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メタデータ	言語: en 出版者: 公開日: 2022-09-28 キーワード (Ja): キーワード (En): 作成者: 奥村, 裕, マスダ, ヨシオ, スズキ, ノリアキ, 筧, 茂穂, ハラ, モトユキ メールアドレス: 所属: 水産研究・教育機構, 宮城県水産技術総合センター, 宮城県, 水産研究・教育機構, 東北大学
URL	https://fra.repo.nii.ac.jp/records/72

Temporal changes in the nutrient status of Matsushima Bay after a wastewater plant was destroyed by a tsunami on 11 March 2011

Yutaka Okumura[1*], Yoshio Masuda[2], Noriaki Suzuki[3], Shigeho Kakehi[1], and Motoyuki Hara[4]

1* Fisheries Resources Institute, National Research and Development Agency, Japan Fisheries Research and Education Agency, 3-27-5, Shinhama, Shiogama, Miyagi 985-0001, Japan
2 Miyagi Prefecture Fisheries Technology Institute, Ishinomaki, Japan, 97-6, Sodenohama, Watanoha, Ishinomaki, Miyagi 981-3625, Japan
3 Miyagi Prefectural Government, Sendai Regional Promotion Office, Fisheries and Fisheries Port Department, Japan, 1-9-1, Shinhama, Shiogama, Miyagi 985-0001, Japan
4 Graduate School of Agricultural Science, Tohoku University, 468-1, Aramaki, Aoba, Aoba, Sendai, Miyagi 980-0845, Japan

*Corresponding author: okumura@affrc.go.jp

Abstract

We investigated how the nutrient status of Matsushima Bay was affected when a wastewater plant was destroyed by a tsunami in March 2011. The nutrient concentrations in the seawater and the treated water from the wastewater plant increased just after the tsunami, but decreased again to pre-tsunami levels after 2013. The amount of untreated water that passed through the wastewater plant decreased just after the tsunami. It was estimated that approximately 40.7 × $10^3 m^3/d$ of the treated water from the wastewater plant was discharged to Matsushima Bay; therefore, the quantity of effluent from the wastewater plant was less than one percent of the water inflow from Takagi River and Sendai Bay (which are outside Matsushima Bay) to Matsushima Bay. The nutrient concentrations of seawater in Sendai Bay were lower than those in Matsushima Bay. The results suggest that nutrient concentrations in Matsushima Bay after the tsunami did not increase because any untreated or poorly treated effluent was easily diluted by the river flow and the inflow of seawater. Many people were concerned about eutrophication, therefore, because of the decreased functioning of the wastewater plant in Matsushima Bay. Marked eutrophication in the bay was not observed after August 2011.

Keywords: tsunami effect, wastewater plant, coastal environment, time trend, nutrients

Introduction

The 2011 tsunami caused by the Great East Japan Earthquake (Goto et al. 2012), which was the most powerful earthquake ever to hit Japan and had a recurrence interval of between 800 and 1,100 years, caused widespread destruction in coastal areas around Tohoku. Many researchers have studied the effects of this tsunami on coastal environments and marine organisms in the coastal area around Tohoku, Japan (Kogure et al. 2017, Miyazawa et al. 2017, Oozeki et al. 2017, Ito et al. 2018). Some researchers have also studied how the tsunami affected Matsushima Bay, where there are oyster and seaweed farms and famous tourist spots. Although the tsunami measured in Matsushima Bay, which is a closed bay, was lower than in other more exposed coastal areas, it still disrupted the sediment on the sea floor through erosion (Okumura and Masuda 2019) and redeposition (Irizuki et al. 2019), which considerably changed the seafloor environment in the bay (Oota et al. 2017), and caused decreases in the mollusc diversity (Sato and Chiba 2016) and eelgrass beds (Sakamaki et al. 2016). The earthquake also caused land subsidence (Imakiire and Koarai 2012), with the result that the intensity of light reaching the seafloor has decreased, and the eelgrass beds have struggled to recover in some places (Sakamaki et al. 2016).

The tsunami destroyed many facilities on land, including wastewater plants. In the aftermath of the tsunami, the function of more than 20 wastewater plants in the Tohoku area either temporarily stopped or had decreased function (Matsuhashi et al. 2014, Satoh 2017). Of these wastewater plants, one near Matsushima Bay suffered severe damage (Miyagi Prefectural Government 2011). Other researchers have reported that microbial communities in a river that received discharges of sewage effluent changed temporarily in the period immediately after the earthquake (Wells et al. 2013). Other researchers reported that the concentrations and composition of nutrients in coastal areas changed after the 2011 tsunami (Fukuda et al. 2016). There was concern that the trophic state of

Matsushima Bay would increase because of discharges of either untreated or poorly treated wastewater to the bay. While we know that the chemical oxygen demand (COD) and most probable number (MPN) did not change considerably in the months after the tsunami (Sakamaki et al. 2016), there is no information about whether the nitrogen (N) and phosphorus (P) concentrations in wastewater discharges emitted to Matsushima Bay changed in that period. N and P serve as indicators of different aspects of water than COD and the MPN (which indicates bacteria sources such as *E.coli*), and increases in the N and P concentrations might trigger increases in phytoplankton blooms (USEPA 2004). If the N/P ratio changes, the composition of the phytoplankton assemblages might also change (Liu et al. 2013, Xiao et al. 2018) as the demand for nutrients varies with the phytoplankton species. Changes in the phytoplankton species might pose risks for aquaculture; for example, plankton that cause shellfish poisoning would have adverse effects on shellfish aquaculture operations (Officer and Ryther 1980); any pause or decrease in the function of a wastewater plant might be harmful for shellfish aquacultures.

In this study, we investigated the nutrient concentrations in Matsushima Bay before and after the tsunami. We compared information in data reports about the emissions of N and P and quantities of treated water discharged from a wastewater plant in the bay. We also explored how changes in the function of the wastewater plant (from normal to low) affected the nutrient concentrations in the Matsushima Bay, by calculating the water quantities, and the N and P concentrations, in the river and in Sendai Bay, into which water from Matsushima Bay flows.

Materials and Methods

Investigations

We took samples from 16 stations in Matsushima Bay from August 2011 to December 2015 (Fig. 1). The salinity and water temperature were measured by a Conductivity, Temperature, and Depth (CTD) profiler (RINKO-Profiler, JFE-Advantech, Hyogo, Japan). Changes in the seabed topography at each station were measured in meters using the depth sensor feature of the CTD profiler, and this provided information about the erosive action of the tsunami and the subsidence caused by the earthquake (Online Resource 1). Samples of seawater to be analyzed for their nutrient concentrations were collected from two depths close to the surface and from 50 cm above the seabed. To calculate how much seawater flowed from the outer area into Matsushima Bay, we also collected samples from three stations in Sendai Bay, outside of Matsushima Bay, from April to November (Figs. 1 and 2). These samples were collected from two depths close to the surface and at a depth of 10 m, because the bed at the mouth of Matsushima Bay is at about 10 m. A water sample was also collected from the Takagi River, which flows into Matsushima Bay, on seven occasions from 2009 to 2013. The surface water and river water samples were collected in a bucket, and seawater from 50 cm above the seabed was collected with a Van Dorn water sampler (RIGOSHA Co. Ltd., Tokyo, Japan).

Nutrients analysis

The samples were stored in a freezer in the laboratory for approximately 1 month before analysis. The concentrations of NO_3-N+NO_2-N, NO_2-N, NH_4-N, and PO_4-P in seawater and river water were determined using an Auto Analyzer (BL-TEC, Osaka, Japan), as outlined in the instrument’s manual. After following the instructions in the instrument’s manual, we found the analytical standards of NO_3-N, NO_2-N, PO_4-P, and NH_4-N to be KNO_3, $NaNO_2$, KH_2PO_4, and $(NH_4)_2SO_4$ (Fujifilm Wako Pure Chemical Co., Osaka, Japan), respectively. After weighing each standard chemical, we adjusted the concentrations with distilled water. The calibration curve of standards and the concentrations of samples were calculated by use of the AACE software (version 6.03) supplied with the Auto Analyzer. The detection limit of each item was less than 0.01

μmol/L and is shown as zero in our figures.

Collecting data from reports

Datasets related to the wastewater plant, such as the concentrations of total N (TN), total P (TP), and various forms of dissolved inorganic nitrogen (DIN; NO_3-N, NO_2-N, and NH_4-N), in untreated and treated water, and the quantities of wastewater discharged, were obtained from the annual reports of the Miyagi Prefectural Government (2010, 2011, 2012, 2013, and annual reports from 2014 to 2016 https://www.pref.miyagi.jp/site/sab/list1796-5263.html). In this study, we used data from April 2009 until December 2015. We calculated the quantity (Q) of river water using the HQ equation from hourly measurements of the river height (H) collected at the Shinainuma Station (Fig. 1) in the Takagi River, obtained from the Miyagi Prefectural Government (unpublished). We obtained data collected before the tsunami about, for example, nutrients and salinities from the Miyagi Prefectural Government (https://www.pref.miyagi.jp/site/kankyo/ in Japanese).

Calculating the seawater inflow from Sendai Bay to Matsushima Bay

The amount of water that flowed into Matsushima Bay from outside of the bay was calculated on the basis of the box model concept (Unoki 1998). The salinity of the seawater flowing into Matsushima Bay generally decreases when it mixes with freshwater discharged from the river and wastewater plant, but increases when seawater from a deeper layer outside of the bay with high salinity flows into the bay. Therefore, the amounts of inflow to, and outflow from, Matsushima Bay can be calculated from the salinities and quantities of water from each source, such as the volume in Matsushima Bay, wastewater, river water, and inflow from Sendai Bay (Fig. 2). To calculate the inflow from Sendai Bay, the volume of Matsushima Bay was calculated, as follows. The bottom depths measured at the 16 stations were converted to the bottom depth for the average tide level by substituting into the observation time to tide table (because the bottom depth changes with the time to the tide). The bottom depth at each station after the tsunami, from August 2011 to February 2013, was averaged. We then created a bathymetric map of isobath lines of 1 m from the average depths of each station using Ocean Data View (https://odv.awi.de/). The areas of each 1-m depth in Matsushima Bay were calculated from a bathymetric map from image J (Rasband 2018). Then, the volume in Matsushima Bay was roughly estimated by integrating the area of each 1-m depth.

Inflows from the Takagi River to Matsushima Bay were calculated by substituting the hourly water heights into the HQ equation. The daily and monthly inflows were calculated from the hourly inflows.

