Nutrient fluxes from rivers, groundwater, and the ocean into the coastal embayment along the Sanriku ria coast, Japan

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Abstract

External nutrient supply from the land and ocean is crucial for sustaining high primary productivity in coastal seas. Submarine groundwater discharge (SGD) is recognized as one of the most important sources of terrestrial nutrients. However, the relative importance of SGD-derived nutrients from different sources in coastal ecosystems controlled by offshore exchange has not been well quantified. Here, we assessed water and nutrient fluxes in the semi-enclosed bay along the Sanriku ria coast, where the intrusion of nutrient-enriched oceanic water is substantial. We conducted seasonal sampling campaigns and monitored the groundwater level throughout the year. Water and nutrient fluxes from fresh groundwater, saline groundwater, river water, and oceanic water were estimated using a hydrological method and radium (Ra) mass balance model. The results indicated that oceanic water was a dominant source, accounting for 99.5%, 86%, 97%, and 84% of the total flux of water, dissolved inorganic nitrogen, dissolved inorganic phosphorus, and dissolved silica, respectively. Although the mean fluxes of land-derived nutrients were small, the contribution increased to 28–59% in October, when nutrient fluxes of oceanic water weakened. Of the terrestrial sources, SGD dominated (41–94%), particularly saline SGD (>99% of total SGD). We concluded that an efficient supply of the primary limiting nutrient from land to the coastal ecosystem can accelerate coastal primary production during certain seasons, even if oceanic nutrients are typically the dominant source.

Coastal seas are among the most productive regions of the Earth’s biosphere, wherein land and ocean physical and biogeochemical processes interact (Jickells 1998). The external supply of nutrients is essential for sustaining the high primary productivity of coastal seas. Offshore seawater serves as a significant nutrient source in coastal seas (Kobayashi and Fujiwara 2008; Sugimoto et al. 2016). The magnitude and timing of oceanic nutrient flux are greatly influenced by physical processes, such as the movement of ocean current paths (e.g., Yoder et al. 1981; Sugimoto et al. 2009), wind intensity (e.g., Graham and Largier 1997; Carstensen and Conley 2004), and river discharge (e.g., Schubel and Pritchard 1986; Watanabe et al. 2017). Nutrient inputs from land via rivers and groundwater can also fertilize coastal ecosystems (Valiela et al. 1990). The importance of river inputs is well established; however, two decades of research on groundwater discharge into coastal seas have also highlighted the importance of groundwater-derived nutrients as an essential flux into coastal ecosystems (Taniguchi et al. 2019; Santos et al. 2021).

Submarine groundwater discharge (SGD) refers to flow out of an aquifer across the seafloor (Moore 1996). SGD includes the discharge of meteoric fresh groundwater (fresh SGD) and recirculated saline groundwater (saline SGD) (Taniguchi et al. 2002). Fresh SGD supplies nutrients to coastal systems, and the fluxes and compositions of nutrients derived from fresh SGD are controlled by hydrologic conditions and anthropogenic perturbations (e.g., Knee et al. 2010; Cho et al. 2019). Saline SGD transports large amounts of recycled nutrients within sediments into the overlying water column (Santos et al. 2008). The nutrient flux of saline SGD is usually comparable with or higher than that of fresh SGD (e.g., Santos et al. 2009b; Rodellas et al. 2018).

The Sanriku ria coast is located in northeastern Japan and is characterized by numerous flooded valleys and a narrow shelf (Fig. 1a). In this region, coastal currents, such as the Tsugaru Warm Current and Oyashio Current, affect the physical and biogeochemical environment of the coastal...
embayment (e.g., Fukuda et al. 2016; Ishizu et al. 2017). Notably, the Oyashio Current supplies large amounts of offshore nutrients to the coastal embayment (e.g., Furuya et al. 1993; Sawada and Hayakawa 1997). In addition, the ria coast is a hot spot of SGD (Cherkauer and McKereghan 1991). Recent studies along the Sanriku ria coast have demonstrated that SGD enhances the biological production of local coasts (Fujita et al. 2019; Yamane et al. 2019). Many burrows of benthic animals in the seafloor can be found along the inner part of the Sanriku coast (Masuda et al. 2016), and intermittent discharge of saline SGD from some of these burrows has been reported (Fig. 1e). However, SGD-derived nutrient flux and its component fractions (fresh SGD and saline SGD) have not yet been assessed in a system controlled by offshore exchange.

Radioisotopes such as radium (Ra) and radon (Rn) are useful for quantifying SGD flux (Swarzenski et al. 2007; Rodellas et al. 2017). Because half-lives differ among Ra isotypes, ranging from several days to over 1000 years ($^{223}\text{Ra} = 11.4$ d,
Materials and methods

Study area

Moune Bay is located in the inner region of Kesennuma Bay along the Sanriku ria coast (Fig. 1). The bay is a semi-enclosed embayment; it is 200–400 m wide, 800 m long, and has a maximum depth of 25 m at the bay mouth. Water exchange between Moune Bay and Kesennuma Bay occurs through the narrow bay mouth. The mean tidal range is approximately 1 m.

The Higashi-Moune and Nishi-Moune Rivers flow into the bay head; their combined watershed accounts for 92% of the entire watershed of Moune Bay. The land use of the watershed is primarily forest (96%); abandoned agricultural land and residential areas account for the remaining 4%. Annual precipitation is approximately 1360 mm at Station (Stn) K (Fig. 1b) and varies seasonally, with a summer high (∼40% of the total; June to August) and winter low (∼10%; December to February).

Sampling

We conducted five field surveys in June, August, and October 2018, and January and March 2019, at nine stations within Moune Bay and one station outside of the bay (Fig. 1c). Because diurnal variation in $^{222}$Rn activity was significantly lower at neap tide (14.9–32.0 dpm L$^{-1}$) than at spring tide (12.1–223.2 dpm L$^{-1}$, with a tidal range of 1.2 m) (T. Nakajima, unpubl.), all samplings were conducted during neap tide to minimize differences in the effect of SGD according to sampling time. Temperature, salinity, and dissolved oxygen (DO) concentration were measured vertically from the surface to the bottom using a conductivity-temperature-depth (CTD) profiler (RINKO-Profiler ASTM102 or AAQ117; JFE Advantech Co., Ltd., Hyogo, Japan). Surface seawater (~0.5 m depth from the surface) was collected for Ra isotopes and nutrients using a submerged bilge pump. The bottom seawater was pumped from 1 m above the seafloor at Stns 5, 6, 9, and KB. Seawater samples for Ra isotopes (60–71 L) were filtered through a MnO$_2$-impregnated acrylic fiber (Mn-fiber) at a flow rate of <1 L min$^{-1}$. The Mn-fiber was rinsed carefully using Ra-free seawater until all particles flowed out. Nutrient samples were immediately filtered through syringe filters (celloose-acetate membrane, 0.8-µm pore size; Advantec, Tokyo, Japan) and stored at −25°C until analysis.

