Laguna (2017) 24: 19-25 ISSN 2185-2995

短　報

Salinity fluctuation factor in the brackish Lake Shinji

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Abstract: The aim of this work is the identification of the main factor affecting the monthly salinity variation in Lake Shinji, Japan. A strong correlation was observed between the mean daily flow rate of the Hii River, measured over 80 days at Kamishima, and the chlorinity in the central part of the lake. The fluctuation of chlorinity in Lake Shinji could be reproduced based on the flow rate at Kamishima. This result demonstrates that the salinity fluctuation of Lake Shinji significantly depends on the flow rate of the Hii River.

Key words: Chlorinity, Estuary, Flow rate, Hii River, Lake Shinji, Lake Nakaumi, Ohashi River

Introduction

Lake Shinji is a lagoon between the Shimane Peninsula and the Japanese mainland. It is a brackish lake, characterized by a salinity range from oligohaline to, rarely, mesohaline. The lake is located downstream of the Hii River, a Class A river flowing from Mount Sentsu, on the border with the Hiroshima Prefecture. The main stream of the Hii River flows into the western side of Lake Shinji and supplies about 80% of the total freshwater inflow. Lake Nakaumi (polyhaline) is situated to the east of Lake Shinji and the two lakes are connected by the Ohashi River. Both lakes are managed as part of the Class A Hii River system.

The Ohashi River is characterized by reciprocating currents that correspond to the tidal variations of the Sea of Japan. This implies that when the water level at the eastern end of the river (downstream) is higher than that at the western end (upstream), saline water flows upstream from Lake Nakaumi to Lake Shinji. These intrusions of saline water through the Ohashi River have been reported in several studies (Fukuoka et al. 2004, 2005; Ishitobi et al. 1989, 1999; Mizoyama et al. 2011). The intruded saline water forms a saline bottom stratum that plays an important role in the cycling of matter within the lake. This saline bottom stratum is found to be closely related to the return of inorganic nutrients (Kamiya et al. 1996, 2001; Sugai et al. 1986, 2012, 2015).

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受付日：2016 年 9 月 1 日，受理日：2017 年 7 月 18 日

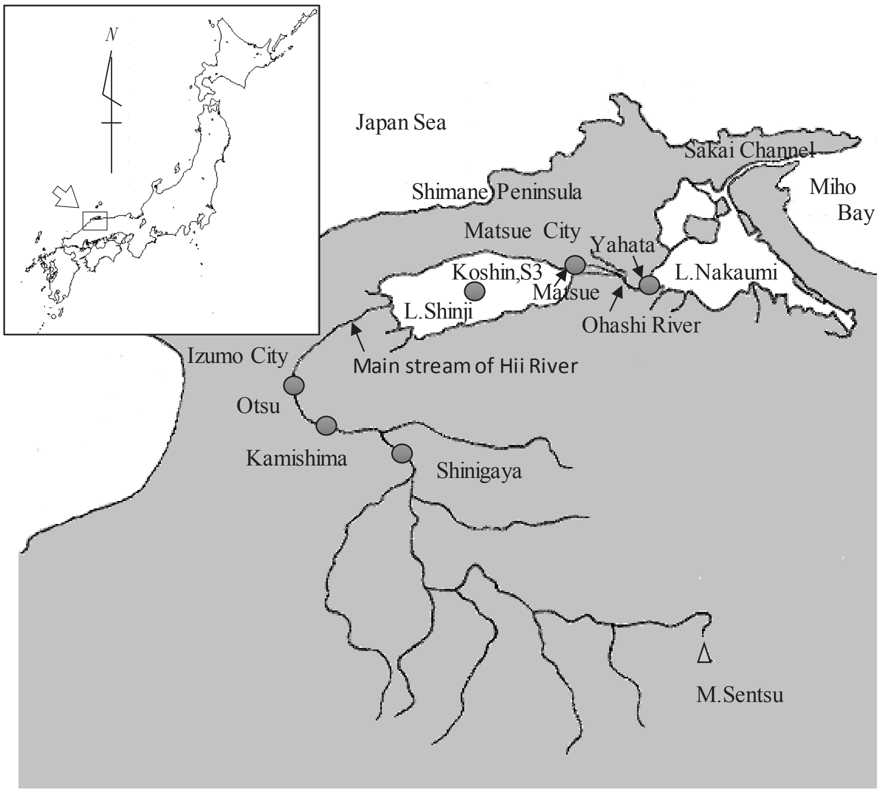

Fig. 1 Study area.

