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Article

Estimation of Changes in Nutrient Release Rate from Sediments after Tsunami by Incubation Experiment

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Abstract: Nutrient release from marine sediments in Osaka Bay has a significant impact on nutrient concentrations in seawater. A tsunami induced by the Nankai Trough earthquake may disturb marine sediments in the inner part of Osaka Bay. An incubation experiment to estimate the release rates of NH_4-N and PO_4-P was conducted to understand the present conditions and to quantify the changes caused by tsunamis. Two types of cores were created: a "control core" representing the current sediment, and a "redeposition core" representing the redeposition after the tsunami. The release rates have been decreasing since the year 2000 and have remained low. The experimental results suggest that the release rate after exposure to an aerobic environment by a tsunami may decrease to approximately 70% for NH_4-N and 60% for PO_4-P of the current level. In the past, the release rates were values experienced in the inner part of Osaka Bay. However, the reduction in the release rate by tsunamis may be more limiting for primary production under the current situation where the contribution of release for nutrients in seawater is significant.

Keywords: nutrient release rate; marine sediment; redeposition; incubation experiment; Osaka Bay; Nankai Trough earthquake; primary production

1. Introduction

Earthquakes occur frequently in Japan, and tsunamis often strike coast areas. The 2011 off the Pacific coast of Tohoku earthquake caused a massive tsunami to hit the Tohoku coast, resulting in drastic changes to the marine environment, including changes in bathymetry [1], changes in marine sediment quality [2], outbreaks of toxic plankton blooms and shellfish poisoning [3,4], and the destruction of seaweed beds [5]. Seagrass beds and fishery resources recovered quickly [6,7], but it has been noted that the impact on macrobenthos continues [8,9].

Such changes may occur even in inner bays, such as Osaka Bay, as shown in Figure 1, due to a tsunami being induced by the Nankai Trough earthquake, which will hit with a probability of 90% within 40 years and 60% within 20 years with magnitude 8 or 9 [10]. The possibility of severe sediment disturbance in the inner part of Osaka Bay by the tsunami was shown, and was simulated by using a numerical model [11]. It was predicted by a tidal transport simulation that disturbed sediments will be transported to and redeposited near Okinose along the shoreline and the convergent zone at the sea surface [12]. If the tsunami disturbs the sediment, nutrient release may change. To quantify the change in release rates of nutrients from tsunamis, an incubation experiment was conducted on ammonia nitrogen (NH_4-N) and phosphoric phosphorus (PO_4-P). In addition, the impact of the release rate change on primary production was discussed.

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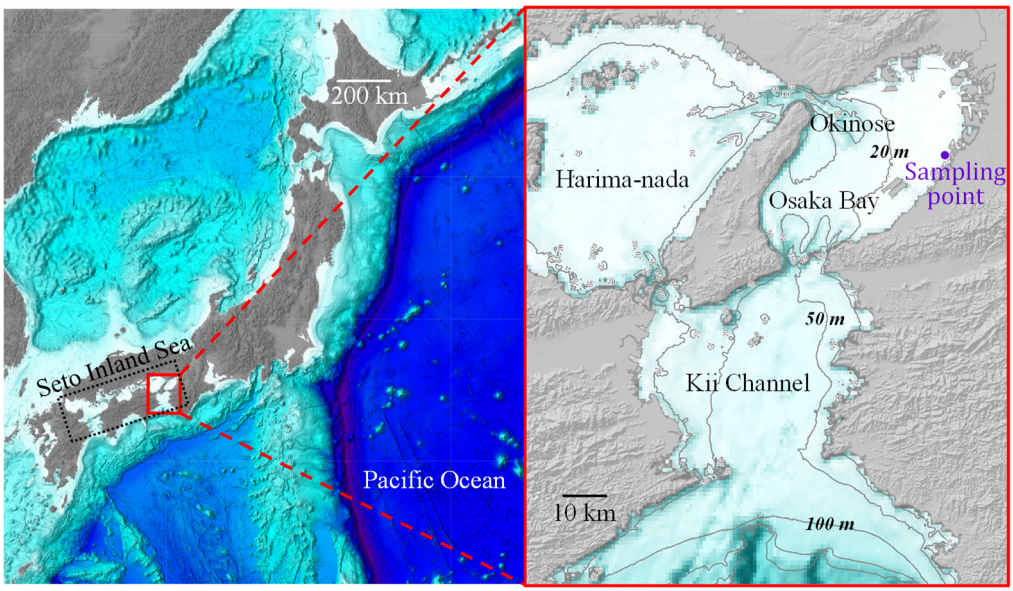

Figure 1. Location of the sampling point (34°-29′-33.71″N, 135°-21′-47.94″E) and the bathymetry of Osaka Bay, Japan.