River water samples for Ra isotopes and nutrients were collected from the Nishi-Moune River (Stn RW1) and Higashi-Moune River (Stn RW2) at each sampling time. We filtered 120–130 L of river water through the Mn-fiber. In addition, water velocity was measured using a current meter (VR–301; Kenek, Tokyo, Japan) at Stns RW1 and RW2 to estimate river discharge.

Fresh groundwater (90–120 L) was collected from a shallow well (FGW2), and from cracks of a riverine revetment at different sites (FGW1, 3, and 4). To collect groundwater samples (19–22 L), a hole was dug using a hand auger at the tidal flat of the bay head, where many benthos burrows were observed (Fig. 1d). Shallow groundwater was purged using a peristaltic pump until it replaced new groundwater, and was then collected. Samples for Ra isotopes and nutrients were filtered through the Mn-fiber and syringe filters, respectively.

We monitored the GL, temperature, and conductivity of the well at Stn FGW2 (Fig. 1c) from June 2018 using the CTD-DIVER instrument (DIK-603C-C1; Daiki Rika Kogyo Co., Ltd., Saitama, Japan). The GL was calibrated to the height based on the mean seawater level (SL) of Tokyo Bay (Tokyo Peil: T.P.) using an atmospheric pressure meter (DIK-615-E1; Daiki Rika Kogyo Co., Ltd.), and the daily SL at Stn O (Fig. 1b) monitored by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Daily precipitation at Stn K was obtained from the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency.

Chemical analysis

Nitrate (NO$_3^-$) + nitrite (NO$_2^-$), phosphate (PO$_4^{3-}$), and silicate (SiO$_2$) concentrations were measured using an autoanalyzer (QuAatro 2-HR; Bran-Luebbe, Norderstedt, Germany). We measured certified reference materials under ISO Guide 34 (JIS Q 0034) (KANSO-CRM; KANSO Co., Ltd., Tokyo, Japan) to calibrate the accuracy. Analytical precision was less than 3.0%. The NH$_4^+$ concentration was measured fluorometrically using the orthophthalaldialdehyde (OPA) method (Holmes et al. 1999) with a Trilogy fluorometer (Turner Designs, Sunnyvale, CA). We defined dissolved inorganic nitrogen (N) as the sum of NO$_3^-$ + NO$_2^-$ and NH$_4^+$, dissolved inorganic phosphorus (P) as PO$_4^{3-}$, and dissolved silica (Si) as SiO$_2$.

The activities of $^{223}$Ra and $^{224}$Ra in the Mn-fibers were analyzed using a radium delayed coincidence counter (RaDeCC) (Moore and Arnold 1996) within 1 week of the sampling date. We measured $^{228}$Th and $^{227}$Ac in the Mn-fibers after 4 weeks and 2 months. In this study, $^{223}$Ra and $^{224}$Ra represent the
excess activities of $^{223}$Ra and $^{224}$Ra, respectively. In the estimates of saline SGD flux, we used $^{224}$Ra in Ra mass balance model because $^{223}$Ra activity might have larger analytical uncertainty (Diego-Feliu et al. 2020). After a sufficient amount of time (>1 yr) had elapsed to produce $^{228}$Th distinguishable from $^{228}$Ra decay, we measured $^{228}$Th and estimated the initial $^{228}$Ra activity ($^{228}$Ra$_i$) according to the following equation (Moore 2008):

$$^{228}\text{Ra}_i = \frac{^{228}\text{Th}_m - \text{exp}\left(-\lambda\text{Th}t\right)}{1.499\exp\left(-\lambda\text{Ra}t\right) - \left(-\lambda\text{Th}t\right)}$$ (1)

where $^{228}$Ra$_i$ and $^{228}$Th$_m$ are the initial activities of $^{228}$Ra and $^{228}$Th, respectively, in the sample, $^{228}$Th$_m$ is the measured $^{228}$Th activity after $t$ days, and $\lambda$$_{\text{Ra}}$ and $\lambda$$_{\text{Th}}$ are the decay constants of $^{228}$Ra (0.999 $\times$ 10$^{-3}$ d$^{-1}$) and $^{228}$Th (0.33 $\times$ 10$^{-3}$ d$^{-1}$), respectively. $^{228}$Th$_m$ corresponds to the $^{228}$Th activity measured after 4 weeks of sampling date.

**Experiments for Ra supply via diffusion and desorption**

To estimate diffusive Ra flux from the sediment, we collected sediment samples at two sites (Fig. 1c) in June 2018 using an Ekman dredge and a shovel. The sediment samples were placed into containers that were then filled with Ra-free seawater. After incubation (>60 d), the overlying water was filtered through the Mn-fiber, and the activities of $^{224}$Ra were analyzed using the RaDeCC. The diffusive flux ($F_{\text{diff}}$) of $^{224}$Ra was calculated following the method of Beck et al. (2007). For the incubation experiment, the inventory of Ra at time $t$ (It; dpm) was given by the following equation:

$$It = \left[\frac{F_{\text{diff}} \times \text{A}_{\text{incubation}}}{\lambda}\right] \left(1 - e^{-\lambda t}\right)$$ (2)

where $F_{\text{diff}}$ is the diffusive flux (dpm m$^{-2}$ d$^{-1}$), A$_{\text{incubation}}$ is the surface area of the incubation container (m$^2$), and $\lambda$ is the decay constant of $^{224}$Ra ($= 0.189$ d$^{-1}$).

To measure the desorption rates of $^{224}$Ra from river particles, we added salt to a barrel filled with fresh river water (130 L) to reach a salinity of ~33. After more than 12 h, we filtered the salted river water through the Mn-fiber and then measured the activities of $^{224}$Ra. The difference in Ra activity between the non-treated sample (i.e., dissolved $^{224}$Ra) and the salted sample (i.e., total $^{224}$Ra) was assumed to be due to desorption from riverine particles.

