Research papers

Negligible contribution of reservoir dams to organic and inorganic transport in the lower Mimi River, Japan

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ABSTRACT

Rivers fulfill an essential ecological role by forming networks for material transport from upland forests to coastal areas. The way in which dams affect the organic and inorganic cycles in such systems is not well understood. Herein, we investigated the longitudinal profiles of the various components of the water chemistry across three cascade dams in Japan: the Yamasubaru Dam, Saigou Dam, and Ohuchibaru Dam, which are situated along the sediment-productive Mimi River in different flow conditions. We analyzed the following water quality components: suspended solids (SS), turbidity, total iron (TFe), dissolved iron (DFe), total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), humic substance (HS), and major ionic components (Na^+, Mg^{2+}, Ca^{2+}, Cl^-, NO^{3-}, and SO_4^{2-}) in the downstream channels of the three dams during the low–intermediate-flow and high-flow events from 2012 to 2014. We estimated hourly loads of each component using hourly turbidity data and discharge data (i.e., L–Q model) separately, and the results are integrated to estimate the annual fluxes. The annual fluxes between the methods were compared to verify predictability of the conventional L–Q models. Annual flux of TOC, TN, DFe, and HS estimated by the turbidity displayed similar values, whereas the flux of SS, TFe, and TP tended to increase downstream of the dams. Among the dams, estimated flux proportions for TP and TFe were higher during high-flow events (74%–94%). Considering geographic conditions (e.g., absence of major tributary between the dams), the result implies that accumulated TP and TFe in the reservoirs may be flushed and transported downstream with SS over the short height dams during flood events. Assuming this process, the reservoir dams probably make only a fractional contribution to the organic and inorganic transport in the catchment studied. The percent flux errors for SS, TFe, and TP fluxes ranged from −7.2% to −97% (except for the TP flux in 2013), which highlights the risk of underestimating these components when using an L–Q model.

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1. Introduction

Rivers fulfill an essential ecological role by forming a network system that transports the organic and inorganic materials from upland forests to coastal areas. In such systems, water carries fine-to-coarse sediments and dissolved and particulate compounds such as nitrogen, phosphorus, iron, and ionic components (e.g., Mg^{2+} and Ca^{2+}). Researchers have used various approaches to explore the mechanisms of the organic and inorganic cycles, including comprehensive monitoring (Lobbes et al., 2000; Holmes et al., 2012), isotopic analyses (Guo and Macdonald, 2006), and modeling approaches (Hofmann et al., 2011), and have determined that the terrigenous total dissolved organic matter in

the oceans constitutes just a small fraction of the total (0.7%–2.4%) (Opsahl and Benner, 1997). However, compared with the 1970s, terrigenous dissolved inorganic nutrient loading in the oceans has increased threefold in the 1990s (Smith et al., 2003). Most major river systems are fragmented by the reservoir dams constructed for flood control, irrigation, and hydropower generation. A consequence of the interception of sand and soil by reservoir dams is a worldwide decrease in the supply of sediment to coastal areas (Vörösmarty et al., 2003; Syvitski et al., 2005).

Friedl and Wüest (2002) reported that dams disrupt the global organic carbon cycle and nutrient balance. Humborg et al., (1997) reported that the installation of the Iron Gates on the Danube River reduced the downward export of dissolved silicon to the upper Black Sea, which promoted harmful algae blooms induced by non-diatoms. However, such interceptions may not involve all substances; for example, Teodoru and Wehrli (2005) reported that the Iron Gates Reservoir did not trap total nitrogen and total

phosphorus. Sediment buried in a reservoir and that formed through long-term gradual sedimentation contain a variety of materials such as organic carbon, nitrogen, and phosphorus (Bosch and Allan, 2008; Lopez et al., 2009; Kunz et al., 2011). Organic carbon (including dissolved organic carbon, which forms a complex with iron) is an important element for algal blooms, and previous research has shown that its concentration upstream of reservoir dams differs from that downstream, which reveals the role of reservoirs as important sinks in global carbon cycles (Dean and Gorham, 1998; Cole et al., 2007). An anticipated consequence of these phenomena is an alteration of nutrient supplies to areas downstream of these dams, as has been shown by thorough studies that reveal the subsequent deterioration of coastal ecosystems (see, e.g., Meybeck, 1982; Turner et al., 2003; Li and Bush, 2015). However, few studies have heretofore considered how interception by cascade dams affects the longitudinal material balances along a river.

The Mimi River catchment in southwest Japan is a sediment-productive catchment whose geological layer is mostly composed of the Shimanto supergroup, which is characterized by frequent slope failures. It hosts six reservoir dams along a steep main stem, some of which have experienced severe sedimentation over time (Sumi et al., 2015). In the southern temperate zone of Japan, coastal areas, including the study catchment, have suffered from a dramatic deterioration in the sea algal community and in seagrass meadows (Nagai et al., 2011), potentially because of the lower nutrient and iron supply to the sea than before that result from interception of these components by reservoir dams. In addition, inflows into reservoirs from storm-mediated flooding are also likely to change the water quality (Arfi, 2003; Leigh et al., 2015) and may even flush this material into downstream channels, although such a mechanism has not been thoroughly studied (Huang et al., 2014). Thus, further studies are required to better understand the balances involved in the temporal dynamics of the concentrations of organic and inorganic matter along a river fragmented by reservoir dams during both low- and high-flow events.