To understand the quantities of nutrients that were discharged from the wastewater plant, we investigated temporal trends in the quantities of wastewater and nutrient concentrations using monthly data published in the online annual reports from 2009 to 2015 (Miyagi Prefectural government 2010-2013, https://www.pref.miyagi.jp/site/sab/list1796-5263.html). The information for TN, TP, NO_3-N, NO_2-N, and NH_4-N was aggregated. We had information about TP but not dissolved inorganic phosphate (DIP; PO_4-P). Researchers have reported that the DIP/TP ratio for each wastewater plant is different (Tanaka and Shimamura 2005, Yamashita et al. 2006, Kamohara et al. 2019). After referring to an earlier study (Yamashita et al. 2006), we assumed that the DIP/TP ratio was 70%. Treated water from a wastewater plant was discharged to both Sendai Bay and Matsushima Bay through the Sunaoshi-Teizan Canal in front of a wastewater plant (Figure 1). In 1982 its (Sendai Bay / Matsushima Bay) ratio was reported to be 6:4 (Miyagi Prefectural government 1982). The inflow from the wastewater plant to Matsushima Bay was calculated as 40% of the total emissions from a wastewater plant.

Bi-monthly data for the salinity at the surface and at 50 cm above the seabed were averaged. We averaged the salinities measured at the surface and at a depth of 10 m for each sampling time at the three stations outside of Matsushima Bay (Fig. 1).

Calculation of DIN and DIP flux from each component

The flux of DIN from Takagi River to Matsushima Bay was calculated by multiplying the river water discharge by DIN concentration in that water. The flux of DIN from the wastewater plant to Matsushima Bay was calculated by multiplying the volume of treated water by DIN concentration in that water; this was further multiplied by 40%. This was because the inflow from the wastewater plant to Matsushima Bay was approximately 40% of the total emissions from that wastewater plant, and 60% outflowed to Sendai Bay (Miyagi Prefectural government 1982).

DIP was calculated in the same way as DIN.

Statistical analyses

Statistical analyses were conducted for the highest or lowest month of nutrient concentrations. Significant differences in DIN and DIP concentrations were first compared by the Friedman test. Next, nutrient concentrations each year were compared by pairwise comparisons using the Wilcoxon signed-rank test. We used the Bonferroni method for P value adjustment. All tests were conducted with EZR (ver. 1.54) software (https://www.jichi.ac.jp/saitama-sct/SaitamaHP.files/statmedEN.html), which is based on R software (https://www.r-project.org/). Pairwise comparisons were not carried out on samples from Sendai Bay because the sample size was small.

Results

Temporal trends in the nutrient concentrations

Matsushima Bay

The mean DIN concentrations tended to vary seasonally through the year, and to be high in autumn (Fig. 3a). The annual maximum value of the monthly means during our survey period was the highest in 2012, and decreased afterwards (Online Resource 2). The annual maximum value of the monthly means ranged from 7.2 to 16.6 μmol/L before 2011, was 20.4 μmol/L in 2012, and ranged from 10.2 to 14.2 μmol/L after 2013. The annual maximum value in each year was significantly different (*p* value < 0.05) by the Friedman test (Online Resource 3). The mean surface maximum in 2012 was statistically significant in 2009, 2011, 2013, and 2014 at the 0.05 probability level (Online Resource 4a). The mean maximum of 50 cm above the seabed in 2012 was statistically significant in all years except in 2010, at the 0.05 probability level (Online Resource 4b).

The mean DIN minimum in each month in both layers was at its peak in 2011 and decreased after 2012 (Fig. 3a). The annual minimum value of the monthly means ranged from 1.9 to 2.7 μmol/L before 2010, from 5.6 to 5.9 μmol/L in 2011, and from 0.14 to 0.91 μmol/L after 2012 (Online Resource 2). The annual minimum value in each year was significantly different (*p* value < 0.05) by the Friedman test (Online Resource 3). The mean surface minimum in 2011 was statistically significant after 2012 at the 0.05 probability level (Online Resource 4c). The mean minimum of 50 cm above the seabed in 2011 was statistically significant in all years at the 0.05 probability level (Online Resource 4d). DIN concentrations in Matsushima Bay increased after the tsunami, and tended to be high from 2011 to 2012 and to decrease after 2013.

DIP concentrations also tended to fluctuate in cycles in the same way as DIN concentrations (Fig. 3b). Mean DIP concentrations tended to be high in autumn (Online Resource 2). Over the period of the study, the mean DIP maximums in each month in both layers were at their peaks in 2012, and decreased after 2013. The annual maximum value of the monthly means ranged from ranged from 0.77 to 0.9 μmol/L before 2011, from

1.38 µmol/L to 1.40 µmol/L in 2012, and from 0.97 to 1.27 µmol/L after 2013. The annual maximum value in each year was significantly different (p value < 0.05) by the Friedman test (Online Resource 3). The mean surface maximum in 2012 was statistically significant in 2009, 2010, 2014, and 2015 at the 0.05 probability level (Online Resource 5a). The mean maximum of 50 cm above the seabed in 2012 was statistically significant in all years at the 0.05 probability level (Online Resource 5b).

The mean DIP minimums in each month in both layers were at their peaks in 2011 and decreased after 2012 (Fig. 3b, Online Resource 2). The annual minimum value of the monthly means ranged from 0.23 to 2.3 µmol/L before 2010, from 0.74 to 5.6 µmol/L in 2011, and from 0.04 to 0.91 µmol/L after 2012. The annual minimum value in each year was significantly different (p value < 0.05) by the Friedman test (Online Resource 3). The mean minimums of the surface and 50 cm above the seabed in 2011 were statistically significant in all years at the 0.05 probability level (Online Resources 5c and 5d). DIP concentrations in Matsushima Bay increased after the tsunami, tended to be high from 2011 to 2012, and to decrease after 2013.

The N/P ratio calculated from the average DIN and DIP in each year was 8.7 in 2009, 12.4 in 2010, 8.9 in 2011, 11.3 in 2012, 8.3 in 2013, 5.6 in 2014, and 9.5 in 2015.