In brackish lakes such as Lake Shinji and Lake Nakaumi, salinity is the key element controlling not only the advection between the two bodies of water but also the occurrence of phytoplankton blooms such as the "Aoko". It follows that the identification of the factors affecting the salinity variation in the lake is essential for understanding the chemical composition of its water. Somura et al. (2009) and Sugai (1988) suggested the existence of close relationships between the flow rate in the Hii River measured at Otsu and the chlorinity in Lake Shinji.

This research was conducted to identify the main factor affecting the monthly salinity variation in Lake Shinji, using recent hydrological balance and water quality data. In this research, we used flow rate data at three different locations along the Hii River and the data for chlorinity from the upper layer at the center of Lake Shinji. Data from 2004 to 2013 were considered in the analysis.

Methods

Study area

As shown in Fig. 1, the water areas analyzed for this study were those of Lake Shinji, the Ohashi River, and Lake Nakaumi, from the main stream of the Hii River to Miho Bay. The Hii River water system is a Class A river with a catchment area of 2,070 km^2 and a watercourse of 153 km from Mount Sentsu to Miho Bay. The main stream of the Hii River flows into the western side of Lake Shinji.

Chlorinity and water level

Chlorinity was used in place of salinity. The chlorinity (Cl^- concentration) data based on an automatic monitoring system at the center of Lake Shinji (hereafter Koshin Observatory), and at the outlet of the lake (hereafter Matsue Observatory) were retrieved from a website maintained by the Izumo Office of River, Chugoku Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism (MLIT) (http://www1.river.go.jp/cgi-bin/SelectMapSite.exe). In

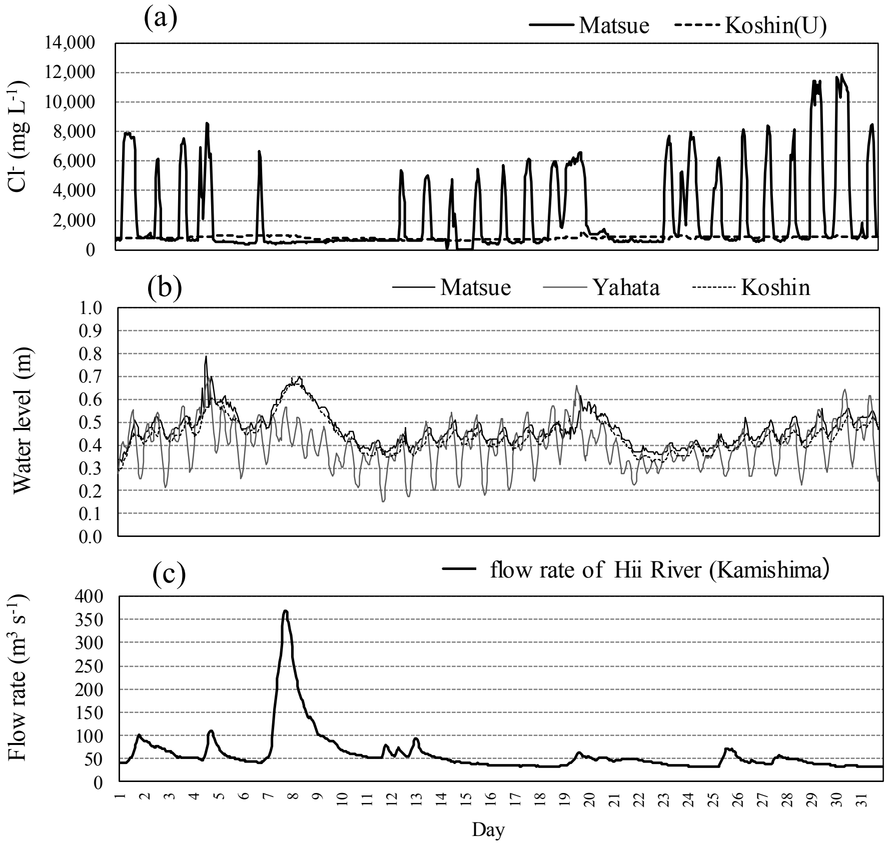

Fig. 2 Changes in (a) Cl^- concentrations at Matsue Observatory and Koshin Observatory, (b) the water levels at Koshin Observatory, Matsue Observatory and Yahata Observatory, and (c) the flow rate of the Hii River (Kamishima Observatory) in July 2011.

addition, the chlorinity data in the upper layer (1m from the water surface) at point S3 (sampling point in the monthly water quality survey located at the center of Lake Shinji; hereafter St.S3) were also used.

