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Spatial and temporal variations in nutrients in water and riverbed sediments at the mouths of rivers that enter Lake Hachiro, a shallow eutrophic lake in Japan

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ABSTRACT

We evaluated the spatial and temporal variations in dissolved inorganic nitrogen (DIN $= NO_3^- + NO_2^- + NH_4^+$) and soluble reactive phosphorus (SRP) concentrations and the processes that control them in water and riverbed sediments at the mouths of five main rivers (MTN, BBM, IKW, TYK, and BFM) that enter Lake Hachiro, a shallow eutrophic lake in Japan. At the river mouths, we sampled water monthly and analyzed the nutrient concentrations and dissolved N_2O and CH_4 concentrations. We also sampled riverbed sediments to determine the SRP release potential, inorganic P fractions, and denitrification potential (dNp). Riverine SRP concentrations showed large spatial and temporal variations, with values increasing from summer to autumn in the three southernmost rivers (IKW, TYK, and BFM). High dissolved CH_4 concentrations were observed in association with high SRP concentrations, indicating that SRP was released from the sediments under hypoxic conditions. In contrast, NO_3^- concentrations did not differ among the rivers and decreased during summer, likely owing to denitrification, thereby decreasing DIN/SRP ratios to a level suitable for the formation of summer algal or cyanobacterial blooms in the three southernmost rivers. Sediment incubation demonstrated high SRP release rates and high dNp values in the sediments of these rivers due to their higher iron (Fe)-bound P and organic matter contents. The riverine SRP concentration was significantly correlated with dissolved CH_4 and sediment dNp in positive, and DIN/SRP in negative. In conclusion, differences in Fe-bound P and sediment organic matter content suggested to cause spatial and temporal variations in water quality, with high SRP release and denitrification under hypoxic summer conditions, resulting in lower DIN/SRP ratios that may trigger algal or cyanobacterial blooms in this shallow eutrophic lake.

1. Introduction

Nitrogen (N) and phosphorus (P) are both required to support plant growth and are the key limiting nutrients in most aquatic and terrestrial ecosystems (Conley et al., 2009; Elser et al., 2007). Human activity has greatly altered N and P flows from river watersheds into aquatic ecosystems, thereby increasing primary production and causing widespread eutrophication (Howarth et al., 1996; Carpenter et al., 1998). Eutrophied lakes sustain damage from blooms of harmful organisms such as cyanobacteria, which can release toxins into the water (Paerl and Tucker, 1995).

Generally, sediments carried in flowing water play an important role in determining the effects of biogeochemical N and P cycles on the functioning of shallow lakes (e.g., Böstrom et al., 1988; Holmroos et al., 2012; Nizzoli et al., 2010; Søndergaard et al., 2003). Previous studies have focused on the release of P from the sediments under hypoxic conditions in shallow lakes and the dependence of this release on biological, chemical, and physical factors (Lukkari et al., 2008; Søndergaard et al., 2001). Iron (Fe)-bound P in these sediments is a primary factor that determines the release of P from sediments under hypoxic and anoxic conditions (Lukkari et al., 2008). Hypoxic and anoxic conditions also affect N cycles by affecting processes such as denitrification and dissimilatory nitrate reduction to ammonium (DNRA) in sediments and the water column (Burgin and Hamilton, 2007). These N and P dynamics will change the N/P ratio in the water, which will in turn affect interactions between algae or cyanobacteria and the nutrients they require for survival and growth (Correll, 1998; Hecky and Kilham, 1988; Niemistö et al., 2008). A suitable N/P ratio (Klausmeier et al., 2004; Smith, 1983) may create conditions suitable for the development of a harmful algal bloom in lake water. Thus, it is prudent to focus on both N and P dynamics unless there is clear evidence or a strong reason to believe that only one of these nutrients is important in a given ecosystem (Conley et al., 2009; Paerl et al., 2011). Unfortunately, the biogeochemical responses of N and P in shallow-water ecosystems and their relationships to eutrophication and hypoxia are less well understood than

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those in larger, deeper estuaries and coastal marine ecosystems (Howarth et al., 2011).

The nutrient and sediment loads transported into lakes by rivers depend on the availability of nutrients in the watershed and their potential for movement to the lake (Fraterrigo and Downing, 2008). Because the nutrients and sediments transported from watersheds depend strongly on rate of loading and of sediment erosion into rivers (Lukkari et al., 2008; Pacini and Gächter, 1999) and on watershed characteristics such as hydrology, geology, soils, topography, and land use (Iglesias et al., 2011; Jiang et al., 2010, 2012; Woli et al., 2004), they are expected to vary in space and in time in a lake. Jin et al. (2006) reported spatial variation in different P fractions in sediments and a relationship between these variations and the trophic status of different parts of Taihu Lake. The sedimentation rate, organic matter content, and amount of sediment-sorbed P transported by erosion were important determinants of the behavior of P in sediments (Lukkari et al., 2008). Despite extensive research on the P dynamics in sediments, the biogeochemical processes that affect N and P in the sediments and water where rivers enter a lake are not yet well understood. To support efforts to improve lake water quality, managers must have access to detailed information about the quality of transported sediment and its spatial and temporal variations before they can predict the impact on a lake's water quality and take measures to mitigate problems, particularly for shallow eutrophic lakes.