Sendai Bay

The DIN concentrations in Sendai Bay also fluctuated throughout the 7 years (Fig. 4a). In contrast to Matsushima Bay, the concentration levels in Sendai Bay varied by year and the month of mean maximum concentrations ranged from April to November; the month of mean minimum concentrations ranged from May to September (Online Resource 6).

Time courses of monthly mean maximums were similar to those of Matsushima Bay. The mean DIN maximums in each month in both layers were at their peaks in 2012 and decreased after 2013. The annual maximum value of the monthly means ranged from 1.19

to 3.74 μmol/L before 2012, from 4.88 to 5 μmol/L in 2012, and from 0.55 to 2.95 μmol/L after 2013. The annual maximum value at a depth of 10 m in each year was significantly different (p value < 0.05) by the Friedman test (Online Resource 3), but that of the surface was not significantly different (p value > 0.05).

The mean DIN minimums in each month in both layers were at their peaks in 2010, and tended to decrease gradually over time. The annual minimum value of the monthly means ranged from 0.62 to 0.64 μmol/L in 2009, from 1.05 to 0.88 μmol/L in 2010, and from 0 to 0.55 μmol/L after 2011. The annual minimum value in each year was significantly different (p value < 0.05) by the Friedman test (Online Resource 3).

The monthly mean DIP maximums and minimums resembled those of DIN (Fig. 4). The mean DIP maximums in each month in both layers were at their peaks in 2012, and decreased after 2013 (Online Resource 6). The annual maximum value of the monthly means ranged from 0.13 to 0.42 μmol/L before 2012, from 0.45 to 0.49 μmol/L in 2012, and from 0.02 to 0.42 μmol/L after 2013. The annual maximum value at the two depths were significantly different (p value < 0.05) by the Friedman test (Online Resource 3).

The mean DIP minimums in each month in both layers were at their peaks in 2010, and tended to decrease gradually with time (Fig. 4b, Online Resource 6). The annual minimum value of the monthly means were 0 μmol/L in 2009, and ranged from 0.02 to 0.08 μmol/L in 2010, and from 0 to 0.03 μmol/L after 2011. The periods below the detection limits were 3 months in 2013, 5 months in 2014, and 3–4 months in 2015. The annual maximum value of surface was significantly different (p value < 0.05) by the Friedman test, but that at a depth of 10 m was not significantly different (Online Resource 3).

The N/P ratio calculated from the average DIN and DIP in each year was 11.3 in 2009, 12.2 in 2010, 11.1 in 2011, 9.4 in 2012, 8.6 in 2013, 17.4 in 2014, and 4.2 in 2015.

Temporal trends in N and P in treated water from the wastewater plant

The TN concentrations doubled just after the tsunami, and then gradually decreased with time and returned to the pre-quake concentrations (Fig. 5a). The annual average concentrations were 1,087 ± 98 µmol/L in 2009 and 1,062 ± 62 µmol/L in 2010; they increased to 1,875 ± 540 µmol/L in 2011 and to 2,019 ± 273 µmol/L in 2012; decreased to 1,042 ± 340 µmol/L in 2013 and to 987 ± 66 µmol/L in 2014; and increased to 1061 ± 99 µmol/L in 2015.

The pattern of DIN concentrations changed in a similar way to that of time trends in TN. The annual average DIN concentrations were 1,003 ± 95 µmol/L in 2009 and 977 ± 52 µmol/L in 2010; they increased to 1,344 ± 271 µmol/L in 2011 and to 1,529 ± 150 µmol/L in 2012; they decreased to 951 ± 317 µmol/L in 2013 and to 914 ± 69 µmol/L in 2014; and increased to 980 ± 92 µmol/L in 2015. The proportions of NH_4-N, NO_2-N, and NO_3-N varied over time. NH_4-N was approximately 55% of total DIN from April 2009 to February 2011, approximately 100% from April 2011 to December 2012, and approximately 55% from January 2013 to February 2015. NH_4-N, therefore, dominated the total DIN in the 2 years after the disaster. NO_3-N was approximately 42% of total DIN from April 2009 to February 2011, approximately 0% from April 2011 to December 2012, and approximately 41% from January 2013 to February 2015. NO_3-N was, therefore, almost undetected in the 2 years after the tsunami, in contrast to NH_4-N. Levels of NO_2-N were always low during these periods, at approximately 3% of total DIN.

The DIN/TN ratio also varied over time. The ratio was approximately 92% from April 2009 to February 2011, 73% from April 2011 until December 2012, and 92% from January 2013 until December 2015. The DIN/TN ratio was low in the 2 years following the tsunami. The average DIN concentrations in the treated water emitted from the wastewater plant were higher than those in seawater of Matsushima Bay (Figs. 3a and 5a). The concentrations in the treated water were 170, 257, and 270 times higher than those in seawater from Matsushima Bay from April 2009 to December 2010, August 2011 to December 2012, and from February 2013 to December 2015, respectively.

The TP concentration was high just after the tsunami and the changes in TP over time were similar to those of TN (Fig. 5b). The annual average TP concentrations were 52 ± 18 μmol/L in 2009 and 68 ± 19 μmol/L in 2010; they increased to 87 ± 35 μmol/L in 2011 and to 71 ± 29 μmol/L in 2012; decreased to 48 ± 17 μmol/L in 2013; and increased to 65 ± 21 μmol/L in 2014 and to 65 ± 19 μmol/L in 2015. The DIP concentrations were calculated from the TP concentration at 36.4 (52 × 0.7) μmol/L in 2009, 47.6 (68 × 0.7) μmol/L in 2010, 60.9 (87 × 0.7) μmol/L in 2011, 49.7 (71 × 0.7) μmol/L in 2012, 33.6 (48 × 0.7) μmol/L in 2013, and 45.5 (65 × 0.7) μmol/L in 2014 and 2015. The DIP concentrations calculated in the treated water were also higher than those in the seawater of Matsushima Bay. The concentrations in the treated water were 87, 98, and 95 times higher than those in Matsushima Bay seawater from April 2009 to December 2010, from August 2011 to December 2012, and from February 2013 to December 2015, respectively.

Although TN, TP, and NH_4-N were higher and NO_3-N was lower immediately after the earthquake, the levels always fluctuated, and the seasonal changes were unclear.

The N/P ratio calculated from the average DIN and DIP in each year was 27.5 in 2009, 20.7 in 2010, 22 in 2011, 30.8 in 2012, 28.3 in 2013, 20 in 2014, and 21.6 in 2015.

Raw water inflows to the wastewater plant

The trends in the TN, TP, and NH_4-N concentrations in the raw water inflows to the wastewater plant differed from those in the treated water (Fig. 5c). The annual average concentrations of TN were 3,275 ± 257 μmol/L in 2009, 3,289 ± 282 μmol/L in 2010, 2,836 ± 600 μmol/L in 2011, 3,039 ± 286 μmol/L in 2012, 3,135 ± 277 μmol/L in 2013, 3,212 ± 262 μmol/L in 2014, and 3,087 ± 289 μmol/L in 2015.The TN concentrations in the raw water were greater than those in the treated water, and were 3.1 times greater from

April 2009 to February 2011, 1.4 times greater from April 2011 to December 2012, and 3.1 times greater from February 2013 to December 2015.

NH_4-N was the main component of the DIN in the raw water, and the concentrations of NO_2-N and NO_3-N were frequently lower than the detection limits of 0.64 and 2.1 μmol/L, respectively. The trends in the NH_4-N and TN concentrations were similar. The average concentration of NH_4-N was 2,152 μmol/L from April 2009 to February 2011, 1,765 μmol/L from April 2011 to December 2012, and then 2,077 μmol/L. DIN in raw water accounted for approximately 60% of TN through all these periods, but was the main part of TN in the treated water throughout, apart from the period immediately after the tsunami.

Nutrient concentrations in the Takagi River

The average concentrations of DIN and DIP in the Takagi River were 19.1 ± 15.1 μmol/L and 1.8 ± 0.6 μmol/L, respectively (Table 1). The nutrient concentrations in the Takagi River were lower than those in the treated water from the wastewater plant and were higher than those in seawater. The average DIN/DIP ratio was 10.5.

Salinity of water in Matsushima Bay

The salinity tended to vary seasonally (Fig. 6a). The average salinities from May to October ranged from 28.3 to 30.2 PSU at the surface and from 29.1 to 30.9 PSU at 50 cm above the bottom. The average salinities ranged from 30.9 to 32.1 PSU at the surface, and from 31.6 to 32.3 PSU at 50 cm above the bottom from December to April. The salinities in both layers tended to be lower between May and October than between December and April. The surface salinities generally decreased from June to August and, over this time, the difference between the salinity in the surface and 50 cm above the seabed tended to be greater than in other months.

The salinities of 50 cm above the seabed tended to be slightly higher after the tsunami than before the tsunami (Fig. 6a). The salinities from April 2009 to February 2011 ranged from 26.6 to 32.1 PSU at the surface and from 28.3 to 32.3 PSU of 50 cm above the seabed. The salinities at the surface and 50 cm above the seabed from August 2011 to December 2012 ranged from 29.3 to 32.7 PSU and from 29.6 to 32.8 PSU, respectively. The salinities at the surface and 50 cm above the seabed from February 2013 to December 2015 were between 21.5 and 32.9 PSU and 27.9 and 33 PSU, respectively. Although the salinity was very low around August 2013, the highest salinity observed between February 2013 and December 2015 was higher than the pre-tsunami maximum.

Salinity at the stations in Sendai Bay outside Matsushima Bay

The salinities at the surface generally decreased from June to September (Fig. 6b). The average salinities at the surface ranged from 26.5 to 33 PSU from April 2009 to November 2010, from 26.1 to 33.3 PSU from September 2011 to November 2012, and from 29.6 to 33.3 PSU from April 2012 to November 2015. The average salinities at a depth of 10 m ranged from 32.4 to 33.4 PSU from April 2009 to November 2010, from 32 to 33.4 PSU from September 2011 to November 2012, and from 31.8 to 33.4 PSU from April 2012 to November 2015. There was little seasonal change in the salinity at a depth of 10 m, which contrasted with the patterns in the surface salinities in Sendai (Fig. 6a) and at both depths measured in Matsushima Bay (Fig. 6b).

Quantity of water discharged from the wastewater plant

The quantities of treated water discharged from the wastewater plant decreased immediately after the tsunami (Fig. 7a). The average water discharges were 110 × 10^3 m^3/d from April 2009 to February 2011, 56.5 × 10^3 m^3/d in April 2011, which was approximately half of the average value before the tsunami, 83.6 × 10^3 m^3/d from April 2011 to December 2012, and then 110 × 10^3 m^3/d, the same as the pre-tsunami level, from

January 2013 to February 2015. It took 2 years for the wastewater quantity to recover to pre-tsunami levels.

When the inflow to Matsushima Bay was assumed to be 40% of the total (Miyagi Prefectural Government 1982), the inflow of treated water to Matsushima Bay averaged 44×10^3 m^3/d from April 2009 to February 2011 and from January 2013 to February 2015.

Discharge from the Takagi River to Matsushima Bay

Although there were occasional spikes, the discharge from the river showed a clear seasonal pattern (Fig. 7b). The discharge averaged 1.3×10^6 m^3/d from April to September and 0.5×10^6 m^3/d for the other periods, from January to March and again from October to December. Although the discharge showed annual variation, the average discharge from April to September was between 1.8 and 3.2 times higher than that from October to the following March. The river water discharge to Matsushima Bay was between 114 (5,000/44) to 295 (13,000/44) times greater than the discharge of treated water from the wastewater plant.

Calculating the inflow from Sendai Bay to Matsushima Bay

The inflow from Sendai Bay to Matsushima Bay calculated by the box model varied seasonally. The inflow ranged from 3,200 to $115{,}000 \times 10^3$ m^3/d, and the average was $17{,}600 \times 10^3$ m^3/d (Fig. 7c). The average water quantity calculated was 13.5 times higher than that from the Takagi River from April to September and was equivalent to approximately 10% of the capacity of Matsushima Bay. The inflow from Sendai Bay to Matsushima Bay tended to increase after the tsunami, although the values varied in different periods. The average inflow was $10{,}925 \times 10^3$ $m^3/day \pm 7{,}200 \times 10^3$ from 2009 to 2010, and $19{,}493 \times 10^3$ $m^3/day \pm 21{,}164 \times 10^3$ after 2011.

Calculating the flow of DIN and DIP in Matsushima Bay

The inflow of DIN to Matsushima Bay was in the order: wastewater plant > Takagi River > Sendai Bay (Figure 8a). The average inflow of DIN was 0.62 ± 0.11 ton/day from the wastewater plant, 0.2 ± 0.1 from Takagi River, and 0.15 ± 0.28 from Sendai Bay. The inflow from the wastewater plant was 3× and 4× higher than that from Takagi River and Sendai Bay, respectively.

The inflow of DIP to Matsushima Bay was in the order: wastewater plant ≥ Takagi River > Sendai Bay (Figure 8b). The average inflow of DIP was 0.06 ± 0.02 ton/day from the wastewater plant, 0.05 ± 0.03 from Takagi River, and 0.04 ± 0.11 from Sendai Bay. However, smaller differences in DIP were found between the inflow from the wastewater plant, Takagi River, and Sendai Bay than were found for DIN.

Discussion

Nutrient sources in Matsushima Bay

The inflow of DIN into Matsushima Bay, ranked from high to low, was highest from the wastewater plant, followed by Takagi River, and the lowest was from Sendai Bay (Fig. 8a). DIN concentrations, ranked from high to low, were highest in the wastewater plant, followed by the Takagi River and Matsushima Bay, and were lowest in Sendai Bay (Figs. 3, 4, and 5; Table 1). As the nutrient concentrations were higher at the wastewater plant and in the Takagi River than in Matsushima Bay, we considered that the river and the wastewater plant were the main sources of DIN to Matsushima Bay. We also thought that the DIN in Matsushima Bay was mainly diluted by seawater from Sendai Bay, because the DIN concentrations in Sendai Bay were lower than those in Matsushima Bay. The results suggest that treated water from the wastewater plant, river water, and seawater were mixed in Matsushima Bay, and then seawater from near to the surface in the bay flowed to the outer area of Sendai Bay (Fig. 2). We already know that the nutrient concentrations are influenced by the concentrations outside of the bay through mixing by estuarine circulation (Yamamoto et al. 2000). If the concentrations outside the bay are lower than those in the inner areas, such as Matsushima Bay, the concentrations in the bay are diluted.

The quantities of water flowing into Matsushima Bay were ranked in order, from high to low, with most water flowing in from Sendai Bay, followed by the Takagi River, with the lowest inflow from the wastewater plant (Fig. 7). These results suggest that the nutrients and surface salinity in the Matsushima Bay mainly reflect the complex fluctuations and seasonal changes in the seawater inflows from Sendai Bay and the spikes in river water, driven by the weather. The low salinities in the surface seawater during summer reflect the increases in the river water, and thermoclines that develop in the water column.

Various researchers have reported that the seafloor changed because of the tsunamis (Murakami et al. 2013, Nishi et al. 2013, Kamiyama et al. 2014, Naiki et al. 2015, Seike et al. 2017, Matsuoka et al. 2018, Okumura et al. 2020), and that the earthquake caused land subsidence (Imakiire and Koarai 2012, Matsumoto et al. 2018) along the Tohoku Coast. We thought that the inflows from Sendai Bay increased after the earthquake as the bay mouth became deeper and water exchange was easier because of the erosion of the bed of Matsushima Bay close to the bay mouth by the tsunami (Okumura and Masuda 2019) and land subsidence by the earthquake (Sakamaki et al. 2016).

The inflow of DIP into Matsushima Bay tended to be similar to that of DIN, but the influence of DIP from the wastewater plant water was not as high as that of DIN (Fig. 8b). Because the N/P ratio in the treated water was lower than that of seawater and river water, the levels of DIP from the wastewater plant were lower than those of DIN (Figs 3, 4, 5a, and Table 1). We considered, therefore, that the contribution of DIP from the wastewater plant was low.

