Ecological Modelling 387 (2018) 172–186

Contents lists available at ScienceDirect

Ecological Modelling

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

Impact of global major reservoirs on carbon cycle changes by using an advanced eco-hydrologic and biogeochemical coupling model

Tadanobu Nakayama[a,*], Gregory J. Pelletier[b]

[a] National Institute for Environmental Studies (NIES), 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan
[b] Washington State Department of Ecology, P.O. Box 47600, Olympia, WA 98504-7600, USA

ARTICLE INFO

Keywords:
Reservoirs
Biogeochemical cycle
Eco-hydrology
Coupling model

ABSTRACT

Recent research suggests that reservoirs might be a potentially important source of greenhouse gases to the atmosphere that is often unaccounted for in carbon cycle. The authors developed an advanced model coupling eco-hydrology with biogeochemical cycle (NICE-BGC). The model incorporates complex coupling of hydrologic-carbon cycle in terrestrial-aquatic linkages. In this study, NICE-BGC was further extended to apply to river basins to include the effect of 82 major reservoirs created by dams on hydrologic and biogeochemical cycles. The model result showed the differences in horizontal carbon transport (DOC flux = −66.4 TgC/yr, POC flux = −11.8 TgC/yr, and DIC flux = −43.5 TgC/yr) and vertical fluxes (CO_2 evasion = 76.6 TgC/yr, and carbon burial = 45.0 TgC/yr) in presence of the reservoirs. The model also calculated CO_2 evasion and carbon burial in global 82 reservoirs were 66.5 ± 35.9 TgC/yr and 54.7 ± 29.1 TgC/yr. Further, the result showed that the land carbon sink decreases more with the presence of reservoirs (−0.97 ± 0.61 PgC/yr) than without the presence of reservoirs (−1.05 ± 0.62 PgC/yr). These results are great improvements from previous research based on only field measurement because field measurements only accounted for emissions directly from the reservoirs and didn't evaluate total carbon cycle. The model calculates the emission from the river downstream from the reservoirs in addition to the emission directly from the reservoirs. Therefore, the total simulated CO_2 evasion increased not only in rivers with reservoirs but also in rivers downstream from reservoirs, which implies the need to include field observations of emissions from rivers downstream from reservoirs to quantify the total emissions due to reservoirs in the future. This finding provides valuable insights for re-evaluation of carbon cycle change of the biosphere in reservoirs.

1. Introduction

Previous studies about the carbon cycle have suggested that variability and uncertainty in the biogeochemical cycle in terrestrial ecosystems are larger than those in the atmosphere and ocean (Le Quere et al., 2009), and that the terrestrial biosphere absorbs more CO_2 by sequestration than the ocean, but the largest component of the carbon dioxide (CO_2) emissions stays in the atmosphere (Raupach, 2011). Some recent studies have pointed out that inland waters including rivers, lakes, and groundwater may act as a gigantic transport pathway for both water and dissolved substances and play a globally significant role in continental biogeochemical cycling, the so-called 'boundless carbon cycle' (Cole et al., 2007; Battin et al., 2009; Tranvik et al., 2009). A comprehensive analysis has revealed a global CO_2 evasion (degassing) rate of 2.1 PgC/year from inland waters (rivers and lakes) (Raymond et al., 2013), which is much higher than previous estimates of 1.2 PgC/year (Aufdenkampe et al., 2011) and 1.4 PgC/year (Tranvik et al., 2009), and also predicted global hotspots in which 70 per cent of the flux occurs over just 20 per cent of the land surface. Recently, Lauerwald et al. (2015) also reported a global distribution of CO_2 evasion similar to that reported by Raymond et al. (2013). While the partial pressure of CO_2 and methane (CH_4) in water (pCO2 and pCH4) are necessary for evaluation of CO_2 and CH_4 flux to the atmosphere (evasion), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and particulate organic carbon (POC) are also important for evaluation of CO_2 flux to the ocean (0.9 PgC/year) and sediment storage (0.6 PgC/year) in the global carbon cycle (Cole et al., 2007; Tranvik et al., 2009; Aufdenkampe et al., 2011; Raymond et al., 2013).