Lake Hachiro in Japan's Akita Prefecture is an example of such a shallow eutrophic lake. Currently, cyanobacterial blooms occur every summer (Kondo, 2010; Okano et al., 2015), and managers consider it urgently necessary to improve the lake's water quality (Kondo, 2010; Sasaki, 2010). Twenty significant rivers enter the lake, and differences in the nutrients and sediments transported from each river's watershed will influence the water quality where these rivers enter the lake. Unfortunately, there is little or no information on these factors. To provide this information, we designed a study of the biogeochemical processes that affect N and P transport in riverbed sediments and their delivery into the lake at river mouths, which represent the interface between river watershed and the lake. We hypothesized that these processes, that is, P release from and denitrification in riverbed sediments would control the spatial and temporal variations in water quality among the rivers that enter Lake Hachiro. To test this hypothesis, we selected the five main rivers that enter the lake and evaluated the spatial and temporal variations in dissolved inorganic nitrogen (DIN) and soluble reactive phosphorus (SRP) concentrations and the processes that control them in water and riverbed sediments.

2. Materials and methods

2.1. Site description

Lake Hachiro and its watershed are located in western Akita Prefecture, facing the Sea of Japan (Fig. 1). The entire watershed covers 894 km^2. Lake Hachiro had a surface area of 220 km^2 and was the second largest lake in Japan before the implementation of the Hachirogata National Land Reclamation Project, which was designed to improve self-sufficiency in food production (Ogata-mura Village Office, 2014; Sasaki, 2010). The project started in 1957 and finished in 1977 (Sasaki, 2010). As part of the project, Japan's largest polder, Ogata-mura Village, was constructed, leading to reclamation of nearly 80% of the lake's area and transforming the remaining lake water from brackish to fresh by controlling the lake water table by the floodgate (Fig. 1). Currently, Lake Hachiro is a shallow eutrophic lake, with a mean depth of 2.8 m,

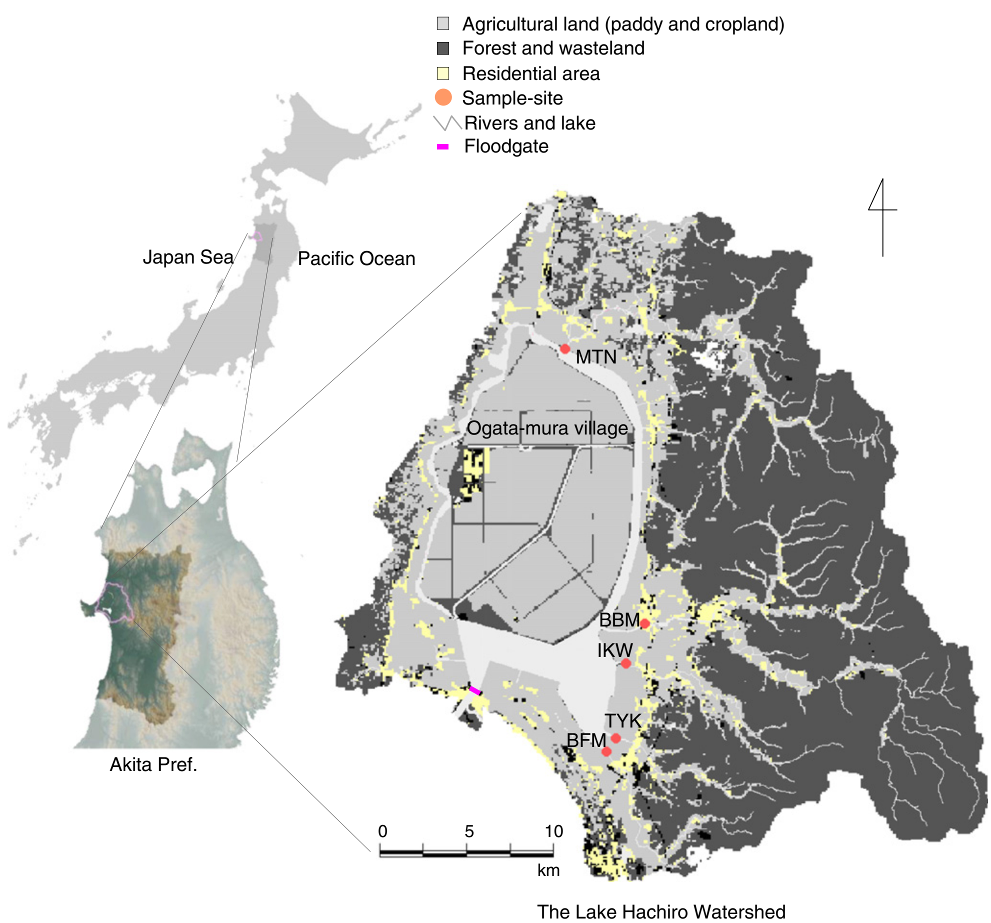

Fig. 1. Location of the Lake Hachiro watershed, in Japan's Akita Prefecture, and the land-use distribution and locations of the sampling sites in the five main rivers that enter the lake.