**Quantification of fresh SGD rate**

To quantify the flux of fresh SGD from the alluvial plain to Moune Bay, we applied Darcy’s law as follows (Taniguchi and Iwakawa 2004; Santos et al. 2009a):

$$Q_{\text{FGD}} = -k \times dh/dl \times A,$$ (3)

where $Q_{\text{FGD}}$ is the fresh SGD flux (m$^3$ d$^{-1}$), $k$ (cm s$^{-1}$) is the hydraulic conductivity, dh/dl is the hydraulic gradient (dimensionless), and $A$ is the area (m$^2$) through which groundwater passes. Because the aquifer of the unconfined groundwater is composed of silty sand mixed with gravel (Fig. S1), we used $k = 0.5 \times 10^{-2}$ cm s$^{-1}$ (Freeze and Cherry 1979). The dh is the difference between the GL of the well at Stn FGW2 and the SL near the tidal flat in Moune Bay, while dl is the distance from the location of SL to the well (71 m). To calculate $A$, we multiplied the depth (3–5 m) of the unconfined groundwater aquifer by the width (124 m) of the alluvial plain based on the boring-core data (Fig. S1).

**Quantification of offshore seawater inflows**

Under steady-state conditions, the inflow of offshore seawater ($Q_{\text{KB}}$) from Kesennuma Bay to Moune Bay (Fig. 2a) was expressed as follows:

$$Q_{\text{KB}} = Q_{\text{MB}} - Q_{\text{RW}} - Q_{\text{FGD}},$$ (4)

where $Q_{\text{MB}}$ is the outflow of Moune Bay water. This value can be calculated as the seawater exchange rate by dividing the volume of Moune Bay ($V = 2.1 \times 10^6$ m$^3$) by the mean residence time ($\tau$) in Moune Bay water.

We took Ra age to be $\tau$, as this value is the time elapsed since entering groundwater (with a constant ratio of Ra isotopes entering the water column) and shows good agreement with water residence time (e.g., Moore et al. 2006). Here, we used the activity ratio (AR) of $^{224}$Ra to $^{228}$Ra, following the method of Moore et al. (2006):

$$\tau_{\text{Ra}} = (\text{AR}_{\text{gw}} - \text{AR}_{\text{SW}})/\text{AR}_{\text{SW}}\lambda_{224},$$ (5)

where $\text{AR}_{\text{gw}}$ is the AR of $^{224}$Ra to $^{228}$Ra ($^{224}$Ra/$^{228}$Ra) in groundwater, $\text{AR}_{\text{SW}}$ is the mean $^{224}$Ra/$^{228}$Ra in Moune Bay water, and $\lambda_{224}$ (0.189 d$^{-1}$) is the decay constant of $^{224}$Ra. To obtain the most conservative estimates of $\tau_{\text{Ra}}$ and $Q_{\text{MB}}$ (Eq. 4), we used the maximum AR in groundwater as an endmember. This model assumes that Ra supply through the sediment occurs continuously over a wide area.

**Quantification of saline SGD rates**

We constructed a mass balance model for $^{224}$Ra under steady-state conditions to quantify saline SGD flux ($Q_{\text{SGD}}$) to Moune Bay (Fig. 2b), because Ra isotopes are especially enriched in brackish and saline groundwater (e.g., Nakajima et al. 2018). Therefore, our estimate of $Q_{\text{SGD}}$ represents the flux of brackish and saline groundwater, excluding fresh groundwater. Radium is supplied from river water, fresh groundwater, saline groundwater, and offshore seawater, as well as through diffusion from sediment and desorption from riverine particles. Radium is lost by advection to offshore and radioactive decay. Thus, we solved for $Q_{\text{SGD}}$ as follows:

$$Q_{\text{SGD}} = \left[\left((Q_{\text{MB}}\text{Ra}_{\text{MB}} + \text{Ra}_{\text{MB}}V_{\text{A}}) \right)\right.$$ (6)

$$\left.-\left((Q_{\text{RW}}\text{Ra}_{\text{RW}} + Q_{\text{RW}}\text{Ra}_{\text{des}} + Q_{\text{FGD}}\text{Ra}_{\text{FGW}} + Q_{\text{KB}}\text{Ra}_{\text{KB}} + F_{\text{diff}})\right)\right]/(\text{Ra}_{\text{GW}} - \text{Ra}_{\text{MB}}),$$
where $Q_{RW}$, $Q_{FSGD}$, and $Q_{KB}$ are the variables from Eqs. 3 and 4, $Q_{MB}$ is the flux of Moune Bay water to the offshore area. $Ra_{RW}$, $Ra_{des}$, $Ra_{FGW}$, $Ra_{SGW}$, and $Ra_{KB}$ are the $^{224}$Ra activity of river water, desorption from riverine particles, fresh groundwater, saline groundwater, and offshore seawater (Stn KB), respectively. $Ra_{MB}$ is the mean activity of $^{224}$Ra in Moune Bay. $F_{diff}$ denotes diffusive inputs of $^{224}$Ra from the sediment. We calculated $F_{diff}$ by multiplying the mean diffusive flux of $^{224}$Ra by the area of Moune Bay ($1.6 \times 10^5$ m$^2$). Decay loss ($Ra_{MB}V\lambda$) of $^{224}$Ra was calculated by multiplying the $Ra_{MB}$ volume of Moune Bay ($2.1 \times 10^6$ m$^3$), and decay constant ($\lambda = 0.189$ d$^{-1}$).

To accurately estimate $Ra_{MB}$ and $Ra_{KB}$ at the study site under stratified conditions (Rodellas et al. 2021), we determined the pycnocline depth ($z_{pyc}$) at each sampling station, using vertical density data to calculate the square of the Brunt Väisälä frequency ($N^2$) as a measure of buoyancy frequency or stratification strength for every depth $z_i$ (Murphy et al. 2011):

$$N^2(z_i) = (g/\rho_i) \times (\partial \rho/\partial z)$$

where $g$ is the gravitational constant, $\rho_i$ is the density (kg m$^{-3}$) at depth $z_i$, and $\partial \rho/\partial z$ is the density gradient at 1-m depth intervals. We determined the maximum $N^2$ as a pycnocline depth in Moune Bay and Stn KB. Based on the determined pycnocline depth of Moune Bay, we calculated $Ra_{MB}$ as a volume-weighted mean as follows:

$$Ra_{MB} = \frac{Ra_s \times V_{upper} + Ra_b \times (V - V_{upper})}{V}$$

where $Ra_s$ and $Ra_b$ are the mean Ra activities of surface and bottom seawater, respectively, and $V_{upper}$ is the volume above the pycnocline depth (m$^3$). Similarly, $Ra_{KB}$ was calculated as follows:

$$Ra_{KB} = \frac{Ra_s \times z_{pyc} + Ra_b \times (z - z_{pyc})}{z}$$

where $z_{pyc}$ is the pycnocline depth at Stn KB (m), and $z$ is the depth at Stn KB (=25 m).