2. Methods

2.1. Study field

Osaka Bay, as shown in Figure 1, is one of the semienclosed bays in the Seto Inland Sea located in western Japan. The southern part of Osaka Bay is connected to the Pacific Ocean through the Kii Channel. The bathymetry of the west side, the inner part of Osaka Bay, is less than 20 m. There are many cities, factories and river mouths around the inner part of Osaka Bay. Osaka Bay was eutrophic in the 1970s, and red tides occurred frequently. Total nitrogen (TN) and total phosphorus (TP) concentrations in marine sediments in Osaka Bay tend to be higher in the inner part of the bay [13]. The results of seasonal surveys conducted in the Seto Inland Sea during 1993~1994 showed that the nutrient release flux per unit area from marine sediments in Osaka Bay tended to be larger than that in other areas of the sea [14].

Dredging was conducted in the Kishiwada Passage on October 21, 2021. Sediment dredged from a depth of 16 m was used for this experiment. The sediment was clay-silt, similar to most of Osaka Bay. Therefore, it is considered that the sample represents the bottom sediments of Osaka Bay. The sediment had a hydrogen sulfide odor. Further, because this site is deeper than the surrounding area, sediments tend to be sludge. The dredged sediment was maintained at ordinary temperature and was not disturbed until it was placed in the laboratory.

2.2. Incubation Experiment

Three cores were made as the "control cores" (Core 1, 2 and 3), and the other three were made as the "redeposition cores" (Core 4, 5 and 6), as shown in Figure 2(a). The inner diameter of the clear cylinder was 10 cm. The dredged sediment was placed 30 cm thickness in the control cores and 28 cm thickness in the redeposition cores. Control cores represent the present seafloor of Osaka Bay. A part of the dredged sediment was aerated for 8 hours and then redeposited. This sediment was then covered with 2 cm of the surface redeposition cores to represent post-tsunami redeposition. Artificial seawater was carefully poured into the upper part of the cores to avoid sediment suspension. The cores were sealed by a silicone lid fitted with a dissolved oxygen (DO) sensor (DO-24P, TOA DKK, Tokyo, Japan), a Fluororesin propeller, and two water sampling tubes, as shown in Figure 2(b). The water overlying the sediment was agitated using a propeller with a rotation speed of 20 rpm for thorough mixing and to control the hydrodynamic conditions in the cores [15,16]. No resuspension of the sediment particles was observed. The DO concentrations in the overlying water were measured

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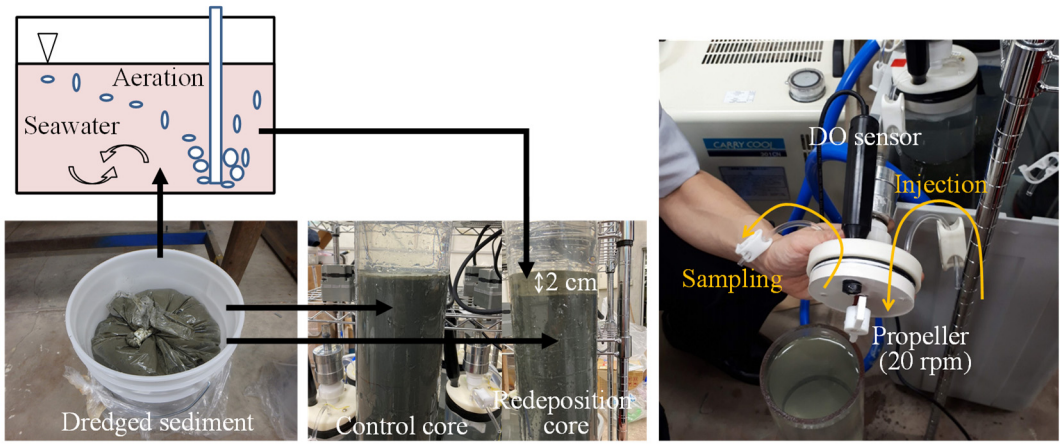
at 10 min intervals (WA-2017SD, FUSO, Tokyo, Japan) to confirm anoxic conditions. The cores were installed in water baths and were maintained at 23 °C, consistent with the water temperature of the sampling site in the summer. Incubation was continued for five days after 1 day of preincubation, which was inferred to be sufficient to achieve in situ conditions [17]. The overlying water was sampled three times (November 10, 12, and 15) during the incubation. When artificial seawater (50 mL) was injected into the upper part of the overlying water with a syringe from the tube (4 mm inner diameter, 6 mm outer diameter, LMT-55, Saint-Gobain K.K., Tokyo, Japan) on one side, the overlying water was pushed out from the other tube. The propeller was stopped at this time. Artificial seawater has a lower temperature than the overlying water, so it sunk and was not pushed out. The first 10 mL of overlying water that was exposed to air was discarded. The latter 40 mL was collected in a syringe and immediately filtered using a disposable filter with a pore size of 0.45 μm (Minisalt SM16555 K, Saltrius, Tokyo, Japan).



