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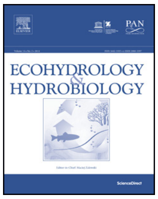

Original Research Article

New perspective for eco-hydrology model to constrain missing role of inland waters on boundless biogeochemical cycle in terrestrial–aquatic continuum

Tadanobu Nakayama

National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan

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ABSTRACT

Recent research shows that inland water may play some role in carbon cycling though its contribution has remained uncertain due to a limited reliable data. From the viewpoint of scale similarity and discontinuity of eco-hydrological processes, it is important to identify spatial coupling of ecosystems including energy, materials, and organisms flows across their boundaries. One of the fundamentals of eco-hydrology model is to incorporate a complex relation between soil, water, temperature, plant, and carbon. In this paper, the author reviewed previous progress in eco-hydrology model focusing on surface–groundwater connectivity and hydrologic–geomorphic–ecological processes interaction. He also reviewed the recent progress in modeling, the role of inland water on biogeochemical cycle by compiling various datasets of hydrological and biogeochemical cycle. Then, he showed a new advanced model coupling eco-hydrology and biogeochemical cycle (NICE-BGC). The model results of both CO_2 evasion and carbon transport to the ocean were reasonably in good agreement with previous data. In order to decrease uncertainty about carbon cycle, it became clear the previous empirical estimation should be extended to this process-oriented model and higher resolution data to further clarify mechanistic interplay between inorganic and organic carbon and its relationship to nitrogen and phosphorus in terrestrial–aquatic linkages. NICE-BGC would play important role in re-evaluation of greenhouse gas budget of the biosphere, quantification of hot spots, and bridging gap between top-down and bottom-up approaches in global carbon budget. This will also help to integrate knowledge and provide understanding needed for reaching sustainability by 2030 in UN Sustainable Development Goals.

1. Background for evaluation of boundless biogeochemical cycle in inland water

Previous studies of the conventional/traditional carbon cycle have suggested that variations and uncertain aspects of the biogeochemical cycle in terrestrial ecosystems are larger than those in the atmosphere and ocean, and that the terrestrial biosphere sequesters most of the available carbon (Raupach, 2011). Recently, some 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 some role in continental biogeochemical cycling, so-called ‘boundless carbon cycle’ (Cole et al., 2007; Battin et al., 2009; Tranvik et al., 2009). The vast majority of carbon dioxide (CO_2) and methane (CH_4) emissions are usually related to the natural cycles, but sometimes and somewhere land-use change,

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E-mail address: nakat@nies.go.jp.

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hydraulic constructions, anthropogenic emissions, and climatic change affect certainly the great change in carbon cycle through water pollution, hydrologic change, and CO_2 concentration in the air, etc. Their contribution to continental-scale carbon cycling has remained uncertain because they are generally more difficult to measure and the available data for global aquatic ecosystems are fewer and more heterogeneous than those for terrestrial ecosystems (Cole et al., 2007; Aufdenkampe et al., 2011). In particular, inland waters may play a significant role in 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 fluxes. Further, 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 for up to 80% of the total radiative forcing from well-mixed GHGs (Ciais et al., 2013; Settele et al., 2014).

A recent comprehensive analysis of Raymond et al. (2013) revealed global CO_2 evasion (degassing) rate of 2.1 PgC/year from inland waters (rivers and lakes), 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 predicted global hotspots with 70% of the flux occurring over just 20% of the land surface. Recently, Lauerwald et al. (2015) also shows a similar distribution of CO_2 evasion in the global as that in Raymond et al. (2013). While wetlands (the evasion rate of 2.1 PgC/year), that are functionally different from rivers and lakes because a vegetation canopy can alter the direction of atmospheric CO_2 exchange (Raymond et al., 2013), play an important role in hydrologic and biogeochemical cycling and act as a reservoir for valuable species, boreal, and subarctic wetlands store relatively high amounts of soil carbon as peat, thus affecting the dynamics of greenhouse gases such as methane (Limpens et al., 2008). Further, some research has shown that CO_2 emission from rivers may account for up to 10% of net ecosystem exchange, thus possibly altering the carbon balance of terrestrial systems (Butman and Raymond, 2011). These results imply the inland water should not be ignored and considered as ‘passive pipes’ or just as a residual term in global carbon budget, but actually functions as active transformation through outgassing and carbon burial (Cole et al., 2007; Aufdenkampe et al., 2011).