**Quantification of nutrient fluxes**

Nutrient fluxes through river water, fresh groundwater, offshore seawater, and Moune Bay water were calculated by multiplying $Q_{RW}$, $Q_{FSGD}$, $Q_{KB}$, and $Q_{MB}$ by the mean concentration, respectively. Mean nutrient concentrations in Moune Bay and Stn KB were calculated using Eqs. 8 and 9, respectively. To estimate saline SGD-derived nutrient fluxes, we multiplied $Q_{SSGD}$ by mean concentration in saline groundwater (salinity > 15) subtracting mean seawater concentration, because net nutrient fluxes derived from saline SGD represent the difference between nutrient flux from saline groundwater and that from coastal seawater (Santos et al. 2008).

**Results**

**Characteristics of seawater in Moune Bay**

The mean temperature of the surface and bottom waters varied seasonally, with higher values in August (>20°C) and lower values in March (<10°C) (Fig. 3a). The difference in mean temperature between the surface and bottom waters was largest in June. The mean salinity of the surface and bottom waters was lower than 33 in summer (June and August) and higher than 33 in winter (October to March) (Fig. 3b). In August, the salinity of the surface water rapidly decreased to less than 30 due to the heavy rain that occurred prior to the sampling date. Although the mean DO concentrations were
higher than 6 mg L\(^{-1}\), the values exhibited seasonal variation, with lower DO in August and October (Fig. 3c).

The mean dissolved inorganic N concentrations of the surface and bottom waters were 1.4–4.3 and 4.5–5.5 μmol L\(^{-1}\), respectively (Fig. 3d). The dissolved inorganic P concentration of the surface layer was lower than 0.2 μmol L\(^{-1}\) from June to October and higher than 0.2 μmol L\(^{-1}\) in January and March (Fig. 3e). In the bottom layer, the mean dissolved inorganic P concentration increased between August (0.1 ± 0.1 μmol L\(^{-1}\)) and March (0.6 ± 0.2 μmol L\(^{-1}\)). In contrast to dissolved inorganic P, the dissolved Si concentrations of the surface and bottom layers were higher in summer (June and August) and lower in winter (October to March) (Fig. 3f).

Activities of \(^{223}\)Ra, \(^{224}\)Ra, and \(^{228}\)Ra in the surface and bottom waters were higher in June than in January (Fig. 3g–i); the concentrations of these isotopes were also significantly correlated \((r > 0.83, p < 0.001)\), regardless of season.

**Characteristics of river water**

\(^{223}\)Ra activity at Stns RW1 and RW2 ranged from 0.1 to 1.0 dpm 100 L\(^{-1}\) and 0.0 to 0.4 dpm 100 L\(^{-1}\), respectively (Table S1). \(^{224}\)Ra activity at Stns RW1 and RW2 ranged from 2.6 to 6.7 dpm 100 L\(^{-1}\) and 3.6 to 12 dpm 100 L\(^{-1}\), respectively. \(^{228}\)Ra activity at Stns RW1 and RW2 ranged from 3.2 to 4.9 dpm 100 L\(^{-1}\) and from 3.5 to 10 dpml 100 L\(^{-1}\), respectively. The concentrations of dissolved inorganic N, dissolved inorganic P, and dissolved Si at RW1 were 3.0–6.2, 0.1–0.2, and 77.5–261.4 μmol L\(^{-1}\), respectively (Table S1), while the concentrations at RW2 were 24.8–37.5, 0.2–0.5, and 114.5–303.4 μmol L\(^{-1}\), respectively. Dissolved inorganic N and dissolved inorganic P concentrations at RW2 were significantly higher than those at RW1 \((p < 0.05)\).

Hereafter, we present riverine fluxes of water and nutrients as the sum of the values from the two rivers. Water fluxes \((Q_{\text{RW}})\) varied from 1200 to 7600 m\(^3\) d\(^{-1}\), with a mean of 4600 m\(^3\) d\(^{-1}\) (Fig. 4a). These fluxes were highest in October and lowest in January. The mean fluxes of \(^{224}\)Ra were \(370 \times 10^3\) dpm d\(^{-1}\) (range: 48 \(\times 10^3\)–710 \(\times 10^3\) dpm d\(^{-1}\)). The mean fluxes of \(^{223}\)Ra desorbed from riverine particles were 63 \(\times 10^3\) dpm d\(^{-1}\). The fluxes of dissolved inorganic N, dissolved inorganic P, and dissolved Si were 100, 1.4, and 1100 mol d\(^{-1}\), respectively (Fig. 4b–d). Temporal variations of nutrient fluxes were determined by \(Q_{\text{RW}}\) \((r > 0.93, p < 0.02)\).

**Characteristics of meteoric fresh groundwater**

The groundwater at Stn FGW2 exhibited a constant water temperature (~13.4°C) and conductivity (<0.3 mS cm\(^{-1}\)) throughout the year. The daily mean GL showed seasonal trends, with decreases from early summer to early spring, followed by increases into summer (Fig. 5). GL increased rapidly after heavy precipitation (>20 mm d\(^{-1}\)). The GL was higher than the mean SL over time, although SL showed seasonal variation, with higher values from summer to autumn.
and lower values from winter to spring. This result indicates that fresh groundwater continuously flowed toward the bay from the watershed. The temporal variation in daily mean fresh SGD rate \(Q_{\text{SGD}}\), estimated by Eq. 3, varied from 5.5 cm d\(^{-1}\) in early summer (June to July) to 3.0 cm d\(^{-1}\) in winter (Fig. 5c). Consequently, the total flux of fresh SGD \(Q_{\text{SGD}}\) into Moune Bay on each sampling date was estimated to be 15–22 m\(^3\) d\(^{-1}\), with a mean of 17 m\(^3\) d\(^{-1}\) (Fig. 4e).

