Reconstruction of 100-years variation in phosphorus load using the sediment profile of an artificial lake in western Japan

GUANGZHE JIN[1], SHIN-ICHI ONODERA[1], ATSUKO AMANO[2], YUTA SHIMIZU[1] &TAKAHARU SATO[1]

1 *Graduate School of Integrated Arts and Science, Hiroshima University, 1-7-1, Kagamiyama , Higashi-Hiroshima , Hiroshima 7398521, Japan*
jinguangzhe@live.cn

2 *Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, 1-1-1 Higashi, Tsukuba 305-8567, Japan*

Abstract In this research, the phosphorus (P) discharge was reconstructed for the last 100 years. We used the ^{210}Pb and ^{137}Cs activities to date a core sample. The total phosphorus (TP) and the total inorganic phosphorus (TIP) in the sediment showed a slightly decreasing trend with depth and a peak of P content at the depth with an age of around 1970s. This suggests eutrophication in Kojima Lake, Japan, during the last century and a peak of nutrient load around the 1970s. In addition, TP and TIP contents in the sediment indicated yearly variations. These variations are not affected by annual precipitation, local population and paddy field area; in contrast, they are related to the annual number of rainstorms with daily rainfall over 100 mm. This suggests that most of the TP load is transported in stormflows during extreme rainstorms. An increase in the number of torrential rainstorms is assumed to increase the P that is transported to the ocean.

Key words sediment; phosphorus; precipitation; extreme events; rainstorms; Japan

INTRODUCTION

Climate change has recently become one of the most significant environmental issues. Significant increases in extreme droughts, flood periods, and air temperature are predicted, all of which may result in nutrient load increases in river catchments. Consequently, eutrophication is likely to occur in coastal embayments and inland lakes (Lioret *et al*., 2008). However, the lack of observation data does not permit the confirmation of such predictions. To verify the effect of climate change on phosphorus (P) load, it is necessary to reconstruct the long-term variation in P load, using sediment core information.

Coastal sediment is an important sink for terrestrial derived nutrients. Sediment cores extracted from these environments can provide a vertical P distribution, which correlates with historical patterns of P sedimentation (Hupfer *et al*., 1995). Coastal lake sediment therefore provides information on P that can be used to reconstruct the palaeoecological and pollution history of the lakes and their catchment basins. In addition, lake sediments may record climatic changes.

This research aims, using a sediment core, to reconstruct the history of the P load that is related to climatic change, to confirm the variations of P in the core, and to establish the effect of climate change on the nutrient load variation.

STUDY AREA

The research area is located in the Okayama prefecture in Western Japan. Kojima Lake is an artificial shallow lake (Fig. 1). It was formed in 1959 by the construction of a dyke that separates it from Kojima Bay to preserve inflowing freshwater for irrigation and to prevent saltwater damage to agriculture. The average retention time of water in the lake is 12 days and the area of the lake is 10.8 km^2, with a mean depth of 1.8 m. There are two inflowing rivers, the Sasagase River (23.8 km length) and the Kurashiki River (13.6 km length); these rivers provide 60% and 30% of the total water inflow to the lake, respectively. The Sasagase River and the Kurashiki River flow through the cities of Okayama and Kurashiki. Paddy fields and residential areas comprise 80% of the Kurashiki River basin. Kojima Lake is eutrophic, and has been since immediately after the construction of the lake, and had a notable freshwater red tide bloom start from 1994.