Estimating the temporal profile of suspended solids (SS) or nutrient loads is typically done by using the L–Q equation, which estimates pollutant loads by flow discharge at a location of interest. Although this approach is often applied on the basis of the data acquired under low- to-intermediate flow conditions (because of the relative ease in data acquisition), it is less used with data acquired under high-flow conditions. In low-to-intermediate flow conditions, hysteresis is difficult to adequately assess because, during a storm event, a temporal gap appears in the concentrations of specific chemicals in the rising and falling limbs of a hydrograph (Webb and Walling, 1985; Bowes et al., 2005; Bieroza and Heathwaite, 2015). House and Warwick (1998) pointed out that disregarding such a hysteresis may result in an underestimation of the sediment or nutrient flux during flooding. Recently, high-frequency turbidity data have often been used to estimate the SS load (see, e.g., Bieroza and Heathwaite, 2015; Lloyd et al., 2016). Researchers claim that such high frequency data should more accurately predict the temporal trends of chemical loads and concentrations during flood events than does the L–Q model, which is only based on observed discharge (House and Warwick, 1998; Nu-Fang et al., 2011; Bieroza and Heathwaite, 2015). The accurate determination of the temporal profile of pollutant loads based on the SS concentration estimated by turbidity data supports this claim (Harrington and Harrington, 2013; Lessels and Bishop, 2013).

We thus investigate the longitudinal profiles of various components of the water chemistry in the Mimi River during both low- and high-flow events to understand the contribution of the reservoir dams to organic and inorganic transport. We used *in situ* high-frequency gauging data of discharge and turbidity for

the outflow from three dams and estimated annual fluxes of water quality components. This approach allows us to assess the balance of materials among the reservoir dams. In addition, by combining the high-frequency gauging data and seasonally observed chemical data across multiple years, we examine the usefulness of L–Q models for estimating the fluxes of SS and nutrients.

2. Study area

We investigated the Mimi River, which originates in the Sampo Mountains and flows 94.8 km east to drain in the Pacific Ocean (Fig. 1). Most of the Mimi River catchment (884.1 km^2) is forested and mountainous and has a rugged topography, although partial flatlands are found along the main stem and tributaries in the lowland domain. The river has six reservoir dams for generating electricity along the main stem and one along a tributary. Most of these reservoirs have experienced sedimentation over time (Sumi et al., 2015), one of which may have triggered flooding in the town of Morotsuka as a result of the largest typhoon of 2002. Of these reservoir dams, we focus on the three most-downstream dams: the Yamasubaru Dam, Saigou Dam, and Ohuchibaru Dam (the reservoir capacities and heights are 1,598,000 m^3 and 29.4 m, 1,404,000 m^3 and 20.0 m, and 7,488,000 m^3 and 25.5 m, respectively). These dams have suffered from sedimentation, and the Yamasubaru and Saigou Dams are undergoing improvements to flush out the sediment in the reservoirs (Fig. 1). The studied river does not have any major tributaries and is characterized by a steep bed slope, particularly in the upper streams of the Saigou and Ohuchibaru Dams (1/200–1/300). The area studied has no effluent of point source pollution.

3. Material and methods

3.1. Sampling and measurement

We compiled hourly turbidity data from January 2012 to December 2014 by using automated turbidity meters installed at the Arayabashi Bridge, the Tateishibashi Bridge, and the Haebaruohashi Bridge, which are located downstream of the Yamasubaru Dam, the Saigo Dam, and the Ohuchibaru Dam, respectively (Fig.1). Over the same period, we acquired hourly monitoring data of rainfall and outflow discharge at the Yamasubaru Dam, the Saigou Dam, and the Ohuchibaru Dam. The partial data for turbidity, SS, and total phosphorus observed in streams under these three bridges and the hourly turbidity, rainfall, and outflow discharge data were provided by Kyushu Electric Power Company. Note that the hourly turbidity data are missing for the Yamasubaru Dam for 2013 and 2014.

Samples of stream water were taken at the Arayabashi Bridge, the Tateishibashi Bridge, and the Haebaruohashi Bridge during the low–intermediate-flow events (sample size (n) = 13) and high-flow events (n = 15) for subsequent chemical analyses. Here, we define a high-flow event as an outflow discharge greater than 150 m^3/s and a low–intermediate-flow event as any other flow event. The following parameters were measured for the material balance: SS, turbidity as compared with the kaolin standard (Mitsubishi Kagaku Co., SEP-PT-706D), total iron (TFe) and dissolved iron (DFe) (measured by using a spectrophotometer with the Ferrozine method; Shimadzu Co., UV-2450) (Stookey, 1970), total organic carbon (TOC) and total nitrogen (TN) (Shimadzu Co., TOC-V), total phosphorus (TP) (Hitachi Co., U-1800), humic substance (HS) (Shimadzu Co., RF5300PC), and major ionic components (Na$^+$, Mg^{2+}, Ca^{2+}, Cl$^-$, NO$_3^-$, and SO$_4^{2-}$, measured by ion chromatography, Dionex ISC-3000, Thermo Fisher Scientific). To determine the dissolved iron, humic substance, and ionic