The activities of \(^{223}\)Ra, \(^{224}\)Ra, and \(^{228}\)Ra of fresh groundwater were 0.0–0.4 dpm 100 L\(^{-1}\), with a mean of 0.2 ± 0.2 dpm 100 L\(^{-1}\), 3.8–8.4 dpm 100 L\(^{-1}\) with a mean of 6.0 ± 2.0 dpm 100 L\(^{-1}\), and 3.0–6.3 dpm 100 L\(^{-1}\) with a mean of 5.2 ± 1.3 dpm 100 L\(^{-1}\), respectively (Table S2). The fluxes of \(^{224}\)Ra varied from 890 to 1300 dpm d\(^{-1}\) with a mean of 1000 dpm d\(^{-1}\). The mean concentrations of dissolved inorganic N, dissolved inorganic P, and dissolved Si were 38.6, 0.4, and 252.1 μmol L\(^{-1}\), respectively (Table S2). The mean fluxes of dissolved inorganic N, dissolved inorganic P, and dissolved Si were estimated to be 0.7, 0.01, and 4.3 mol d\(^{-1}\), respectively (Fig. 4f–h).

Characteristics of offshore seawater

Although the temperatures of surface- and bottom offshore waters at Stn KB were slightly lower than within Moune Bay, the seasonal variation was similar to that within the bay (Fig. 3a). The salinity of surface and bottom waters increased from <33 in summer (June and August) to >33.2 in autumn and winter (October and January), and slightly decreased to approximately 33 in spring (March). Figure 6 presents a temperature-salinity diagram of offshore seawater with various potential water sources: brackish water (BR), surface water at the Sanriku coast (SW), Tsugaru Warm Current water (TWC), and Oyashio Current water (OY) (Hanawa and Mitsudera 1986; Ishizu et al. 2017). Lower-salinity waters during the summer season can be explained by the major and modest contributions of BR and SW, respectively, while the higher salinity waters from autumn to winter were due to TWC. The colder seawater (<10°C) in early spring indicated a substantial contribution from OY.

The activities of \(^{223}\)Ra, \(^{224}\)Ra, and \(^{228}\)Ra in the surface waters at Stn KB were 0.1–0.9 dpm 100 L\(^{-1}\), 1.2–22 dpm
inorganic N, dissolved inorganic P, and dissolved Si were 55 × 10^2, 350, and 130 × 10^2 mol d⁻¹, respectively (Fig. 4j–l). Temporal variation in the nutrient fluxes primarily depended on Q_{KB} (r > 0.93, p ≤ 0.02).

**Characteristics of recirculated saline groundwater**

Salinity in groundwater collected from the tidal flat ranged from 15.8 to 27.9 (Table S2). Lower salinity indicates a mixture of meteoric groundwater and seawater. The activities of 223Ra, 224Ra, and 228Ra were 9.9–34 dpm 100 L⁻¹ (mean = 25 ± 9.5 dpm 100 L⁻¹), 430–1100 dpm 100 L⁻¹ (mean = 780 ± 260 dpm 100 L⁻¹), and 200–740 dpm 100 L⁻¹ (mean = 510 ± 190 dpm 100 L⁻¹), respectively (Table S2). The activities of the isotopes were significantly linearly related (r = 0.89, p < 0.04), except for 222Ra and 228Ra (r = 0.82, p = 0.09). The mean concentrations of dissolved inorganic N, dissolved inorganic P, and dissolved Si in groundwater were 39.7 ± 25.4, 0.6 ± 0.3, and 89.6 ± 18.3 μmol L⁻¹, respectively (Table S2). The coefficient of variation (CV) was higher than 48% for dissolved inorganic N and dissolved inorganic P, but lower for dissolved Si (20%). These concentrations did not exhibit significant relationships with salinity or Ra activity. Notably, dissolved inorganic N and dissolved inorganic P concentrations were considerably higher than the theoretical concentration under mixing with meteoric fresh groundwater and Moune Bay seawater (Fig. S2).

To quantify saline SGD flux (Q_{SSGD}), we calculated the mass balance of 224Ra using Eq. 6, with the F_{diff} of 224Ra (90 dpm m⁻² d⁻¹) determined by the incubation experiment. The Q_{SSGD} calculated by 224Ra was calculated as 41 × 10^3 m³ d⁻¹ in June, 23 × 10^3 m³ d⁻¹ in August, and 18 × 10^3 m³ d⁻¹ in October.
5.2 × 10^3 m^3 d^{-1} in January, and 26 × 10^3 m^3 d^{-1} in March (Fig. 4m and Table S4). These fluxes were one to three orders of magnitude higher than those of Q_{RW} and Q_{SGD}.

The mean fluxes of dissolved inorganic N, dissolved inorganic P, and dissolved Si derived from saline SGD were 7.9 × 10^2, 8.1, and 15 × 10^2 mol d^{-1}, respectively (Fig. 4n-p). The temporal variation in dissolved inorganic N flux was significantly correlated with that in Q_{SSGD} (r = 0.99, p < 0.001). Dissolved inorganic P flux was greatest in June and decreased from June to January. Dissolved Si flux was greater in June, August, and March than in the other months.

**Budgets of Ra and nutrients**

The budgets and fractions of the ^{224}Ra mass balance models are shown in Table S4. The primary Ra sources were saline SGD and offshore seawater. The fluxes of ^{224}Ra derived from saline SGD accounted for 47.1% of all influxes, while those from offshore seawater accounted for 48.8%. The diffusive flux (F_{diff}) of ^{224}Ra accounted for 4.0%, while the river, fresh SGD, and desorption from river particles were only minor sources (≤0.3%). In terms of Ra loss, the eflux of Moune Bay water to offshore seawater accounted for 73.8% of the total ^{224}Ra eflux, respectively. The decay losses of ^{224}Ra were 26.2%, respectively.