In spite of these previous studies, the contribution of inland waters to continental-scale carbon cycling has remained uncertain because it is generally more difficult to measure and the available data for global aquatic ecosystems are fewer and more locally site-specific than those

* Corresponding author.
E-mail address: nakat@nies.go.jp (T. Nakayama).

https://doi.org/10.1016/j.ecolmodel.2018.09.007
Received 29 May 2018; Received in revised form 5 September 2018; Accepted 8 September 2018

for terrestrial ecosystems (Cole et al., 2007; Aufdenkampe et al., 2011). In particular, inland waters may play a significant role in the sequestration, transport and mineralization of carbon (Battin et al., 2009), which would be further complicated by surface–groundwater interactions around wetland and riparian areas, where complex water movement drives carbon storage and flux. Furthermore, because the biogeochemical cycles of nitrogen and carbon are tightly coupled with each other owing to the metabolic needs of organisms for these two elements, CO_2, CH_4, and nitrous oxide (N_2O) amount to 80% of the total radiative forcing from well-mixed greenhouse gases (GHGs) (Ciais et al., 2013; Settele et al., 2014). These previous studies have indicated that estimates of emissions are variable or biased, and sometimes increased or reduced, depending on various conditions related to nutrients, water depth, DOC, chlorophyll *a*, and dissolved oxygen. From this viewpoint, it is very important to develop a process-oriented model that is conserved in water, heat, carbon, nitrogen, and phosphorus budgets. This would help to clarify the mechanism of the carbon cycle in more detail, particularly the interplay between inorganic and organic carbon and its relationship to nitrogen and phosphorus and biogeochemical processes.

The vast majority of CO_2 and CH_4 emissions are usually related to natural cycles, but changes in land use, hydraulic modifications, anthropogenic emissions, and climatic change also have significant effects on the carbon cycle through water pollution, hydrologic change, and CO_2 concentration in the atmosphere, etc. (Regnier et al., 2013). In particular, some recent research has suggested that reservoirs created by dams (Fig. 1) (Lehner and Döll, 2004) might be a potentially important source of greenhouse gases to the atmosphere in addition to providing a variety of services such as hydropower, flood control, navigation, irrigation, recreation, and water supply, and negative impacts on fish migration and other riverine biota (St Louis et al., 2000; Barros et al., 2011; Deemer et al., 2016). Barros et al. (2011) estimated that hydroelectric reservoirs emit about 48 TgC/yr as CO_2 and 3 TgC/yr as CH_4, corresponding to 4% of global carbon emissions from inland waters. These values are similar to those estimated by Deemer et al. (2016) (36.8 TgC/yr as CO_2) and Hertwich (2013) (76 TgC/yr as CO_2), whereas they are much smaller than those estimated by Cole et al. (2007) (280 TgC/yr as CO_2) and St Louis et al. (2000) (270 TgC/yr as CO_2). Sediment processes in reservoirs are also important in the carbon cycle, including burial (90.4 TgC/yr), as well as the emission of CH_4 (Mendonça et al., 2012). Some other studies also showed this carbon burial has a range of 100–300 TgC/yr depending on the reservoir age, type, and water temperature, etc. (Mulholland and Elwood, 1982; Downing et al., 1993; Dean and Gorham, 1998; Stallard 1998; Cole et al., 2007; Clow et al., 2015) except some scattering values estimated by Maavara et al. (2017) (26.2 TgC/yr) and St Louis et al. (2000) (600 TgC/yr).

Nakayama (2014, 2015) developed the National Integrated Catchment-based Eco-hydrology (NICE) model, which takes into account complex interactions between the forest canopy, surface water, the unsaturated zone, aquifers, lakes, and rivers. NICE incorporates a three-dimensional groundwater sub-model and is able to simulate lateral transport of groundwater in addition to surface runoff. NICE was further developed to couple it with five biogeochemical cycle models, including those for terrestrial ecosystems, those for water quality in aquatic ecosystems, and those for carbon weathering. The revised NICE model (NICE-BGC) incorporates the connectivity of carbon, nitrogen, and phosphorus cycles accompanied by the hydrologic cycle between surface water and groundwater, hillslopes and river networks, and other intermediate regions (Nakayama, 2016, 2017a). The model simulates both horizontal transport to the ocean and vertical fluxes and includes aquatic metabolism and terrestrially derived carbon together in major rivers without the presence of reservoirs, which is a potential improvement from the previous studies (Cole et al., 2007; Tranvik et al., 2009; Aufdenkampe et al., 2011; Raymond et al., 2013).

