

Spatially resolved groundwater and river nutrient inputs to Baltic Sea coastal waters via radium isotopes

Aprajita S. Tomer^{a,*}, Tristan McKenzie^a, Claudia Majtényi-Hill^a, Ceylena Holloway^b, Júlia Rodríguez-Puig^{c,d}, Gloria Reithmaier^a, Linnea Henriksson^a, Beata Szymczycha^e, Isaac R. Santos^a

^a Department of Marine Sciences, University of Gothenburg, Gothenburg, