 30% of dissolved Si on a yearly basis (Maavara et al., 2015a). The annual retention of N varies widely, with up to 40% dissolved inorganic N (DIN) retention in some years, and net export in others (R. North, University of Saskatchewan, pers. comm.; Donald et al., 2015). In 2013–2014, retention of dissolved Si peaked in June with 85% less dissolved Si leaving the reservoir than entering, while in December the outflow of dissolved Si was 344% higher than the inflow (Maavara et al., 2015a). The observed seasonal pattern is explained by diatom production in the reservoir during the summer months, which removes dissolved Si, and net dissolution of diatom frustules following the growth season, which releases dissolved Si. The data collected in Lake Diefenbaker therefore highlight (1) the large differences in retention efficiencies of different nutrient elements, and (2) the large seasonal variability in nutrient retention efficiencies.

Biogeochemical cycling in Lake Diefenbaker decouples the riverine fluxes of nutrient elements and imparts large differences between the N:P:Si ratios of water flowing in and out of the reservoir. This case study thus illustrates how the construction of even a single dam may profoundly change nutrient flows within a river system. While damming generally homogenizes the flow regime of rivers (Poff et al., 2007), it may introduce new temporal variability in riverine nutrient fluxes and stoichiometry. In our opinion, a predictive understanding of the decoupling of nutrient fluxes by dams should be a research priority in watershed ecohydrology, in particular given the current global damming boom (Zarfl et al., 2015), and the mounting evidence that changes in the relative and absolute delivery of macronutrients by rivers severely impacts the ecology and water quality of receiving water bodies (Humborg et al., 2006, Garnier et al., 2010).

3.2. Global nutrient retention by dams

Over 75,000 dam reservoirs larger than 0.1 km^2 already exist worldwide, and their number will continue to rise within the foreseeable future. This contrasts sharply with the limited number of published papers assessing the fate and transport of nutrients in reservoirs. For example, an extensive literature search only yielded 17 studies from which the retention of Si by dams could be estimated (Maavara et al., 2014). A similar search for P produced 149 studies with whole-reservoir P budgets, which still represents less than 0.2% of the global inventory of reservoirs (Fig. 2; Maavara et al., 2015b). It is highly unlikely that the data extracted from these small numbers of reservoirs are statistically representative of worldwide nutrient retention by dams.