How the damage to the wastewater plant by the tsunami affected the eutrophication in Matsushima Bay

There was concern that the trophic status in the bay would deteriorate because of the damage to the wastewater plant. Although the TN and TP concentrations in the treated water from the wastewater plant increased (Fig. 5a, and b), the average DIN and DIP concentrations in the bay only increased slightly (Fig. 3). We considered that (1) the quantities of wastewater decreased because the houses near the coast were destroyed by the tsunami; (2) the inflows of treated water to Matsushima Bay were limited to approximately 40% in all water and the remaining 60% was outflow to Sendai Bay (which is not directly connected to Matsushima Bay) via the canal (Miyagi Prefectural Government 1982, Fig. 7a); (3) the inflow from Sendai Bay was much greater than the inputs of treated water from the wastewater plant or from the river, and the high nutrient concentrations in the treated water were diluted by the seawater from Sendai Bay. While the nutrients in the treated water increased after the tsunami, we consider that, because of the combination of these factors, the concentrations in Matsushima Bay increased only slightly.

The nutrient concentrations in treatment water from the wastewater plant doubled just after the tsunami, and then gradually decreased with time and returned to the pre-quake concentrations in 2013 (Fig. 5a and b). With regard to the functioning of sewage treatment plants, the destroyed wastewater plant was restored progressively between March 2011 and April 2013 (Miyagi Prefectural government 2013b). Sedimentation and sterilization of wastewater was started in a temporary sedimentation basin from 21 March 2011, about 10 days after the tsunami. Simple aeration processing was started by use of a temporary fan machine from 28 June 2011, about 3 months after the tsunami. Microorganism processing was partially started from 4 January 2012. All facilities were restored by 29

March 2013. Nutrient concentrations decreased with the restoration of the wastewater plant.

The TN/DIN and NH_4-N/DIN ratios in the treated water increased just after the tsunami (Fig. 5a). The high NH_4-N/DIN ratio resembled the DIN composition of raw water (Fig. 5c). These changes may reflect changes in the nitrifying bacteria that convert ammonia to nitrate by nitrification in the wastewater plant (USEPA 2004). Bacteria can convert from nitrate to nitrogen gas by denitrification in a wastewater plant (USEPA 2004). Therefore, we considered that the TN/DIN and NH_4-N/DIN ratios changed because of a decrease in the treated capacity of the wastewater plant caused by the decline in the nitrifying bacteria and other bacteria.

The influence of the tsunami on the bottom environment

The seabed near the mouth of Matsushima Bay was scoured by the tsunami (Irizuki et al. 2019, Okumura and Masuda 2019). After the tsunami, there was less silt in the bottom sediments and the particles were larger than before, so there were fewer chemicals and less oxygen in sediments (Oota et al. 2017). Researchers have reported changes in various sediment properties in Tohoku area, such as the mud contents, COD, acid volatile sulfides (Naiki et al. 2015), and organic matter (Nishi et al. 2013), after earthquakes. Sediments in the Matsushima Bay environment also improved as a result of outward flow to bottom sediments further offshore through the erosion and resuspension of sediments during the tsunami.

When oysters are farmed continuously over a long period, the seabed environment deteriorates because of fecal deposits and other materials (Kimura 1999, Mori 1999, Kawaguchi et al. 2004, Yamamoto et al. 2009). Because of this deterioration, the seabed at the oyster farm was reworked regularly before the earthquake. According to a fisherman, this was no longer necessary after the earthquake. Although N and P are known to leach from the seabed (Kamiyama et al. 1997, Yamamoto et al. 1998), it is possible that the amount of N and P released from the seabed also decreased. These results infer that there were limited increases in the N and P concentrations because of the changes or improvements in the seabed environment.

Prior to this study, various researchers had reported how the 2011 tsunami influenced organisms and environments, but few had studied how the marine environment changed when the wastewater plants were destroyed. There was great concern that the trophic status would deteriorate rapidly; however, analysis of the nutrient data showed that the nutrients in Matsushima Bay did not increase sharply.

The TN and DIN concentrations and the TN/DIN and NH_4-N/DIN ratios in the treated water changed just after the tsunami because of a decline in the function that caused a decrease in the nitrifying bacteria. However, the inflows of treated water to Matsushima Bay were very small compared to those of river water and seawater from outside of the bay. Inflows of water with low nutrient concentrations from Sendai Bay increased after the tsunami because of increases in the water exchange, which helps explain why the nutrient concentrations did not increase sharply immediately after the tsunami. Before this study, we predicted that eutrophication would progress when a wastewater plant was destroyed because of the limited water exchange in closed bays, such as Matsushima Bay. However, we found that eutrophication was prevented after the tsunami by increases in the inflows to Matsushima Bay from outside. About 20 wastewater plants were destroyed by the tsunami. Each wastewater treatment plant has different sources and also different capacities for treating water. Bays along the coastline, to which treated wastewater from wastewater plants is discharged, may be closed, semi-closed, or open. This study highlights the need for continuous monitoring of coastal environments close to wastewater plants.

Acknowledgments

This work was mainly supported by a grant from an earthquake damage recovery fund from the Fisheries Agency and the Reconstruction Agency, Japan. This was a collaborative study between the Tohoku National Fisheries Research Institute and Tohoku University. We would like to thank the employees at the wastewater plant for their contribution. We thank Edanz Group (https://jp.edanz.com/ac) for editing the English text of a draft of this manuscript.