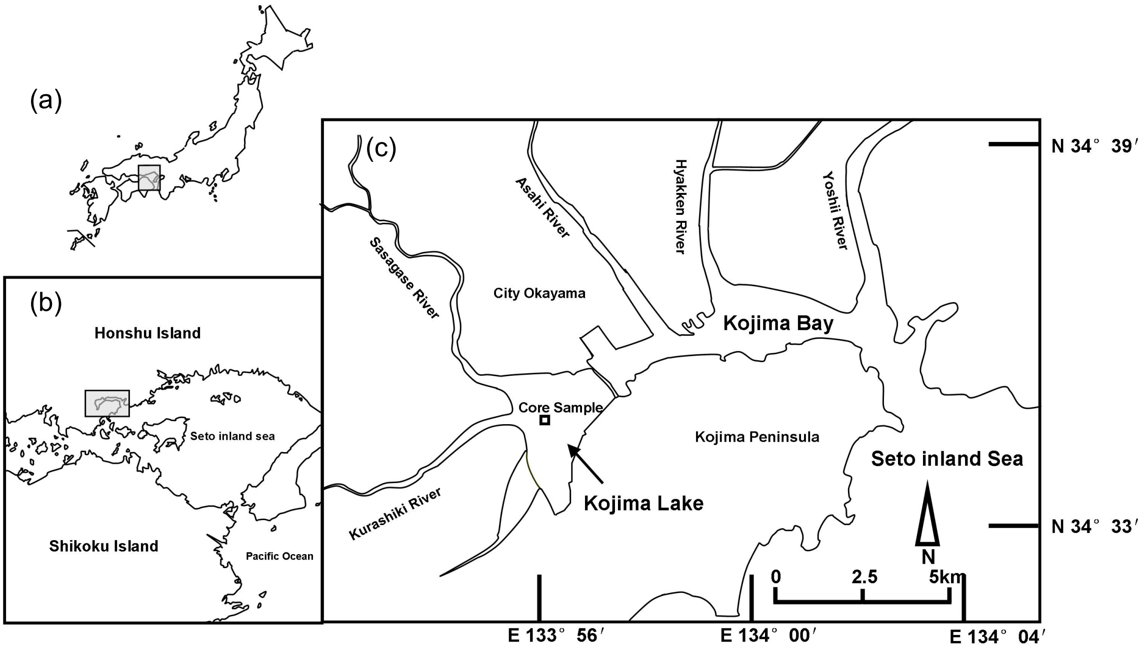

Fig. 1 The research area and location of the core sampling sites in Kojima Lake.

METHOD

Sediment core sampling

One 124-cm long core sample was taken with a piston core sampler during September 2009 (Fig. 1). Subsequently, 1-cm long sediment samples were collected from the core after sampling, and frozen for later analysis.

Analytical methods

The P content in the sediment was determined using the methods of Aspila *et al.* (1976). The sediment samples were dried at 50°C in the laboratory. The dry samples were homogenized and sieved with a standard 100-mesh sieve. The total inorganic phosphorus (TIP) was measured in a 1M HCl extraction of each sediment sample (18 h of shaking at room temperature). Total phosphorus (TP) was measured in a 1M HCl extraction of the sample after ignition (18 h of shaking after 550°C ignition for 2.5 h). Organic P (OP) was calculated as the difference between TP and TIP (Aspila *et al.*, 1976). Before the analysis, all extracted samples were filtered with 0.2 μm cellulose ester membrane filters. The sediment pore water was extracted by centrifugation for 30 min at 3500 rpm.

The phosphate in each of the sample treatments was measured by spectrophotometry (Swaat autoanalyser, Bltec), and the P content of the pore water samples was measured by ICP-AES. The concentrations of P are given in μg/g dry sediment weight. ^{137}CS and ^{210}Pb activities were measured by gamma-ray spectrometry. for sediment dating. The Okayama city precipitation data were obtained from the Automated Meteorological Data Acquisition System (AMeDAS), which is published in the Japan Meteorological Agency website (http://www.data.jma.go.jp/obd/stats/etrn/index.php). The paddy field area was calculated using ArcGIS software and aerial photography of six points during 1949–2006. The photography was obtained from national digital land information (land use map data), which was made by Ministry of Land, Infrastructure, Transport and Tourism Japan. The population data was obtained from the Japan population census (http://www.e-stat.go.jp/SG1/estat/GL02100104.do?tocd=00200521).