In the present paper, the author reviewed the recent progress in modeling the role of inland water in biogeochemical cycle toward coupling of eco-hydrology and biogeochemical cycle model in terrestrial–aquatic continuum. One of the fundamentals of eco-hydrology model is to incorporate a complex relation between soil, water, temperature, plant, and carbon (Zalewski, 2002; Zalewski et al., 2003). Because these mechanisms are closely interconnected with each other (Jenerette and Lal, 2005; Regnier et al., 2013; Kiel and Cardenas, 2014) and sometimes the carbon cycle may be triggered or greatly altered by extreme events (Reichstein et al., 2013), the coupling simulation system will play an important role in the integration of greenhouse gas budget of the biosphere, quantification of hot spots in boundless biogeochemical cycle along a terrestrial–aquatic continuum, and bridging the gap between top-down (satellite data and atmospheric inverse modeling) and bottom-up (site-level observations and process-based modeling) approaches (Cole et al., 2007; Battin et al., 2009; Frei et al., 2012; Regnier et al., 2013; Kiel and Cardenas, 2014).

2. Previous progress in process-based eco-hydrology and biogeochemical cycle models in inland water

With regard to the scale similarity and discontinuity of eco-hydrological processes, it is heuristically important to identify spatial coupling of local ecosystems including energy, materials, and organisms, across ecosystem boundaries. Recent research has given rise to serious concerns about extrapolation of small-scale experimental results to entire landscapes, suggesting that it is imperative to bridge the gap between ecosystems on various scales (Deegan et al., 2012). It is therefore valuable to re-evaluate ecosystems by extrapolating the ‘metabolic theory of ecology’ (Brown et al., 2004) from the perspective of a meta-ecosystem analysis by considering multi-scaled aspects on the global–regional–micro level, similarly to the ‘river continuum concept’ (Vannote et al., 1980). This is also related to the previous result that geophysical and microbial capacities act as enhancement in net heterotrophy in inland waters (Battin et al., 2008).

From this viewpoint, the author and colleagues have developed the National Integrated Catchment-based Eco-hydrology (NICE) model (Nakayama, 2008a,b, 2009, 2010, 2011a,b, 2012a,b,c, 2013, 2014, 2015; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Shankman, 2013a,b; Nakayama and Watanabe, 2004, 2006, 2008a,b,c; Nakayama et al., 2006, 2007, 2010, 2012), which takes into account complex interactions between the forest canopy, surface water, the unsaturated zone, aquifers, lakes, and rivers. The model also simulates surface–groundwater interactions assimilating land-surface processes to reproduce variations of LAI (leaf area index) and FPAR (fraction of photosynthetically active radiation) derived from satellite data (Nakayama and Watanabe, 2004). Because NICE incorporates a three-dimensional groundwater sub-model and has been expanded from previous one-/two-dimensional and steady-state – or so-called equilibrium – versions onto a global scale model (Niu et al., 2007; Maxwell and Kollet, 2008; Fan et al., 2013), the advanced model is able to simulate lateral transport of groundwater in addition to surface runoff, which is more pronounced in regions with steeper slopes or riparian/floodplain areas with frequent surface water–groundwater connectivity. This model also extends the traditional concept of a ‘dynamic equilibrium’ with atmospheric forcing on a global scale (Maxwell and Kollet, 2008), and would help to improve the accuracy of estimations of methane emission from wetlands, where groundwater plays the dominant role. Further, the model can simulate iteratively nonlinear interactions between hydrologic, geomorphic, and ecological processes, and include new feedback through a process of down-scaling from regional to local simulation employing finer resolution. Because NICE includes vegetation