(**a**) (**b**)

Figure 2. (a) The schematic diagram of making the cores, and (b) the attached parts on covers.

After the incubation experiment, the overlying water was drawn, and three layers from the surface of the sediment, each 1 cm thick, were cut off. These sediments were centrifuged at 3,000 rpm for 10 min to separate pore water. The supernatant of the pore water was filtered in the same manner as the overlying water.

The overlying and pore waters were reacted with NH_4-N and PO_4-P pack test reagents (WAK-NH4-4 and WAK-PO4(D), Kyoritsu Chemical-Check Lab., Corp., Kanagawa, Japan) based on the indophenol and colorimetric methods, respectively. The water samples were analyzed using a spectrophotometer (SP-808, T&T Co., Ltd., Kanagawa, Japan) at 630 nm and 870 nm.

2.2. Calculation Methods

The oxygen consumption rate, R (g m^{-2} day^{-1}), of the overlying water was calculated as follows:

$$R = -\frac{dDO}{dt}\frac{V}{A}, \quad (1)$$

where dDO/dt is the variation in DO concentration during time t and is obtained as the slope in a linear regression equation, as shown later. A is the cross-sectional area of the core, and A=78.5 cm^2 for all cores. V is the volume of the overlying water, calculated by measuring the height of the overlying water of each core (Core 1: 19.4 cm, Core 2: 20.2 cm, Core 3: 19.4 cm, Core 4: 19.4 cm, Core 5: 18.5 cm, Core 6: 18.5 cm).

Release rates were estimated by the sediment core incubation method [18] and the mathematical modeling method [15]. The core incubation method considers that the release from sediment leads to

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a change in concentration in the overlying water. The mathematical model method is based on the diffusion equation from the vertical gradient of concentration in the pore water. Since the pore water was collected after the incubation experiment, the release rates by the mathematical model method are reference values. The release rate, Fc (mg m^{-2} day^{-1}), by the core incubation method was obtained as follows:

$$F_c = \frac{dC_w}{dt}\frac{V}{A}, \quad (2)$$

where *Cw* is the concentration in the overlying water. Three evaluation periods were established with November 10~12 being referred to as the first half, 12~15 as the latter half, and 10~15 as the entire period, and concentration gradients were determined for each period. The release rate, F_d (mg m^{-2} d^{-1}), by the mathematical modeling method was obtained as follows:

$$F_d = \varphi D \frac{dC_p}{dz}, \quad (3)$$

where φ is the porosity, *D* is the diffusion coefficient, *Cp* is the concentration in the pore water and *dz* is the layer thickness. The release rates were determined by the concentration gradient, *Cp*/*dz*, between the first layer of pore water and the overlying water, which has *dz* = 0.5 cm. The diffusion fluxes in the pore water can also be calculated with Equation 1, in this case using *dz* = 1 cm. We used moisture content observations by the Research Institute of Environment, Agriculture and Fisheries of Osaka Prefecture in 2013 as φ, where the inner part of Osaka Bay is generally 65~75% [12], and φ = 0.7 in this study. *D* (cm^2 s^{-1}) in the sediment depends on the pore water temperature, *T* (°C), and was determined as follows [19]:

$$RD = (m_0 + m_1 T) \times 10^6, \quad (4)$$

where m_0 and m_1 are coefficients and different for each ion: m_0 = 9.50 and m_1 = 0.413 for NH_4-N and m_0 = 2.62 and m_1 = 0.143 for PO_4-P.

3. Results

3.1. Oxygen Consumption Rate

Figure 3 shows the time series of oxygen concentrations in the overlying water of the control cores and redeposition cores. The rates of decrease in oxygen concentration are approximately constant in all cores, and can be expressed by a linear regression equation in each core. The oxygen consumption rates calculated by Equation 1 were 4.68 g m^{-2} day^{-1} for the redeposited core compared to 7.10 g m^{-2} day^{-1} for the control core and, on average, a 66% decrease. This result suggests that the oxygen consumption rate may decrease for a while after a tsunami because the redeposition of oxidative sediments by the tsunami reduces oxygen uptake from the overlying water. The consumption rate obtained by this experiment was larger than typical values (~4 g m^{-2} day^{-1} in maximum [15,20,21]). The pore water may have been extruded to the overlying water in the early stages of the experiment due to the sediment settling.