The nutrient fluxes from offshore seawater were one to four orders of magnitude higher than those from other sources (Fig. 7 and Table 1). The mean nutrient contributions of the dissolved inorganic N, dissolved inorganic P, and dissolved Si fluxes of offshore seawater reached 86%, 97%, and 84%, respectively. These results demonstrate that offshore seawater

![Fig 7. Comparison of (a) dissolved inorganic nitrogen, dissolved inorganic phosphorus, and dissolved silica fluxes and (b) their fractions derived from river discharge (riverine), fresh submarine groundwater discharge (fresh SGD), recirculated submarine groundwater discharge (saline SGD), and the inflow of offshore seawater (oceanic). White circles and red triangles represent the values obtained at each sampling time and the mean values of all sampling times, respectively.](image-url)
| Table 1. Summary of nutrient inflows and outflows to Kesennuma Bay including riverine flux, fresh SGD, saline SGD, and oceanic inflow. |
|---------------------------------------------|
| **June** | **September** | **October** | **January** | **March** | **Mean** |
| **Flux (mol d\(^{-1}\))** | **Fraction (%)** | **Flux (mol d\(^{-1}\))** | **Fraction (%)** | **Flux (mol d\(^{-1}\))** | **Fraction (%)** | **Flux (mol d\(^{-1}\))** | **Fraction (%)** |
| **Dissolved inorganic nitrogen (N)** | | | | | | | |
| Input | | | | | | | |
| Riverine | 97 | 0.6 | 140 | 2.0 | 150 | 11.8 | 21 | 1.3 | 100 | 1.9 | 100 | 1.6 |
| Fresh SGD | 0.9 | <0.1 | 0.6 | <0.1 | 0.6 | <0.1 | 0.6 | <0.1 | 0.6 | <0.1 | 0.7 | <0.1 |
| Saline SGD | 1400 | 8.9 | 790 | 11.0 | 620 | 47.3 | 180 | 11.4 | 930 | 17.6 | 790 | 12.5 |
| Oceanic | 15,000 | 90.5 | 6300 | 87.1 | 530 | 40.9 | 1400 | 87.3 | 4300 | 80.5 | 5500 | 85.9 |
| Output | 8600 | – | 1300 | – | 1300 | – | 3300 | – | 3900 | – | |
| Output – input | –7700 | – | –2800 | – | 800 | – | –280 | – | –2000 | – | –2400 | – |
| **Dissolved inorganic phosphorus (P)** | | | | | | | |
| Input | | | | | | | |
| Riverine | 1.2 | 0.1 | 2.2 | 0.9 | 2.5 | 7.3 | 0.3 | 0.2 | 0.9 | 0.2 | 1.4 | 0.4 |
| Fresh SGD | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| Saline SGD | 18 | 2.0 | 12 | 5.0 | 7.0 | 20.3 | 1.4 | 1.2 | 2.2 | 0.5 | 8.1 | 2.3 |
| Oceanic | 880 | 97.9 | 230 | 94.1 | 25 | 72.4 | 110 | 98.6 | 490 | 99.4 | 350 | 97.3 |
| Output | 410 | – | 120 | – | 110 | – | 430 | – | 230 | – | |
| Output – input | –490 | – | –160 | – | 81 | – | 0.2 | – | –61 | – | –130 | – |
| **Dissolved silica (Si)** | | | | | | | |
| Input | | | | | | | |
| Riverine | 1100 | 2.5 | 1600 | 9.3 | 2000 | 34.3 | 120 | 3.6 | 600 | 7.6 | 1100 | 6.9 |
| FSGD | 5.6 | <0.1 | 4.2 | <0.1 | 3.8 | 0.1 | 3.8 | 0.1 | 4.2 | <0.1 | 4.3 | <0.1 |
| RSGD | 1800 | 80.0 | 1800 | 10.6 | 1400 | 23.9 | 420 | 12.5 | 2200 | 24.4 | 1500 | 9.6 |
| Oceanic | 42,000 | 93.5 | 13,000 | 80.0 | 2500 | 41.7 | 2800 | 83.8 | 6200 | 68.0 | 13,000 | 83.5 |
| Output | 92,000 | – | 4500 | – | 2800 | – | 3800 | – | 23,000 | – | |
| Output – input | 47,000 | – | –6200 | – | –1400 | – | –540 | – | –5300 | – | 6700 | – |
was the most significant source of nutrients for Moune Bay throughout the year. On the other hand, the mean contributions of the dissolved inorganic N, dissolved inorganic P, and dissolved Si fluxes from saline SGD were only 12%, 2%, and 10%, respectively. Except for oceanic nutrients, the mean fluxes of dissolved inorganic N, dissolved inorganic P, and dissolved Si through saline SGD accounted for 88%, 85%, and 58% of the land-based total flux, including river, fresh SGD, and saline SGD. These results indicate that saline SGD was a non-negligible source of nutrients for Moune Bay. Mean riverine nutrient flux accounted for <7% and was lower than that of saline SGD. In October, when the fraction of offshore seawater was lowest among all sampling periods, the contributions of dissolved inorganic N and dissolved Si from river water increased to 12% and 34%, respectively (Table 1). Fresh SGD was a minor source throughout the year, with a mean contribution of <0.1%.

**Discussion**

**Uncertainties of flux estimates**

We estimated the water influxes of fresh SGD, saline SGD, and offshore seawater to Moune Bay using different methods involving several assumptions. An evaluation of such uncertainties is a critical aspect of data interpretation and is necessary for confidence in the estimates. First, we evaluated the fresh SGD rate based on Darcy's law using GL data. The calculated mean value of $Q_{\text{SGD}}$ (3.7 cm$^{-1}$) was comparable with the fresh SGD rate measured using a continuous heat-type automated seepage meter coupled with salinity loggers at the bay head (<0.1 to 3.7 cm$^{-1}$; T. Nakajima unpubl.). However, $Q_{\text{SGD}}$ may have been underestimated because our estimates did not include the potential discharge of deeper confined groundwater in the sand gravel layer (Fig. S1).

The uncertainty associated with residence time ($\tau$) propagates to the estimates of $Q_{KB}$ and $Q_{\text{SSGD}}$. In this study, we used Ra age ($\tau_{Ra}$) as a residence time. Although previous studies have reported that the Ra age is consistent with the residence time (e.g., Moore et al. 2006; Charette et al. 2013), the selection of Ra endmember values for Eq. 5 could involve uncertainty. To confirm the validity of Ra age, we estimated residence time based on two methods: the salt mass balance ($\tau_{\text{Salinity}}$) and tidal prism ($\tau_{\text{Prism}}$) approaches (Moore et al. 2006) as follows:

$$\tau_{\text{Salinity}} = \frac{V}{(Q_{\text{RW}} + Q_{\text{FSGD}} + Q_{KB})},$$