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Figure captions

Fig. 1 Sampling sites (◆: Stations in Matsushima Bay, □: Stations in Sendai Bay, ■: wastewater plant, △: station in Takagi River, ●: Shinainuma Station in Takagi River). The Takagi River near Shinainuma Station passes under the Naruse River by the siphon. Treated water emitted from a wastewater plant (■) is discharged to the Sunaoshi-Teizan Canal, which extends in a north–south orientation. The northern end of the canal is connected to Sendai Bay and its southern part is connected to Matsushima Bay. As the inflow ratio of treated water from a wastewater plant to Sendai Bay and Matsushima Bay was reported to be 6:4 in 1982 (Miyagi Prefectural Government 1982), the volume of treated water inflow to Matsushima Bay is thought to be approximately 40% to all treated water

Fig. 2 Outline of the box model (Unogi 1998). The seawater inflow from Sendai Bay to Matsushima Bay (Q; results are shown in Fig. 7c) can be calculated by using the freshwater quantities (R) from the wastewater treatment plant (results are shown Fig. 7a) and Takagi River (results are shown in Fig. 7b), surface salinity in Matsushima Bay (S_1, the result is in Fig. 6a), and salinity at a depth of 10 m in Sendai Bay (S_4, the result is in Fig. 6b). The seawater outflow from Matsushima Bay to Sendai Bay (Q'; results are shown in Fig. 7c) can also be calculated by using the freshwater quantities (R) from the wastewater treatment plant and Takagi River, the salinity of surface in Matsushima Bay (S_1), and the salinity at a depth of 10 m in Sendai Bay (S_4). S_1 is the average surface salinity at 16 stations in Matsushima Bay (Fig. 1). S_2 is the average salinity of 50 cm above the seabed at 16 stations in Matsushima Bay. S_3 is the average salinity of the surface at three stations in Sendai Bay. S_4 is the average salinity at a depth of 10 m at three stations in Sendai Bay

Fig. 3 Temporal trends in the DIN and DIP concentrations at two depths in Matsushima Bay. (a) “Surface” plots are the DIN surface concentrations at 16 stations. “50 cm above the seabed" plots are the DIN concentrations from 50 cm above the seabed at 16 stations. Avg. of 50 cm above the seabed is the average DIN from 50 cm above the seabed at 16 stations. Surface Avg. is the average surface DIN at 16 stations. (b) Surface Avg. is the average surface DIP at 16 stations. Avg. of 50 cm above the seabed is the average DIP from 50 cm above the seabed at 16 stations. "Surface" plots are the DIP surface concentrations at 16 stations. "50 cm above the seabed" plots are the DIP concentrations from 50 cm above the seabed at 16 stations. Arrow indicates March 2011, when the tsunami occurred

Fig. 4 Temporal trends in the dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphate (DIP) concentrations at two depths in Sendai Bay. (a) "Surface Avg." is the average surface DIN at three stations. "Avg. at 10 m depth" is the average DIN from a depth of 10 m depth at three stations. "Surface" plots are the surface DIN concentrations at three stations. "10m depth" plots are the DIN concentrations from a depth of 10 m depth at three stations. (b) "Surface" plots are the surface DIP concentrations at three stations. "10 m depth" plots are the DIP concentrations from a depth of 10 m depth at three stations. Surface Avg. is the average surface DIP at three stations. "Avg. at 10 m depth" is the average DIP from a depth of 10 m at three stations

Fig. 5 Temporal trends in N in treated water discharged from the wastewater plant (a); temporal trends in P in treated water discharged from the wastewater plant (b); and temporal trends in N and P in the inflow to the wastewater plant (c)

Fig. 6 Temporal trends in the salinity concentrations at two depths in Matsushima Bay (a) and Sendai Bay (b). (a) Surface Avg. is the average surface salinity at 16 stations. Avg. of 50 cm above the seabed is the average salinity from 50 cm above the seabed at 16 stations. "Surface" plots are the surface salinities at 16 stations. "50 cm above the seabed" plots are the salinities from 50 cm above the seabed at 16 stations. (b) Surface Avg. is the average surface salinity at three stations. "Avg. at 10 m depth" is the average salinity from a depth of 10 m at three stations. “Surface” plots are the surface salinities at three stations. “10 m depth” plots are the salinities from a depth of 10 m depth at three stations

Fig. 7 (a) Quantities of water discharged from the wastewater plant. A ratio of 6:4 was reported in 1982 for treated water from a wastewater plant that was discharged to Sendai Bay and Matsushima Bay (Miyagi Prefectural Government 1982). Inflow to Matsushima Bay was calculated for 40% of total emissions from the wastewater plant. (b) River water discharged from the Takagi River. The water quantities were calculated by substituting river height into the HQ equation in Shinainuma Station. (c) Water quantities from each parameter in Matsushima Bay. Outflow is from the upper layer of Matsushima Bay to Sendai Bay. Inflow is the lower layer from Sendai Bay to Matsushima Bay. Takagi River is the inflow from Takagi River to Matsushima Bay. Wastewater is the inflow from the wastewater plant to Matsushima Bay. Total volume is the seawater volume in Matsushima Bay (unit is $\times 10^3$ m^3)

Fig. 8 (a) Time courses of total quantities of DIN calculated. “Takagi River” is the inflow of DIN per day (ton/day) from Takagi River to Matsushima Bay. “Wastewater plant” is the inflow of DIN per day in treated water from wastewater plant (ton/day) to Matsushima Bay via the Sunaoshi-Teizan Canal. “Sendai Bay” is the inflow of DIN per day (ton/day) from Sendai Bay to Matsushima Bay. (b) Time courses of total quantities of DIP calculated

Table 1 Nutrient concentrations in the Takagi River

Online Resource 1 Water depth in Matsushima Bay (a) before the tsunami; and (b) after the tsunami