RESULTS AND DISSCUSSION

Dating data

Geochronology with ^{210}Pb is based on the radioactive decay of ^{210}Pb with depth in a column of sediment core. We used the sedimentation rate to establish the dates at different depths. We used the constant initial concentration model (Carroll *et al.*, 1999) to calculate an average sedimentation rate of 0.67 cm^{-1} year^{-1}. The ^{137}Cs peak values indicate that 1963 corresponds to a sediment depth of 32 cm from which the sedimentation rate was determined (Fig. 2). Subsequent dates were determined from the sedimentation rate, i.e. from the ^{137}Cs peak depth and the P content data in the sediment core was used to reconstruct the P variations during the last 100 years (Fig. 3)

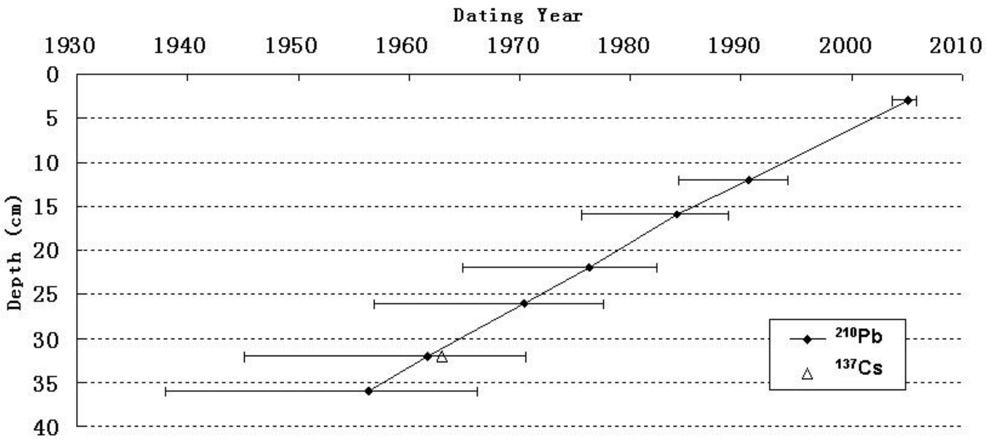

Fig. 2 Age curve by ^{210}Pb dating for core samples.

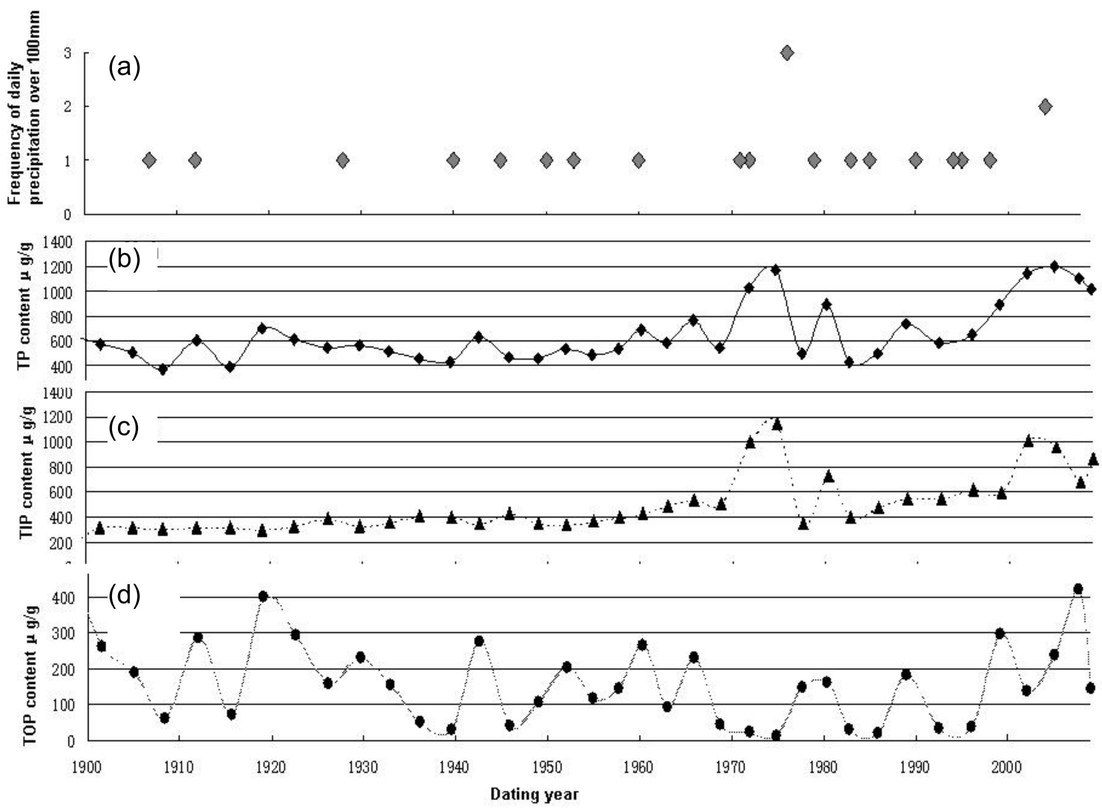

Fig. 3 The total sediment P content in core samples: (a) frequency of daily precipitation over 100 mm, (b) TP content in sediment, (c) TIP content, and (d) TOP content.