Data for the water levels at the Koshin Observatory, at the Matsue Observatory, and at the outlet of the Ohashi River (hereafter Yahata Observatory) were also retrieved from the website.

Hii River flow rate

The primary factor affecting chlorinity variation in Lake Shinji is inferred to be the flow rate of the Hii River. In this study, we analyzed the relationship between the flow rate at the Otsu observatory and the chlorinity in the upper layer at St.S3, located near the Koshin Observatory, using recent data (2004 – 2013). In addition, the relationship between the flow rates at the Shinigaya observatory and the Kamishima observatory, located upstream of the Otsu observatory, and the chlorinity at St.S3 was also examined. We calculated the average flow rate for 70, 80 and 90 days before the day of the monthly water quality survey in Lake Shinji. Then we investigated the relationship between each average flow rate and the measured chlorinity. These data were retrieved from the website.

Results and Discussion

Salinity fluctuation factor

We focused on the differences in salinity variations between July 2011 and July 2013 at two different locations (Koshin Observatory and Matsue Observatory). In the upper layer at the Koshin Observatory, a low level of chlorinity of about 1,000 mg L^{-1} was observed in July 2011 (Fig. 2a), while a high level of chlorinity of around 4,000 mg L^{-1} was observed in July 2013 (Fig.

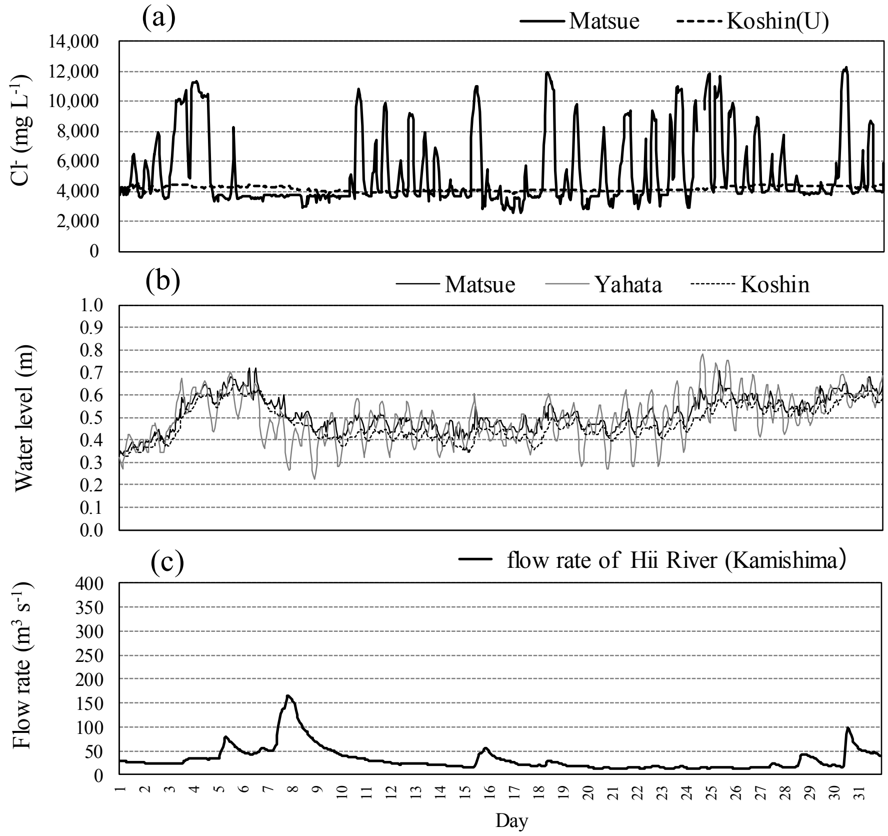

Fig. 3 Changes in (a) Cl^{-} concentration at Matsue Observatory and Koshin Observatory, (b) the water levels at Koshin Observatory, Matsue Observatory and Yahata Observatory, and (c) the flow rate of the Hii River (Kamishima Observatory) in July 2013.