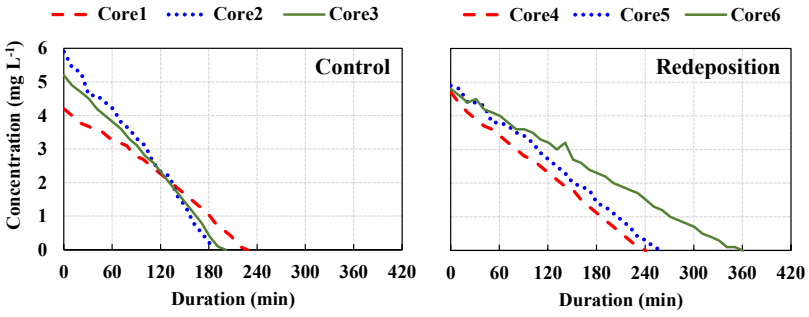

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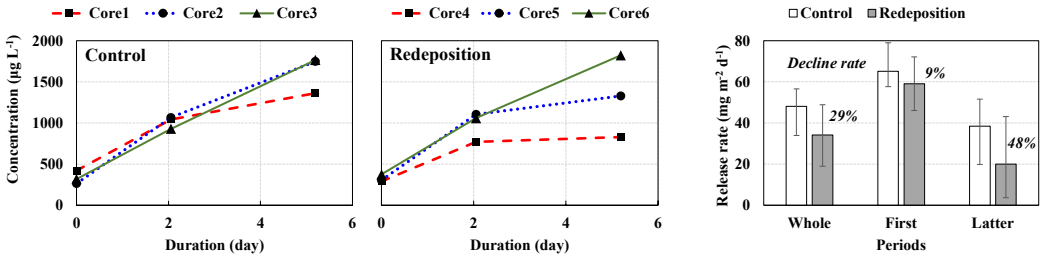
Figure 3. Time series of oxygen concentrations in the overlying water of the control cores and redeposition cores.

3.2. Release Rates

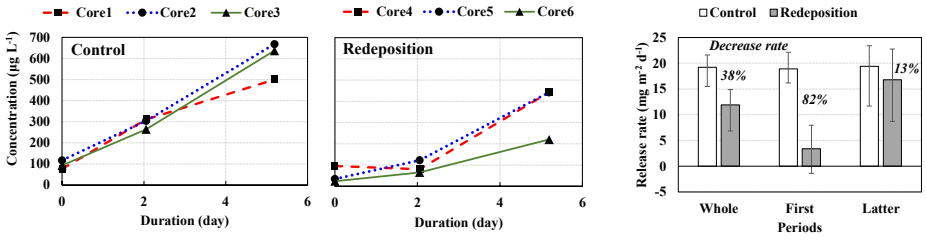
Figure 4(a) shows the temporal change in NH_4-N concentration in the overlying water of the control cores and redeposition cores. Increased concentrations were observed in all cores. Figure 4(b) shows the release rate of NH_4-N estimated by the core incubation method. In all evaluation periods, the release rates were smaller in the redeposition core than in the control core. The decline rate in the redeposition core relative to the control core was 29% over the entire period. Release rates were larger in the first half for both cores. The decline rate of the redeposition core increased in the latter half because the release rate of the redeposition core greatly decreased.



(**a**) (**b**)

Figure 4. Results in NH_4-N by core incubation: (**a**) temporal change in NH_4-N concentration in the overlying water of the control cores and redeposition cores; (**b**) release rate of NH_4-N estimated by the core incubation method. These are the average values of the control and redeposited cores, respectively. Error bars indicate maximum and minimum values.

Figure 5(a) shows the temporal change in the PO_4-P concentration in the overlying water of the control cores and redeposition cores. Figure 5(b) shows the release rate of PO_4-P estimated by the core incubation method. The concentrations in Core 4 decreased over the second measurement; otherwise, the concentrations increased. The release rates of the redeposition core were smaller in all evaluation periods, and the decline rate of redeposition core was 38%. The decline rate of the control core was similar in the first and latter halves. On the other hand, the decline rate for the redeposition core was greater in the first half because of the smaller release rate.



(**a**) (**b**)

Figure 5. Results in PO_4-P by core incubation: (**a**) temporal change in PO_4-P concentration in the overlying water of the control cores and redeposition cores; (**b**) release rate of PO_4-P estimated by the core incubation method that is shown in Figure 4.

Figure 6(a) shows NH_4-N concentrations in the pore water of the control core and redeposited core with NH_4-N concentrations in the overlying water on November 15. Figure 6(b) shows the release rate and diffusion fluxes of NH_4-N estimated by the mathematical modeling method with the release rate in the latter half by the core incubation method. Because the concentrations were higher in the lower layers in all cores, the release rate and diffusion fluxes were upward in all layers.