In this study, NICE-BGC was further extended to apply to river basins including the effect of control structures on hydrologic and biogeochemical cycles. There are three basic science questions as follows: (i) How do reservoirs influence land carbon sink dynamics and carbon dynamics in inland waters? ; (ii) How do reservoirs change the relative importance of land-ocean interactions to land-atmosphere interactions (i.e. the land carbon sink) on global carbon dynamics? ; and (iii) How do reservoirs change the composition of carbon (i.e. DOC, DIC, POC) exported to oceans from land? The model result could show the presence of dams affected the changes in horizontal carbon transport and vertical fluxes separately, whereas previous research was generally based on only field measurements, only accounted for emissions directly from the reservoirs, and didn't evaluate total carbon cycle in each

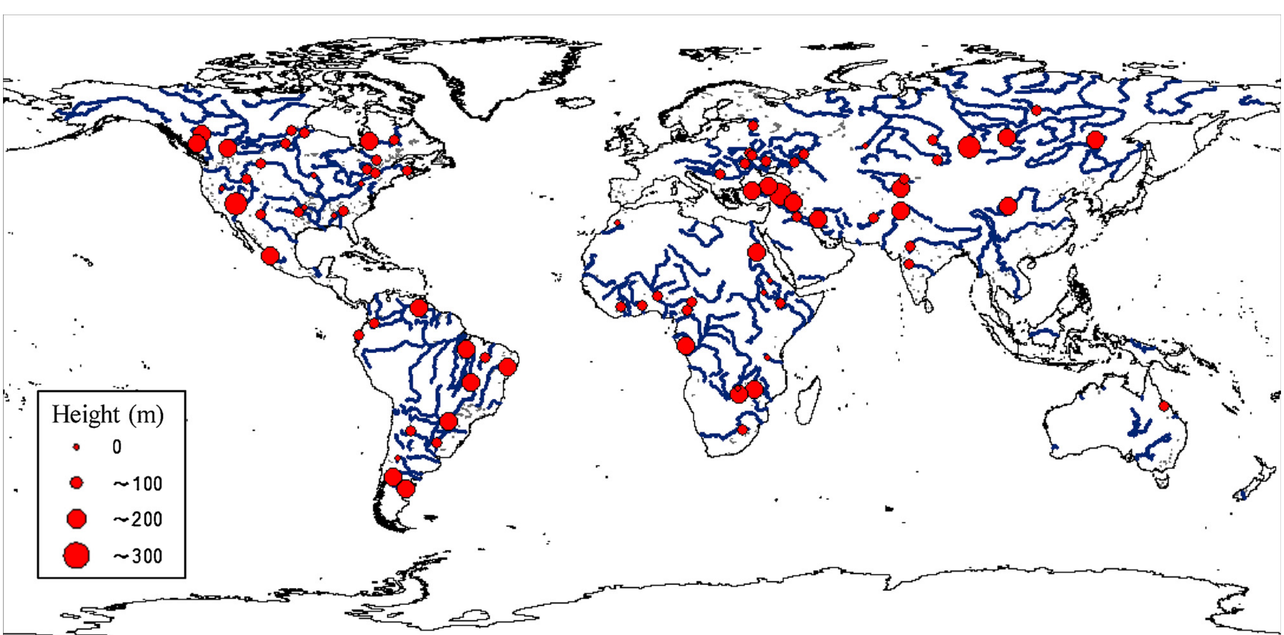

Fig. 1. Location of 82 major reservoirs and their height in the end of the last century used in the model simulation (Lehner et al., 2011). Size of the circle means the height of reservoirs.