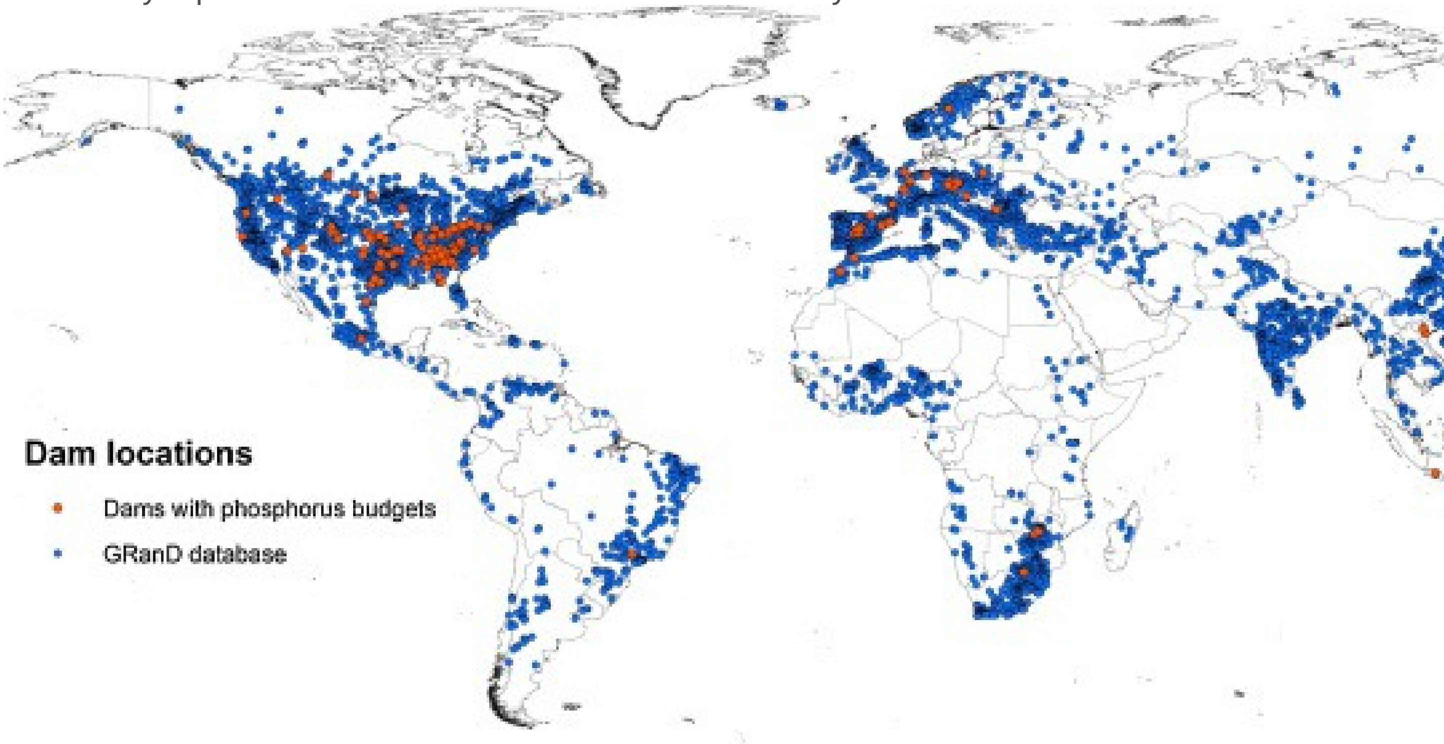

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Fig. 2. World map showing the locations of the reservoirs included in the GRanD database, as well as the locations of the 149 reservoirs with published phosphorus budgets from which phosphorus retention efficiencies can be derived.

Most global estimations of the effect of dams on riverine nutrient fluxes have relied on very simple approximations. These include accounting for retention by dams by applying a correction factor to nutrient loads (Seitzinger et al., 2005, Laruelle et al., 2009), or extrapolating empirical relationships obtained from the limited available data on reservoirs to the global scale (Harrison et al., 2012). Maavara et al. (2014) proposed an alternative approach to estimate global nutrient retention by dams. It combines observed retentions for individual reservoirs with a mechanistic modeling of biogeochemical nutrient cycling in surface water bodies. Compared to previous approaches, the method builds on a knowledge-based understanding of the processes that regulate the in-reservoir redistribution of a nutrient element over its various chemical forms. The method is summarized in Fig. 3. It was first used to estimate the global scale retention of nutrient Si by dams (Maavara et al., 2014) and, since then also applied to P (Maavara et al., 2015b), with ongoing work focusing on N and carbon.