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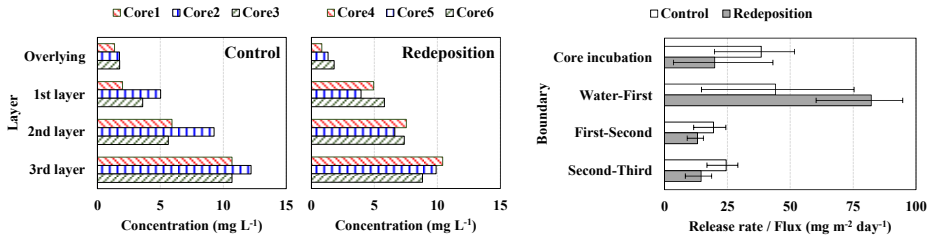
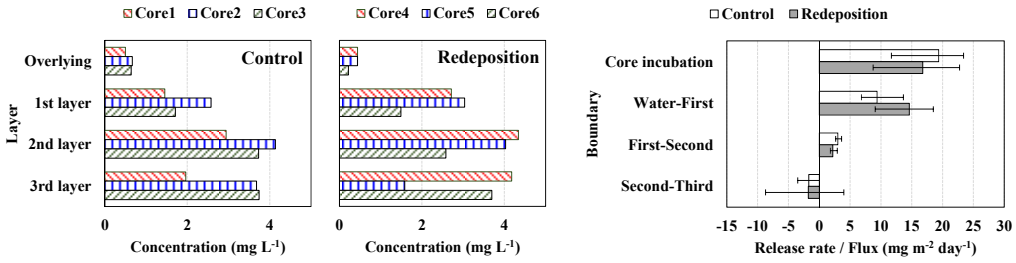
Contrary to the core incubation method, the release rate of the redeposition core by the mathematical modeling method was greater than that in the control core because of the higher concentration in the first layer of the redeposition core compared to the control core. On the other hand, the concentrations in the lower layer of the redeposition core were than the concentrations in the control core, resulting in a smaller diffusion flux in the redeposition core. The diffusion flux under the first layer was 1/2 for the control core and 1/6 for the redeposition core compared to the release rate, and the vertical concentration gradient of the redeposition core was larger than that of the control core. The release rates estimated by the mathematical modeling method were 1.1 times higher than those estimated by the core incubation method for the control core and 4.1 times higher for the redeposition core.



(**a**) (**b**)

Figure 6. Vertical distributions of (**a**) NH_4-N concentration of the pore water in control and redeposition cores and of the overlying water on November 15, and (**b**) release rates and diffusion fluxes of NH_4-N estimated by the mathematical modeling method and release rates in the latter half by the core incubation method. These are the average values of the control and redeposited cores, respectively. Error bars indicate maximum and minimum values.

Figure 7(a) shows the PO_4-P concentrations in the pore water of the control core and redeposition core, and Figure 7(b) shows the release rates and diffusion fluxes of PO_4-P estimated by the mathematical modeling method with the release rate in the latter half by the core incubation method. PO_4-P concentrations did not differ significantly between the control and redeposition cores, and reached a maximum in Layer 2 with the exception of Core 6. Therefore, the diffusion fluxes in the second-third boundary layer were downward. The release rate of the redeposition core by the mathematical modeling method was greater than that in the control core, similar that of NH_4-N. The vertical concentration gradient of the redeposition core was larger than that of NH_4-N, as the diffusion flux under the first layer was 1/3 for the control core and 1/7 for the redeposition core compared to the release rate. The release rates estimated by the mathematical modeling method were 0.5 times for the control core and 0.9 times for the redeposition core of that estimated by the core incubation method, and did not differ significantly between the mathematical modeling and the core incubation methods.



(**a**) (**b**)

Figure 7. Vertical distributions of (**a**) PO_4-P concentration of the pore water in the control and redeposition cores and of the overlying water on November 15, and (**b**) release rates and diffusion fluxes of PO_4-P estimated by the mathematical modeling method and release rates in the latter half by the core incubation as shown in Figure 6.

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4. Discussion

4.1. Oxygen Consumption Rate

Two possibilities for the large oxygen consumption rate by extrusion of pore water were verified for the control cores. The first is that pore water with a DO concentration of 0 mg L^{-1} is extruded, and then the DO concentration in the overlying water decrease: therefore, the oxygen consumption rate increases. This possibility was verified by the oxygen budget expressed as follows:

$$DO_0 + \Delta DO = \frac{VDO_0}{V + \Delta DO}, \quad (5)$$

where DO_0 is the initial DO concentration. ΔDO is the reduction in concentration in the overlying water and is based on the slope shown in Figure 3(a). ΔV is the volume increase of overlying water and is the volume of pore water extrusion required to change ΔDO. ΔV was 528~665 mL when Δ = 60 min. The pore water volume was approximately 1,649 mL (= $30A\varphi$). To reach the oxygen consumption obtained in the experiment, 30~40% of the pore water must be extruded in one hour. It is impossible to explain the magnitude of the oxygen consumption rate by this phenomenon alone.