3a). In contrast, at the Matsue Observatory, chlorinity varied widely; from 1,000 to 12,000 mg L^{-1} (Fig. 2a) in July 2011 and from 3,000 to 12,000 mg L^{-1} (Fig. 3a) in July 2013. As shown in Fig. 2, when the flow rate of the Hii River at Kamishima Observatory increased rapidly because of a flooding (July 7 to 8, 2011, see Fig. 2c), the water level at the Matsue Observatory, in the upstream portion of the Ohashi River, also rose rapidly (Fig. 2b), along with the water level of Lake Shinji at the Koshin Observatory. In this case, because the Ohashi River had a relatively strong downstream current, the upstream flow was suppressed. The corresponding chlorinity variation at Matsue Observatory shows that saline water had not indeed reached the observatory during July 8 to 12, 2011 as a result of the flooding (Fig. 2a). When the water levels at the Koshin Observatory and the Matsue Observatory went back to normal, the Ohashi River regained its reciprocating current regime, and the chlorinity at the Matsue Observatory peaked with the upstream flow of saline water. It is suggested that a regular supply of saline water is provided to Lake Shinji by this upstream flow of saline water from the Ohashi River, occurring when the water levels at Lake Nakaumi, in combination with the tidal variations in the Sea of Japan (Miho Bay), exceed those at Lake Shinji.

As shown in the results for July 2011 (Fig. 2), during periods characterized by high inflow of freshwater and low salinity, the water level at the Yahata Observatory was rarely higher than the water level at the Matsue Observatory (148/744 hours). These periods was also characterized by a relatively low chlorinity in the upstream flow. Results for July 2013 (Fig. 3) indicated that during periods characterized by low inflow of freshwater and high salinity, the water level at the Yahata Observatory was often higher than the water level at the Matsue Observatory (306/744 hours) and in these period