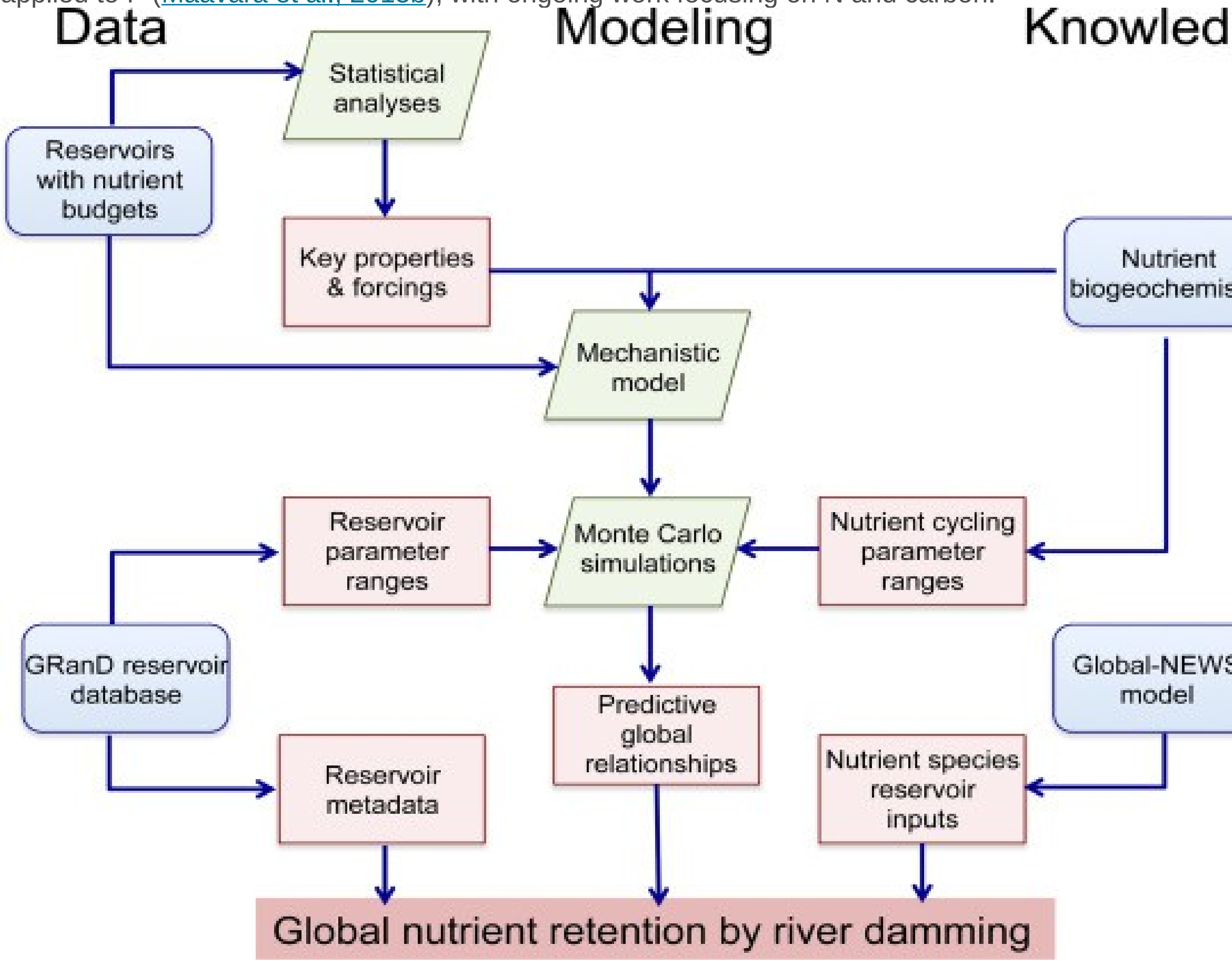

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Fig. 3. Flow chart of the method used for global-scale estimations of nutrient retention by dams. See text for details.

Among the macronutrient elements, modeling the biogeochemical cycling of Si in reservoirs is the most straightforward. In a first approximation, only two reactive Si pools are represented: dissolved silicate and reactive particulate Si. The latter is largely comprised of biogenic silica, but may also include other amorphous and sorbed forms of Si (Saccone et al., 2007). The principal processes controlling the redistribution of nutrient Si are biological fixation by siliceous algae and macrophytes and dissolution of reactive particulate Si. Burial of a fraction of the reactive particulate Si entering the reservoir or produced in the reservoir then results in Si retention. Incorporation of these various processes in a mass balance model yields a number of adjustable parameters for which plausible value ranges can be established. A Monte Carlo simulation approach is then used to account for all possible parameter combinations and generate global relationships for the retention of the two reactive Si pools as a function of the hydraulic residence time of the reservoir (Maavara et al., 2014).

The final steps in the methodology outlined in Fig. 3 consist in (1) using the Global-NEWS-DSi model (Beusen et al., 2009) to predict reactive Si loadings to the reservoirs listed in the Global Reservoirs and Dams (GRanD) database (Fig. 2; Lehner et al., 2011), and (2) applying the global retention relationships for dissolved Si and reactive particulate Si to calculate, for each reservoir, how much reactive Si is buried in the sediments. With their approach, Maavara et al. (2014) estimate that dams currently trap 5.3% of the global total reactive Si loading to rivers. The calculated retention of dissolved Si is even lower (2.6%). The difference reflects the fact that, globally, large reservoirs with long hydraulic residence times accumulate most nutrient Si. These reservoirs efficiently trap particulate matter and, hence, are characterized by greater retentions of reactive particulate Si than dissolved Si.

A similar, knowledge-based scaling up of P retention by river damming shows that globally reservoirs are significantly more efficient at retaining P than Si (Maavara et al., 2015b). This raises the question as to whether the ongoing dam construction may offset the projected increase in anthropogenic P loading to watersheds in the foreseeable future. Our model calculations suggest that this may be the case for the global riverine flux of total P. In other words, the building of new dams over the next two decades may – quite inadvertently – dampen the delivery of anthropogenic P to lakes and coastal areas. The modeling results, however, also show large regional differences in the projected trajectories of anthropogenic P loading to watersheds and the retention of P by reservoirs (Maavara et al., 2015b). In addition, the global analyses only yield annually averaged estimates and, hence, cannot resolve the significant seasonal variations in reservoir P retention (see above *Lake Diefenbaker: A case study*). Thus, one cannot simply downscale the results of global analyses to individual watersheds.