The other is that reducing substances (Fe^{2+}, Mn^{2+}, and H_2S) in the pore water are extruded into the overlying water and combined with oxygen by the following reaction equation; therefore, oxygen consumption is accelerated.

$$\begin{gathered} 2Mn^{2+} + O_2 + 2H_2O \rightarrow 2MnO_2 + 4H^+ \\ 4Fe^{2+} + O_2 + 6H_2O \rightarrow 4FeOOH + 8H^+ \\ H_2S \rightarrow SO_4^{2-} + 2H^+ \end{gathered} \quad (6)$$

The concentrations of Fe^{2+}, Mn^{2+} and H_2S in the pore water of each core were Fe^{2+} = 0.1~1 mg L^{-1}, Mn^{2+} = 0.5~10 mg L^{-1} and H_2S = 20~60 mg L^{-1}. Therefore, the maximum oxygen consumption by Reaction 6 calculated for each core was 0.28~125.25 mg L^{-1}. On the other hand, the oxygen consumption per unit volume in overlying water is determined by the product of the oxygen consumption rate and the time to anoxia. Assuming that the difference between the experimental and general values of the oxygen consumption rate is due to the oxygen consumption of Reaction 6 in the overlying water, we estimated the volume of extruded pore water that could account for this difference. The volume was obtained for each core by dividing the oxygen consumption determined from the difference in oxygen consumption rates by the oxygen consumption due to Reaction 6. The results showed that the required volumes were 30~169 mL. The experimental values are achieved when approximately 2% of the pore water is extruded since oxygen consumption is high when the reducing substance concentration in the pore water is high. Even when the reducing substance concentrations are low, this is achieved when approximately 10% of the pore water is extruded. This is a possible value.

When this extrusion occurs, the apparent oxygen consumption rate increases. This increase was estimated to be 0.10~0.39 g m^{-2} day^{-1}. This oxygen consumption rate is up to 4% of the experimental results. Pore water extrusion due to settling of sediment was considered to occur in the early stages of the experiment and not affect the experiment, and subsequent analyses were performed.

4.2. Release Rates

The release rate from the redeposited sediments after exposure to an aerobic environment decreased to approximately 70% for NH_4-N and 60% for PO_4-P. The marine sediments containing N and P were suspended into the seawater by the tsunami, and it was estimated that TN and TP concentrations in seawater in the inner part of Osaka Bay might be exceed environmental standards [22]. In contrast, NH_4-N and PO_4-P concentrations in the redeposited sediments may be lower. For NH_4-N, it is possible that the NH_4-N concentration in the pore water did not recover for two reasons: the reduction reaction was less advanced than usual in the redeposited sediments, and the diffusion of high NH_4-N in the bottom layer took longer. It is difficult to verify these possibilities because it is difficult to measure the temporal variation in NH_4-N concentrations in the pore water, and information on the substances and bacteria associated with the oxidation and reduction reactions was

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not obtained in the experiment. When the sediment is oxidative, a thin oxide film is formed on the sediment surface by ferric hydroxide. It is possible that PO_4-P adsorbed on this ferric hydroxide and reduced the release rate [23]. As oxygen consumption advances in the sediment and becomes reductive, ferric hydroxide is reduced, the film dissipates, and then desorption and release of the adsorbed PO_4-P begins [16,18]. The precipitous increase in the release rate of PO_4-P in the latter half of the experiment may have been caused by this phenomenon. It has been reported that covering the bottom sediments of aquaculture farms suppressed nutrient release and red tide [24]. These results suggest that disturbance and redeposition of marine sediments by the tsunami may suppress primary production.

4.3. Comparison with Previous Release Rates

The release rates in Osaka Bay by the core incubation method were collected from the literature [14,25–29] listed in Table 1 to compare with the experimental results. It was noted that quantitative comparisons are difficult due to the wide range of estimated release rates, but it is meaningful to understand the values and trends [14,30]. They summarized the release rates for each bay in Japan in tables, but did not show specific months or sampling locations. Therefore, data for June to October at sampling locations with similar environments to the location in this study were extracted from the original study. In addition, new data have been added. The maximum value indicated in reference [27] was used in cases of unknown sampling location. DIN (dissolved inorganic nitrogen) was shown in the literature [26], but most of its forms were NH_4-N.

Table 1. List of literature showing release rates in Osaka Bay by the core incubation method.