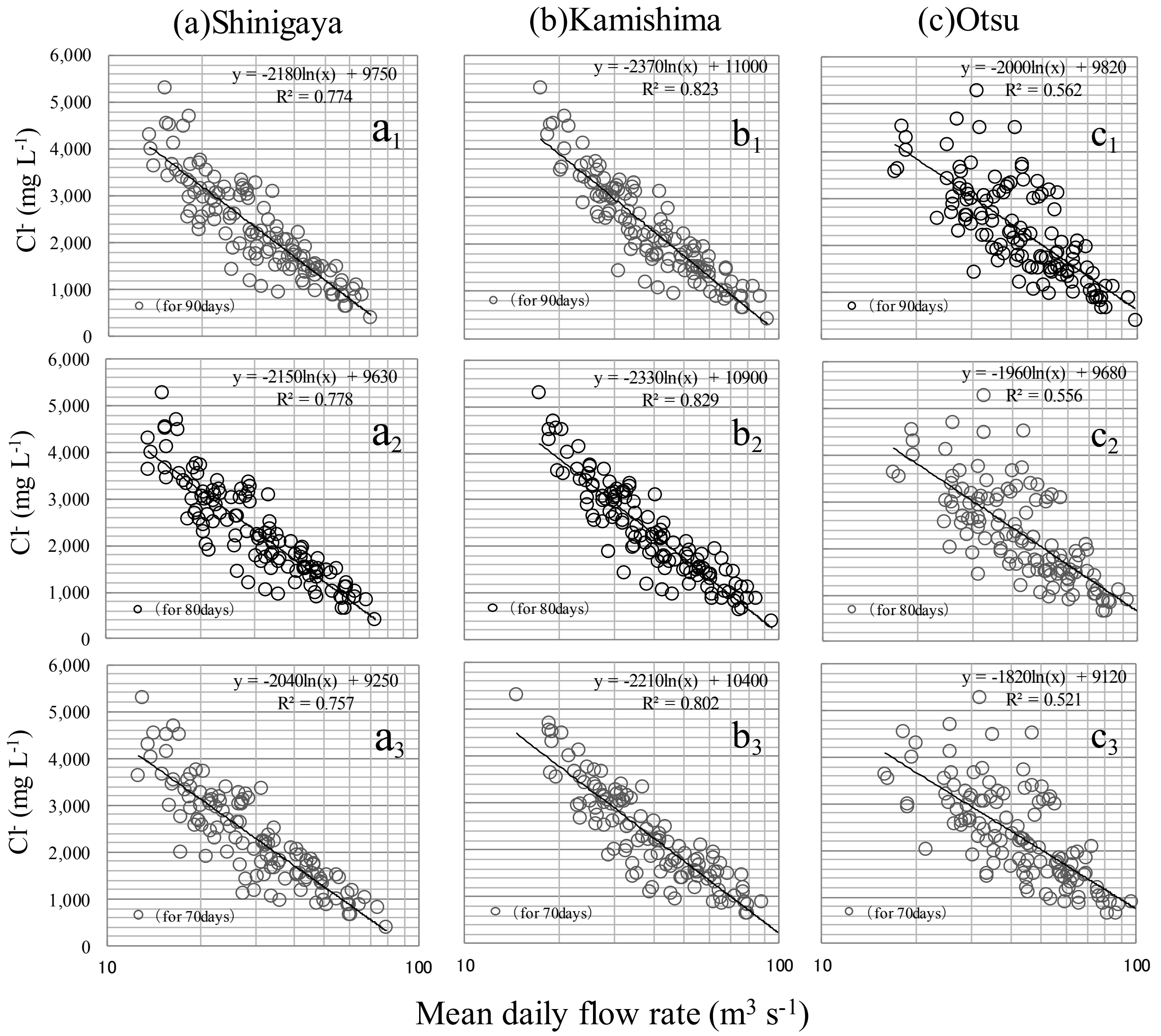

Fig. 4 Relationship between Cl^- concentration (2004~2013) at St.S3 (sampling point of the monthly water quality survey) and the mean daily flow rate in the Hii River at (a) Shinigaya Observatory, (b) Kamishima Observatory and (c) Otsu Observatory for 70, 80, and 90 days before the day of monthly water quality survey (2004~2013) in Lake Shinji.

chlorinity in the upstream flow was relatively high.

We thus hypothesized that the chlorinity in Lake Shinji essentially depends on the flow rate of the Hii River, which indirectly determines the volume of saline water flowing upstream from the Ohashi River. In recent (2004–2013) observational data, as shown in Fig. 4a, close relationships were found between each of the mean daily flow rates for 70, 80 and 90 days at the Shinigaya Observatory in the Hii River and the chlorinity at St.S3 in Lake Shinji. The strongest correlation (coefficient of determination: R^2 = 0.829) was found for an 80-day mean daily flow rate at Kamishima Observatory (Fig. 4b2). In contrast, the correlation was weak for the Otsu Observatory (Fig. 4c, R^2 = 0.521-0.562) compared to the former cases. These results suggest that if interested in salinity variations, the flow rate data at the Otsu Observatory is less reliable compared to those at the Kamishima Observatory and the Shinigaya Observatory. Somura et al. (2009), investigating the impact of climate change on the Hii River basin and salinity in Lake Shinji, have examined the relationship between the monthly averaged flow at Otsu Observatory and the monthly averaged salinity (calculated from chlorinity) in bottom water at the center in Lake Shinji measured by the MLIT.

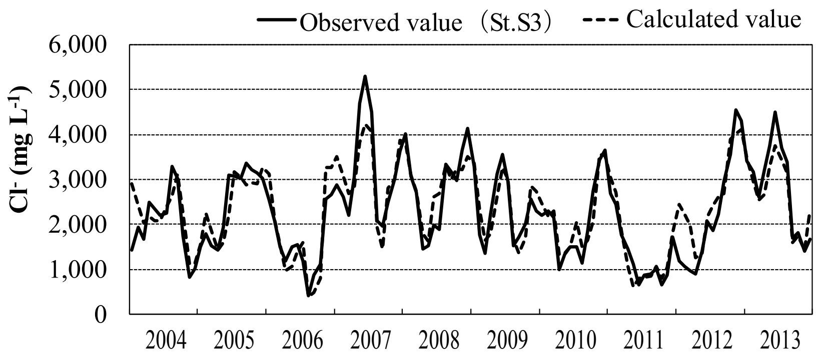

Fig. 5 Comparison of the measured Cl^- concentration at St. S3 (sampling point of the monthly water quality survey) and the Cl^- concentration calculated using the Cl–Q equation (Fig.4 b2).