3.3. Dams and integrated water resources management

An important task of sustainable watershed management is to avoid eutrophication of surface water bodies by controlling the flows of nutrients along the aquatic continuum. Much research has been devoted to the management of in-reservoir eutrophication (Cooke et al., 2005). Artificial aeration techniques have been used to counteract the development of anoxia in reservoirs and consequently reduce the internal loading of P from sediments (Beutel and Horne, 1999). Other approaches include manipulating the operation of the dam to generate artificial turbulence that promotes the shift in phytoplankton communities from cyanobacteria to green algae and diatoms (Visser et al., 2015). Ultimately, however, the success of these interventions in reservoir systems with high anthropogenic nutrient loadings, depend on the up-stream reduction of nutrient sources (Gächter, 1986).

Despite the considerable research into reducing in-reservoir eutrophication, little attention has been given to the potential of using reservoir management as a means to mitigate eutrophication in waterways and water bodies downstream of dams. For instance, targeted manipulation of the flow regime could increase the reservoir retention efficiency of P, in order to reduce its downstream transfer. Similarly, shortening the water residence time during the growth period of diatoms may simultaneously alleviate in-reservoir eutrophication and Si limitation of diatom communities in downstream lakes and coastal marine areas (Garnier et al., 2010, Humborg et al., 2000, Humborg et al., 2006). Such reservoir management strategies could be combined with changes in agricultural fertilizer management practices that lower the application of P and increase that of Si. The use of Si amended fertilizers has been shown to increase crop yields at little added cost (Bocharnikova et al., 2010). Overall, we believe there is significant scope for exploring new reservoir management strategies that minimize the trade-offs between societal benefits and ecological impacts of dam construction.

4. Concluding remarks

Dams and reservoirs are an integral component of today's watersheds. They have profoundly changed the flow regimes of many rivers and streams. In addition, there is an increasing realization that the construction of dams alters the absolute and relative riverine fluxes of macronutrient elements. A holistic analysis of watershed ecohydrology must thus include a quantitative understanding of the effects of dams on the retention, speciation and stoichiometry of nutrients. Such an understanding is part of the scientific basis that should inform the design and implementation of sustainable management strategies for watersheds, lakes and near-shore marine environments.

Regional to global scale assessments of the impacts of river damming are currently hampered by the limited availability of data on nutrient budgets for reservoirs. The way forward will depend not only on the acquisition of more complete time-series data, but also on improved modeling of the processes that regulate the transformation and cycling of nutrients in reservoirs. These efforts will help resolve to what extent damming interacts with nutrient enrichment and other anthropogenic pressures on river systems, and, hence, may reduce or promote eutrophication in receiving water bodies. This question is all the timelier given the ongoing resurgence in dam construction, especially concentrated in South America, central Asia, Africa and Southeast Asia.

Conflict of interest

The authors declare no conflict of interest.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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References

Beusen et al., 2009

A.H.W. Beusen, A.F. Bouwman, H.H. Durr, A.L.M. Dekkers, J. Hartmann**Global patterns of dissolved silica export to the coastal zone: results from a spatially explicit global model**

Glob. Biogeochem. Cycles, 23 (2009), 10.1029/2008gb003281

Beutel and Horne, 1999

M.W. Beutel, A.J. Horne**A review of the effects of hypolimnetic oxygenation on lake and reservoir water quality**

Lake Reserv. Manag., 15 (1999), pp. 285-297

CrossRefView Record in Scopus

Billen et al., 1991

G. Billen, C. Lancelot, M. Meybeck, R. Mantoura, J.-M. Martin, R. Wollast**N, P and Si retention along the aquatic continuum from land to ocean**

Ocean Margin Processes in Global Change, vol. 1, John Wiley & Sons (1991), pp. 19-44

View Record in Scopus

Bocharnikova et al., 2010

E.A. Bocharnikova, S.V. Loginov, V.V. Matychenkov, P.A. Storozhenko**Silicon fertilizer efficiency**