References	Stations	Sampling Mounth & Year
Jyo [25]	Stn.18 & Stn.17	June, July, Aug. & Oct., 1978
Yamamoto *et. al.* [14]	M03	Oct., 1993 & June, 1994
Ministry of the Environment[26]	Unknown	Aug., 2000
Nishio & Shinya [27]	P0	Sept., 2008
Nakajim *et. al.* [28]	Stn.18	Jul. & Oct., 2012
Nakajim *et. al*. [29]	Stn.18	Jul. & Oct., 2013

Figure 8 shows the temporal change in the release rates of NH_4-N and PO_4-P. The release rates obtained in the experiment are considered reasonable compared to the historical values. The history of the biological production environment in Osaka Bay is described based on Figure 9. Eutrophication and large-scale red tides occurred in the Seto Inland Sea including Osaka Bay, with rapid economic growth until the early 1970s [13], and fishing rose with a time lag. Organic pollution loads from rivers were reduced to improve water quality. TN and TP concentrations and red tides in the sea decreased, but fishing also began to decline. Until this time, primary production was mainly supported by river-originating nutrients. TN and TP loads have also been targeted to reductions since 2001, and TN and TP concentrations in the sea were further reduced [31,32]. As a result, discoloration of the seaweed [33] and a further decrease in fishing were observed [34]. The Seto Inland Sea, excluding Osaka Bay, is considered to have become oligotrophic [35], and the load reduction from rivers was suspended in 2006. Fishing has also begun to decline in Osaka Bay, and the water quality policy has shifted from improvement to maintenance in 2022. Under these conditions, the release rate of NH_4-N has been decreasing since 2000, and the control core value is an extension of this trend. The release rate of PO_4-P appears to have remained low since 2008. The reduction in release rates, in addition to the load reduction from the river, led to lower TN and TP concentrations and fishing in Osaka Bay.

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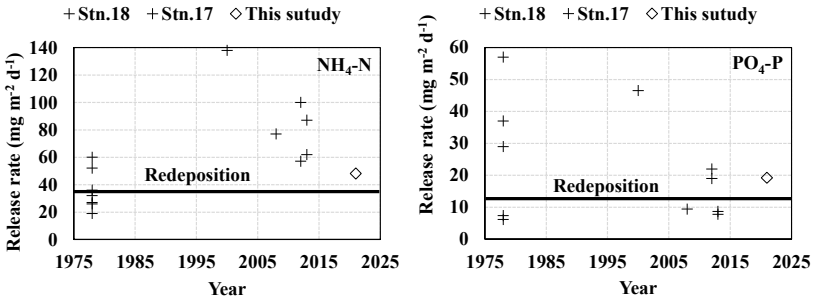

Figure 8. The temporal change in release rates of NH4-N and PO4-P collected from the literature is shown in Table 1 and from the experiment. The release rate from the redeposited sediment is shown by a line.