$$\tau_{\text{Prism}} = \frac{VT}{(1 - b)P},$$

where $Q_{KB}$ is $S_{MB}(Q_{\text{RW}} + Q_{\text{FSGD}})/(S_{KB} - S_{MB})$, $S_{MB}$ is the mean salinity in Moune Bay, and $S_{KB}$ is the mean salinity at Stn KB. $T$ is the tidal period (d), $b$ is the return flow (dimensionless), and $P$ is the domain volume between high and low tide marks (m$^3$). In this calculation, we considered the tidal range (mean = 0.5 m) at neap tide at each sampling time and set return flow $b$ to 0 because the system was controlled by oceanic exchange (Ishizu et al. 2017; Shibasaki et al. 2018). Consequently, $\tau_{\text{Salinity}}$ (2.4 ± 1.6 d) and $\tau_{\text{Prism}}$ (12.3 ± 1.1 d) were similar to and longer than $\tau_{Ra}$ (3.5 ± 2.0 d). (Table S5). The mean $Q_{KB}$ values derived from $\tau_{\text{Salinity}}$ and $\tau_{\text{Prism}}$ were +27.4% and −81.0% of the mean $Q_{KB}$ estimated using $\tau_{Ra}$. Additionally, the difference in each $\tau$ propagated to the estimate of $Q_{\text{SSGD}}$ and the change rate of mean $Q_{SSGD}$ obtained using $\tau_{\text{Salinity}}$ and $\tau_{\text{Prism}}$ were +18.6% and −42.7% of the mean $Q_{SSGD}$ obtained using $\tau_{Ra}$, respectively. Although $\tau_{\text{Prism}}$ showed considerably different results, the similar results of $\tau_{Ra}$ and $\tau_{\text{Salinity}}$ may validate our estimates obtained using $\tau_{Ra}$. However, further studies using water velocity measurements at the mouth of a bay or a numerical model would reduce the uncertainty associated with water exchange.

Several assumptions made when estimating $Q_{\text{SSGD}}$ using the Ra mass balance model involve significant uncertainties. The selection of the endmember value of $Ra_{SGW}$ may involve large uncertainty (Cook et al. 2018), as $Q_{\text{SSGD}}$ was another substantial component of the Ra budget. In this study, we used the mean Ra activity of saline groundwater around a tidal flat that exhibits a salinity of 23.7–27.9 (Table S2). The selection of higher salinity groundwater (>10) is vital for obtaining reasonable estimates of $Q_{\text{SSGD}}$ (Swarzenski 2007; Cho and Kim 2016). Although we could not identify the fraction of meteoric fresh groundwater in $Q_{\text{SSGD}}$, the extremely low flux of $Q_{\text{SSGD}}$ compared with $Q_{\text{SSGD}}$ (Fig. 4) suggests that the contribution of meteoric fresh groundwater to $Q_{\text{SSGD}}$ would be negligible. We also assumed that seasonal variation in Ra activity in groundwater at the tidal flat would be minor, because the seasonal variation in short-lived Ra isotope activity in coastal sediments is smaller than its spatial variability (e.g., Tabor et al. 2017a, 2017b). If we consider the standard deviations of endmember $^{224}\text{Ra}$ activity as levels of uncertainty ($CV = 33.5\%$), then the mean change rates of $Q_{\text{SSGD}}$ become −25.8% to 53.5%. Minor contributions (<0.3%) of other $^{224}\text{Ra}$ fluxes, such as river discharge, fresh SGD, and desorption, to the mean $^{224}\text{Ra}$ budget (Table S4) indicate that the uncertainty in $Q_{\text{SSGD}}$ due to those factors is negligible.

**Significance of oceanic nutrients**

We quantified the nutrient fluxes from land, including river and SGD, as well as from the ocean, into Moune Bay (Figs. 4 and 7a). On average, 86%, 97%, and 84% of the dissolved inorganic N, dissolved inorganic P and dissolved Si, respectively, were derived from oceanic water (Fig. 7). This result revealed that offshore seawater was the most significant water and nutrient conveyor in the bay (Fig. 7b; Table 1). Interestingly, the contribution of oceanic nutrients was more significant compared with other embayments. For example, Sugimoto et al. (2016) reported average oceanic nutrient fluxes of 60% for dissolved inorganic N, 64% for dissolved inorganic P, and 78% for dissolved Si in Obama Bay; these rates were considerably lower than that for water influx.

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was responsible for oceanic nutrient transport into the seasonality of dominant water masses of offshore seawater. Therefore, we can conclude that whereas the TWC is low in nutrients, with a lower N:P ratio (<16) (Harrison et al. 2004; Sugie et al. 2010), Oyashio water is characterized by nutrient enrichment and a shore seawater varies seasonally (Ishizu et al. 2017). The nutrient water mass in the offshore region, as the origin of offshore seawater in Moune Bay is likely controlled by changes in the dominant water mass in the offshore region, as the origin of off-shore seawater varies seasonally (Ishizu et al. 2017). The Oyashio water is characterized by nutrient enrichment and a low N:P ratio (<16) (Harrison et al. 2004; Sugie et al. 2010), whereas the TWC is low in nutrients, with a lower N:P ratio (<16) (Kodama et al. 2015). Therefore, we can conclude that the seasonality of dominant water masses of offshore seawater was responsible for oceanic nutrient transport into Moune Bay.

The seasonal variability of nutrient fluxes from offshore was high (Figs. 4 and 6). The minimum fractions of offshore seawater in all nutrient budgets (41% for dissolved inorganic N, 72% for dissolved inorganic P, and 42% for dissolved Si; Table 1) were observed in October, when the warmer SW and TWC dominated the offshore seawater. On the other hand, offshore seawater fluxes were more significant in June when local BR was prominent in the offshore area. Notably, the intrusion of BR enriched in dissolved inorganic N and dissolved Si in June resulted in the greater fluxes of dissolved inorganic N and dissolved Si, while greater flux of dissolved inorganic P in March was driven by the intrusion of OY. This seasonal variability in the oceanic nutrient fluxes into Moune Bay is likely controlled by changes in the dominant water mass in the offshore region, as the origin of offshore seawater varies seasonally (Ishizu et al. 2017). The Oyashio water is characterized by nutrient enrichment and a low N:P ratio (<16) (Harrison et al. 2004; Sugie et al. 2010), whereas the TWC is low in nutrients, with a lower N:P ratio (<16) (Kodama et al. 2015). Therefore, we can conclude that the seasonality of dominant water masses of offshore seawater was responsible for oceanic nutrient transport into Moune Bay.