They used chlorinity data from the monthly survey and river flow data of the previous month. Their result (R^2 =0.532) is close to our result (R^2 = 0.521-0.562) at the Otsu Observatory, which, however, is less significant if compared to the results obtained with data from the Shinigaya Observatory (R^2 = 0.757-0.778) and from the Kamishima Observatory (R^2 = 0.802-0.829).

The chlorinity at St.S3 in Lake Shinji was then calculated from the obtained Cl–Q formula (Fig. 4b2). From the results, we confirmed that the estimated variations correspond to the measured values, and that the reproducibility is high. Fig. 5 shows the measured chlorinity at St. S3 from 2004 to 2013 and the changes in chlorinity with flow rate calculated from the Cl–Q formula (Fig. 4b2) obtained in this research. As shown in Fig. 5, the chlorinity variations could be successfully reproduced using the flow rate. We thus conclude that the variations in chlorinity in Lake Shinji depend on the flow rate of the Hii River as the primary factor.

After the completion of the Ohashi River Improvement Project, agreed upon by the governors of Tottori and Shimane Prefectures in 2009, we plan to verify whether a significant difference exists between the slope of the Cl–Q formula obtained in this research and the slope of the formula that will be obtained in an analogous study using updated data sets.

References

Fukuoka, S., Matsushita, T., Okamura, S., Imai, S. and Funabashi, S. (2004) Behavior and characteristics of saline water advancing into a brackish lake. Annu. J. of Hydr Eng, JSCE, 48:1405-1410. (in Japanese with English abstract)

Fukuoka, S., Yamamoto, A., Okamura, S. and Mizoyama, I. (2005) Estimation of salinity flux and variation of salinity in Lake Shinji. Annu. J. of Hydr. Eng., JSCE, 49:1249-1254. (in Japanese with English abstract)

Ishitobi, Y., Kamiya, H., Hayashi, K. and Gomyoda, M. (1989) The tidal exchange in Lake Shinji under low discharge conditions. Jpn J Limnol 50:105-113.

Ishitobi, Y., Kamiya, H., Yokoyama, K., Kumagai, M. and Okuda, S. (1999) Physical conditions of saline water intrusion into a coastal lagoon, Lake Shinji, Japan. Jpn J Limnol 60:439-452.

Kamiya, H., Ishitobi, Y., Inoue, T., Nakamura, Y. and Yamamuro, M. (1996) Origin of nutrients accumulated in the bottom water of Lake Shinji in summer. Jpn J Limnol 57:313-326. (in Japanese with English abstract)

Kamiya, H., Ishitobi, Y., Inoue, T., Nakamura, Y. and Yamamuro, M. (2001) Effluxes of dissolved organic phosphorus (DOP) and phosphate from the sediment to the overlying water at high temperature and low dissolved oxygen concentration conditions in a eutrophic brackish lake. Jpn J Limnol 62:11-21. (in Japanese with English abstract)

Mizoyama, I., Ohya, Y. and Fukuoka, S. (2011) Flow mechanism in a connected brackish lake and numerical flow computation over a long period. Journal of JSCE, Ser. B1 (Hydraulic Engineering), 67:101-120. (in Japanese with English abstract)

Somura, H., Arnold, J., Hoffman, D., Takeda, I., Mori, Y. and Di Luzio, M. (2009) Impact of climate change on the Hii River basin and salinity in Lake Shinji: a case study using the SWAT model and a regression curve. Hydrol. Process 23:1887-1900.

Sugai, R., Mutaguchi, S. and Matsumoto, M. (1986) Studies on formations and changes of Micro-stratification in brackish water Lake Shinji. Jpn J Limnol 47:315-324. (in Japanese with English abstract)

Sugai, R. (1988) On the occurrence of cyanobacteria Bloom(Aoko) in the brackish Lake Shinji. Mizu 414:61-65. (in Japanese)

Sugai, R., Nisio, M., Mizoyama, I. and Seike, Y. (2012) Fluxes of inorganic nutrients from bottom sediments in the brackish Lake Shinji. Jpn J Limnol 73:179-186. (in Japanese with English abstract)

Sugai, R., Itou, K., Nishio, M., Mizoyama, I., Sugahara, S. and Seike, Y. (2015) Evaluation of water area based on fluxes of nitrogen, phosphorus, and dissolved organic carbon from bottom sediments in two connected brackish lakes. Jpn J Limnol 73:179-186. (in Japanese with English abstract)