Kojima Lake is a freshwater lake, except near the bay gate of the dyke where there is exchange between freshwater and seawater. The pore water salinity increases with depth in the core from 0.30‰ at the surface (2009) to 16‰ at the 1900-year depth. ^{137}Cs can be mobilized if fresh water sediments are transferred to the marine environment (Oughton *et al.*, 1997). However, in Kojima Lake, the ^{137}Cs geochronology matches the ^{210}Pb chronology well suggesting little post-depositional mobilization. Therefore, the geochronology was used to evaluate the variations of the TP content with time.

Vertical distribution of P in the sediment core

Figure 3 shows the long-term variation in total phosphorus (TP), total organic phosphorus (TOP) and total inorganic phosphorus (TIP) in the sediment. The TP in the surface sediment was the highest concentration (1.2×10^3 μg/g) in the core and much higher when compared with the background values in Seto Inland Sea (Osaka Bay $0.23–0.61 \times 10^3$ μg/g and Hiroshima Bay $0.49–0.58 \times 10^3$ μg/g) (Fukue *et al.*, 2006). Kojima Lake has a very high P content in the lake sediment. The high P content of the sediments in the eutrophic Kojima Lake is assumed to result from the high P content of the sediment in the inflows. The TP and TIP in the sediment core samples increase toward the top of the core. The TP content fluctuates in a range $0.37–1.2 \times 10^3$ μg/g and gradually increases from the bottom to the surface layer with some variations. The pattern is comparable to that of TIP. The TOP content at the surface layer of the sediment core, however, is lower than just below it, but there is a large variation in TOP content throughout the core, i.e. with no pronounced temporal trend. TOP in the sediment probably derives from leachable and refractory sources (Zheng *et al.*, 2004). The TOP variability in the core may derive from the spatial and vertical variations in the decomposition of the organic matter. Also, there is considerable uncertainty in the OP content because TOP is calculated by the difference between TP and TIP.

The 100 years reconstruction of P

The TP content has been increasing slightly during the last 100 years, whereas the TP shows more variability. Some peak values of TP are also recorded in the core. The P content peaks at 1.2×10^3, 1.1×10^3 and 0.89×10^3 μg/g corresponding to the years 2005, 1975, and 1980, respectively. The peak TP content in the sediment was also reflected in the TIP content. The TP variations before 1965 seem to correlate with changes in OP. During this time, the peaks may indicate a high P load because Kojima Lake was heavily eutrophic in the 1970s. Therefore, after 1970, the high P loads may result from the high P discharge and the intense eutrophication at that time. As in the Sasagase and Kurashiki basins, there is a significant amount of farmland and residential areas. In addition, the construction of the dyke enhances the nutrient retention in the lake sediment. Therefore, the impact of the intensive human activity and the diversity of the heavy nutrient discharge from the rivers lead to abrupt changes of TOP and TIP in the sediment. There is no apparent correlation between the sediment TP and population density from 1920 to 2000, and the sediment TP and the rice field area from 1949 to 2006. The P load in the sediment core does not reflect the data on population and rice field area change. This may result from insufficient data to derive proper statistics, i.e. the rice field sample is small (n = 6, from 1949 to 2006) and the population increase during the last 80 years. However, these cannot reflect the variations of the sediment TP. The Japanese Government banned the use of P in detergents in the 1979 and this may be the reason behind the change in TP in the mid-1980s. In the surface layer of the sediment, there is an increasing trend from around 2000 to the surface layer of sediment. This may partly be because the P content is affected by the ferric P or aluminium P, which should exist as an oxide. It will be affected by oxidation–reduction, which often changes with depth and time (Zheng *et al.*, 2004). The newly deposited P resources, both inorganic and organic, may not have enough time to decompose and transfer to other sediment P forms, which may release and exchange with the overlying water; this may be the reason for abundant P content in the surface layer of the sediment core.