Russ. Agric. Sci., 36 (2010), pp. 446-448

CrossRefView Record in Scopus

Cooke et al., 2005

G.D. Cooke, E.B. Welch, S. Petersen, S.A. Nichols**Restoration and Management of Lakes and Reservoirs**

(3rd ed.), CRC Press, Taylor & Francis Group, Boca Raton, Florida, USA (2005)

Donald et al., 2015

D.B. Donald, B.R. Parker, J.-M. Davies, P.R. Leavitt**Nutrient sequestration in the Lake Winnipeg watershed**

J. Great Lakes Res. (2015), 10.1016/j.jglr.2015.03.007

Duan et al., 2007

S. Duan, F. Xu, L.-J. Wang**Long-term changes in nutrient concentrations of the Changjiang River and principal tributaries**

Biogeochemistry, 85 (2007), pp. 215-234

CrossRefView Record in Scopus

Gächter, 1986

R. Gächter**Lake restoration. Why oxygenation and artificial mixing cannot substitute for a decrease in the external phosphorus loading**

Schweiz Z. Hydrol., 49 (1986), pp. 170-185

Garnier and Billen, 2007

J. Garnier, G. Billen**Production versus respiration in river systems: an indicator of an “ecological status”**

Sci. Total Environ., 375 (2007), pp. 110-124

ArticleDownload PDFView Record in Scopus

Garnier et al., 2010

J. Garnier, A. Beusen, V. Thieu, G. Billen, L. Bouwman**N:P:Si nutrient export ratios and ecological consequences in coastal seas evaluated by the ICEP approach**

Glob. Biogeochem. Cycles, 24 (2010), 10.1029/2009GB003583

Grill et al., 2015

G. Grill, B. Lehner, A.E. Lumsdon, G.K. MacDonald, C. Zarfl, C.R. Liermann**An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales**

Environ. Res. Lett., 10 (2015), 10.1088/1748-9326/10/1/015001

Harrison et al., 2005

J.A. Harrison, S.P. Seitzinger, A.F. Bouwman, N.F. Caraco, A.H.W. Beusen, C.J.Vörösmarty**Dissolved inorganic phosphorus export to the coastal zone: results from a spatially explicit, global model**

Glob. Biogeochem. Cycles, 19 (2005), 10.1029/2005GB002480

Harrison et al., 2012

J.A. Harrison, P.J. Frings, A.H.W. Beusen, D.J. Conley, M.L. McCrackin**Global importance, patterns, and controls of dissolved silica retention in lakes and reservoirs**

Glob. Biogeochem. Cycles, 26 (2012), 10.1029/2011gb004228

Humborg et al., 2000

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

Ambio, 29 (2000), pp. 45-50

CrossRefView Record in Scopus

Humborg et al., 2006

C. Humborg, M. Pastuszak, J. Aigars, H. Siegmund, C.M. Morth, V. Ittekkot**Decreased silica land-sea fluxes through damming in the Baltic Sea catchment – significance of particle trapping and hydrological alterations**

Biogeochemistry, 77 (2006), pp. 265-281

CrossRefView Record in Scopus

Kõiv et al., 2011

T. Kõiv, T. Nõges, A. Laas**Phosphorus retention as a function of external loading, hydraulic turnover time, area and relative depth in 54 lakes and reservoirs**

Hydrobiologia, 660 (2011), pp. 105-115

CrossRefView Record in Scopus

Laruelle et al., 20

G.G. Laruelle, V. Roubeix, A. Sferratore, B. Brodherr, D. Ciuffa, D.J. Conley, H.H. Durr, J.Garnier, C. Lancelot, Q.L.T. Phuong, J.D. Meunier, M. Meybeck, P. Michalopoulos, B. Moriceau, S.N.Long phuirt, S. Loucaides, L. Papush, M. Presti, O. Ragueneau, P. Regnier, L. Saccone, C.P. Slomp, C. Spiteri, P. Van Cappellen**Anthropogenic perturbations of the silicon cycle at the global scale: key role of the land-ocean transition**

Glob. Biogeochem. Cycles, 23 (2009), 10.1029/2008gb003267

Lehner et al., 20

B. Lehner, C.R. Liermann, C. Revenga, C. Vörösmarty, B. Fekete, P. Crouzet, P. Doll, M.Endejan, K. Frenken, J. Magome, C. Nilsson, J.C. Robertson, R. Rodel, N. Sindorf, D. Wisser**High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management**