**Contributions of land-derived nutrients**

The fluxes of land-derived nutrients (i.e., river + SGD) were minor components of the nutrient budget in Moune Bay (Fig. 7). However, the sum of these contributions increased drastically to 28–59% in October, when the nutrient fluxes of offshore seawater weakened (Table 1). The increase in fraction of land-derived nutrients in the nutrient budget may be related to the lower temporal variability of land-derived nutrient fluxes (CV = 40–69%) compared with offshore seawater (CV = 89–111%). Notably, the contributions of dissolved inorganic N and dissolved Si were considerably higher compared with dissolved inorganic P, likely because the average N:P:Si molar ratio was 67:1:780 for river water and 68:1:250 for groundwater (fresh and saline), while that of offshore seawater was 16:1:42. These results suggest that land-derived nutrients can be important during certain seasons, as well as for specific elements (i.e., dissolved inorganic N and dissolved Si).

SGD (fresh + saline) is a major component of land-derived nutrients, accounting for 88% of dissolved inorganic N, 85% of dissolved inorganic P, and 58% of dissolved Si on average (Table 1). Although the nutrient concentrations of groundwater (fresh and saline) were comparable with, or slightly higher than, the concentrations in river water (Tables S1 and S2), total SGD flux was 2–9 times higher than river water flux. For example, in Masan Bay (China) land-derived nutrient fluxes accounted for 46–53% of dissolved inorganic N, 71–79% of dissolved inorganic P, and 68–76% of dissolved Si (Lee et al. 2009). The contribution of SGD to land-derived nutrient fluxes of Moune Bay was comparable or slightly higher than that in Masan Bay. Figure 8 presents the range of potential nutrient flux by SGD, and the flux ratio of SGD to river in similar coastal embayments worldwide. Our estimates in Moune Bay were within the 95% CIs for both fluxes and ratios. Considering that riverine nutrient fluxes would be more significant under flood conditions (Eyre 2000), further research is necessary to evaluate the net effects of riverine nutrient fluxes.

![Fig 8](image_url)

**Fig 8.** (a) Dissolved inorganic nitrogen, dissolved inorganic phosphorus, and dissolved silica fluxes derived from SGD and (b) their ratios for rivers calculated in previous studies for bay systems. Red circles represent the mean values in this study. The data for previous studies and this study are shown in table S6.
Saline SGD accounted for a significant fraction of SGD, regardless of season (>99% for water and >98% for nutrients), indicating that saline SGD is a major component of the nutrient flux of SGD (Fig. 7). Significant differences in water flux and nutrient properties between fresh and saline groundwater are often observed (Kroeger et al. 2007; Santos et al. 2008), and saline SGD is more significant than fresh SGD in terms of the fluxes of both water and nutrients (e.g., Kroeger et al. 2007; Knee et al. 2010). Enrichment of nutrients (e.g., dissolved inorganic N and dissolved inorganic P) in groundwater (salinity > 15) indicates that this subterranean estuary is a significant nutrient source (Fig. S2).

Temporal variation in saline SGD-derived water flux (Fig. 4m) suggests that the driving force of saline SGD varied seasonally. Saline SGD is driven by several factors including tidal pumping, nearshore circulation caused by tides and waves, density-driven circulation by dispersion along the freshwater-saltwater interface, and seasonal exchange concurrent with the movement of the freshwater-saltwater interface (Michael et al. 2005). The minimum \(Q_{\text{SGD}}\) (5200 m\(^3\) d\(^{-1}\)) found in January may have been caused by the weakening of density-driven circulation by dispersion and landward movement of the freshwater-saltwater interface, corresponding with decreases in \(Q_{\text{SGD}}\) and terrestrial GL, respectively (Figs. 4e, 5). Conversely, the maximum \(Q_{\text{SGD}}\) in June (41,000 m\(^3\) d\(^{-1}\)) may have been caused by the strengthening of density-driven circulation and seaward movement of the freshwater-saltwater interface, corresponding to increased \(Q_{\text{SGD}}\) and terrestrial GL, respectively.

The magnitude of saline SGD is often enhanced by the existence of benthos burrows (Stiegitz et al. 2000; Santos et al. 2012). In mangrove ecosystems, the contributions of benthic fauna to the recycling of seawater and solute between groundwater and surface water have been well documented (Stiegitz et al. 2013; Tait et al. 2016). The seafloor of Moune Bay harbors many burrows of benthic fauna, such as the mud shrimp (\textit{Upogebia major}), striped sandgoby (\textit{Acentrogobius virgatulus}), and sevenspine goby (\textit{Gymnogobius heptacanthus}) (Masuda et al. 2016). We documented prominent groundwater discharge from the burrows in the intertidal area (Fig. 1d,e), suggesting that seafloor conditions may enhance saline SGD in Moune Bay.

Implications for primary production

SGD can enhance primary production (PP) in coastal ecosystems (e.g., Waska and Kim 2011; Sugimoto et al. 2017). In Moune Bay, negative differences between nutrient inflows and outflows (Table 1) suggest the biological assimilation of nutrients, possibly due to PP. Based on the Redfield ratio (N:P:Si = 16:1:15; Redfield et al. 1963; Brezezinski 1985), the primary limiting nutrient for PP was likely to be P from June to October (N:P:Si > 22:1:55) and N in January and March (N:P:Si < 12:1:25). Therefore, theoretical total PP is 270–7100 mg C m\(^{-2}\) d\(^{-1}\) (or 21–560 mg C m\(^{-3}\) d\(^{-1}\)) based on the stoichiometric ratio (C:N:P = 106:16:1; Redfield et al. 1963), which is comparable with PP measured using a \(^{13}\)C tracer (ca. 120–230 mg C m\(^{-3}\) d\(^{-1}\)) in coastal bays along the Sanriku coast (Shiozaki et al. 2020). Notably, the most significant saline SGD contribution (460 mg C m\(^{-2}\) d\(^{-1}\); 18% of the total PP) was observed in March, when OY supplied the bay with ample nutrients. This suggests that dissolved inorganic N-enriched saline SGD may effectively stimulate PP under dissolved inorganic P-enriched (dissolved inorganic N-limited) conditions due to the intrusion of OY. In Monterey Bay, which exhibits an upwelling system (N-limited), Lecher et al. (2015) reported that brackish/saline groundwater (dissolved inorganic N- and dissolved Si-enriched) could promote the growth of phytoplankton (mainly as diatoms) in a bioassay incubation experiment. These findings support our results for Moune Bay. Furthermore, land-derived nutrients may have localized biological impacts around the river mouth and nearshore coast. Additional bioassay experiments could enhance our understanding of how PP sustains high biological production in coastal seas.

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