Sediment P content and the effect of climate change

The relationship between the sediment P content and precipitation from 1990 to 2000 was evaluated. The TP content variations are correlated with annual precipitation, but a linear regression of TP on annual precipitation does not explain very much of the variance in TP. Subsequently, the precipitation data were separated into normal precipitation years and high precipitation years (>100 mm/d). Although the variance in the TP content explained by the relationships is relatively low, TP content is more highly correlated with the high precipitation years than the normal precipitation years. Also, the TIP content is not correlated with precipitation. As a result, the precipitation does not influence the P load. Figure 3(a) shows the frequency of daily precipitation of over 100 mm. From it we found some trends that the frequency of daily rainstorms having rainfall more than 100 mm was greater in the recent 50 years than 60 years before that. Compared with the 100 years reconstruction of P, high P load is partly related to the annual number of rainstorms with a daily precipitation over 100 mm. In 1976, there were three daily rainstorms having rainfall of more than 100 mm and it may be that these high rainfalls and related sediment transport led to a high TP content in the sediment core (1.2×10^3 μg g^{-1}). Two large rainstorms in 2005 also led to a high TP content (1.1×10^3 μg g^{-1}). The two large rainstorms in 1971 and 1972 are related to a TP content of 1.0×10^3 μg g^{-1} (Fig. 3(a) and (b)). Intense extreme rainstorms seem to explain most of the high TP contents (>1.0×10^3 μg g^{-1}). The same trend is present in the sediment TIP, which constitutes most of the TP content (Fig. 3(a) and (c)). These results indicate that high rainfall affects the sediment history, especially those years with extreme rainstorms. The P in the sediment is related to the annual number of rainstorms with daily rainfall over 100 mm. This may happen because the regional high rainfall carries more dissolved P from farmland into the lake and also the rainstorms are likely have a direct effect on erosion, transporting more suspended sediment and stormwater runoff (Liu *et al*., 2006; Javier *et al*., 2008).

Climate changes due to global warming may alter rainfall patterns and increase the occurrence of extreme events (floods and droughts), i.e. a change in the frequency and intensity of rainstorms (Nicholls & Hoozemans, 1996). Climate change affects have been reported for daily precipitation in Japan, including typhoons (Yurij, 2007). Accordingly, it may be further enhanced over Japan due to the increase in the atmospheric moisture availability (Yurij, 2007). If precipitation changes are toward more intensive and more severe rainstorms, this may lead to high soil erosion and high P loads in rivers. This process may decrease the retention of P in the soil. The P in the sediment may also increase due to increased frequency and intensity of extreme rainstorms. It may be a potential pool of P which can be released to the environment because the sediment TP is dominated by inorganic P. Consequently, climate change may enhance the P load discharged to the ocean.

CONCLUSION

In this research, the phosphorus (P) in Kojima Lake sediment was reconstructed for a period of 100 years, and the relationship between P load and climate represented by annual precipitation was evaluated.

1 Total phosphorus (TP) and total inorganic phosphorus (TIP) content in the sediment varies markedly. This variation does not appear to be affected by variations in annual precipitation, population, and land use (rice field area). From a multiple regression, annual precipitation has a higher correlation with sediment TP than variations in population or rice field area. Furthermore, rainstorms with a daily rainfall over 100 mm was the most highly significant predictor of TP. High precipitation and normal precipitation years vary significantly and the extreme rainstorms are also related to TP content peaks. This suggests that most of the TP load is transported during extreme rainstorms. If future torrential rainfall increases in magnitude and frequency, this will likely increase the P load transported to the ocean.

2 The sediment TP and TIP concentrations decrease slightly decreasing with depth in the core, i.e. date, and the P content peaks at a depth corresponding to the 1970s. Kojima Lake is eutrophic and has been since it was built in 1959, but eutrophication was extreme during the 1970s. Yearly variations before 1965 in the TP content may be related to changes in the organic P.

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