Front. Ecol. Environ., 9 (2011), pp. 494-502

CrossRefView Record in Scopus

Maavara et al., 2

T. Maavara, H.H. Dürr, P. Van Cappellen**Worldwide retention of nutrient silicon by river damming: from sparse data set to global estimate**

Glob. Biogeochem. Cycles, 28 (2014), pp. 842-855

CrossRefView Record in Scopus

Maavara et al., 2

T. Maavara, J.L.A. Hood, R.L. North, L.E. Doig, C.T. Parsons, J. Johansson, K. Liber, J.J.Hudson, B.T. Lucas, D.M. Vandergucht, P. Van Cappellen**Reactive silicon dynamics in a large prairie reservoir (Lake Diefenbaker, Saskatchewan)**

J. Great Lakes Res., 41 (Suppl. 2) (2015), pp. 100-109

ArticleDownload PDFView Record in Scopus

Maavara et al., 2

T. Maavara, C.T. Parsons, C. Ridenour, S. Stojanovic, H.H. Dürr, H.R. Powley, P. Van Cappellen**Global phosphorus retention by river damming**

Proc. Natl. Acad. Sci., 112 (2015), 10.1073/pnas.1511797112

North et al., 2015

R. North, J. Johansson, D. Vandergucht, L. Doig, K. Liber, K. Lindenschmidt, H. Baulch, J.Hudson **Evidence for internal phosphorus loading in a large prairie reservoir (Lake Diefenbaker, Saskatchewan)**
J. Great Lakes Res., 41 (Suppl. 2) (2015), pp. 91-99
ArticleDownload PDFView Record in Scopus

Poff et al., 2007

N.L. Poff, J.D. Olden, D.M. Merritt, D.M. Pepin**Homogenization of regional river dynamics by dams and global biodiversity implications**
Proc. Natl. Acad. Sci., 104 (2007), pp. 5732-5737
CrossRefView Record in Scopus

Raymond et al.,

P.A. Raymond, J. Hartmann, R. Lauerwald, S. Sobek, C. McDonald, M. Hoover, D.Butman, R. Striegl, E. Mayorga, C. Humborg, P. Kortelainen, H. Durr, M. Meybeck, P. Ciais, P. Guth**Global carbon dioxide emissions from inland waters**
Nature, 503 (2013), pp. 355-359
CrossRefView Record in Scopus

Seitzinger et al.,

S.P. Seitzinger, J.A. Harrison, E. Dumont, A.H.W. Beusen, A.F. Bouwman**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, 19 (2005), 10.1029/2005gb002606

Saccone et al., 2

L. Saccone, D. Conley, E. Koning, D. Sauer, M. Sommer, D. Kaczorek, S. Blecker, E. Kelly**Assessing the extraction and quantification of amorphous silica in soils of forest and grassland ecosystems**
Eur. J. Soil Sci., 58 (2007), pp. 1446-1459
CrossRefView Record in Scopus

Sparks, 1995

R.E. Sparks**Need for ecosystem management of large rivers and their floodplains**
BioScience, 45 (1995), pp. 168-182
CrossRefView Record in Scopus

Ver et al., 1999

L.M.B. Ver, F.T. Mackenzie, A. Lerman**Biogeochemical responses of the carbon cycle to natural and human perturbations: past, present, and future**
Am. J. Sci., 299 (1999), pp. 762-801
CrossRefView Record in Scopus

Visser et al., 201

P.M. Visser, B.W. Ibelings, M. Bormans, J. Huisman**Artificial mixing to control cyanobacteria blooms: a review**

Aquat. Ecol. (2015), 10.1007/s10452-015-9537-0

Vörösmarty et al

C.J. Vörösmarty, *et al.***The storage and aging of continental runoff in large reservoir systems of the world**

Ambio, 26 (1997), pp. 210-219

View Record in Scopus

Zalewski, 2000

M. Zalewski**Guest Editorial. Ecohydrology – the scientific background to use ecosystem properties as management tools towards sustainability of water resources**

Ecol. Eng., 165 (2000), pp. 1-8

ArticleDownload PDFView Record in Scopus

Zarfl et al., 2015

C. Zarfl, A. Lumsdon, J. Berlekamp, L. Tydecks, K. Tockner**A global boom in hydropower dam construction**

Aquat. Sci., 77 (2015), pp. 161-170

CrossRefView Record in Scopus