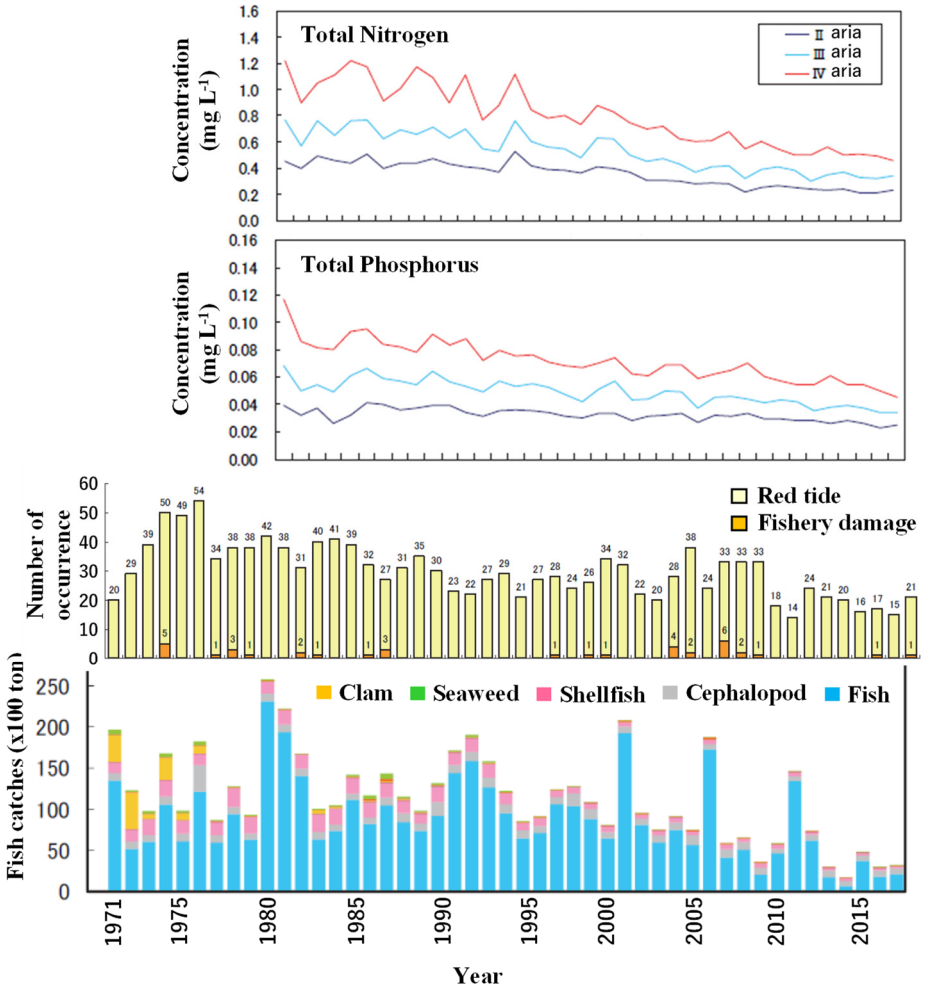

Figure 9. Time series of TN and TP concentrations in seawater, the number of red tide and fishery damages caused by red tide, and fish catches in each species in Osaka Bay, combined figures from the references. Target concentrations of TN and TP in the sea are set for each area type II, III, and IV. In Osaka Bay, Type IV is near the shoreline in the inner part of the bay, and Type II is in the western half of the bay at depths of 20 m (see Figure 1) or greater generally.

The release rate of NH_4-N in the redeposition core was as low as before the increase in fish catches in the 1980s in Osaka Bay, and the release rate of PO_4-P was near the lowest level. The primary production of Osaka Bay is limited by phosphorus, as the TN/TP molar ratio in seawater calculated

from Figure 9 is 20 or more, which is higher than the Redfield ratio of 16. The release rates of the redeposition cores are values experienced in the inner part of Osaka Bay in the past. However, under the current situation where the contribution of release for nutrients in seawater is significant [13], the reduction in the release rate of PO_4-P by tsunamis may be more limiting for primary production.

On the other hand, the release rate of NH_4-N in the redeposition core could be achieved if the current decreasing trend continues, which could be a reality even without a tsunami. The N/P ratio in Osaka Bay decreased, and primary production from spring to summer in the western part of Osaka Bay decreased due to the depletion of DIN, and higher biological production also decreased [36]. If the release rate of NH_4-N decreases, the limiting factor of primary production may change from phosphorus to nitrogen even in the inner part of Osaka Bay, and the tsunami could bring about this change. The supply ratios of DIN required for seaweed culture in Osaka Bay and Harima-nada on the western side of Osaka Bay (see Figure 1) were presented for each source, classified into load from rivers, seawater exchange with adjacent bay, and release from marine sediments [37]. In Osaka Bay, the release accounted for 30% (17 tonN day^{-1}), and in the northern Harima-nada and Kii Channel, the seawater exchange accounted for 48% (32 tonN day^{-1}) and 59% (34 tonN day^{-1}), respectively. Assuming that the supply of DIN through seawater exchange to the northern Harima-nada and Kii Channel comes from Osaka Bay, where DIN concentrations are high, DIN release in Osaka Bay accounts for slightly less than 20% (10 tonN day^{-1}) of the supply ratio in the northern Harima-nada and Kii Channel. In fact, nutrient release from the sediments to seawater in Osaka Bay and Harima-nada had a significant effect on nutrient concentrations in seawater [13]. Osaka Bay is a source of nutrient supply to the surrounding seas, and a decrease in the release rate due to the tsunami has the potential to also affect the primary production in these seas.

5. Conclusions

The nutrient release from the marine sediments in Osaka Bay has a significant impact on the nutrient concentrations in seawater. Tsunami induced by the Nankai Trough earthquake may have disturbed marine sediments in the inner part of Osaka Bay. An incubation experiment to estimate the release rates of NH_4-N and PO_4-P was conducted to understand the present conditions and to quantify the changes due to tsunamis. Two types of cores were created: a "control core" representing the current sediment and a "redeposition core" representing the redeposition after the tsunami. The release rates have been decreasing since the year 2000 and have remained low. The experimental results suggest that the release rate after exposure to an aerobic environment by tsunamis may decrease to approximately 70% for NH_4-N and 60% for PO_4-P of the current level. The release rates are values experienced in the inner part of Osaka Bay in the past. However, the reduction in the release rate by tsunamis may be more limiting for primary production under the current situation where the contribution of release for nutrients in seawater is significant. It is necessary to understand variations in release rates over longer time periods to quantify the effects of tsunamis.

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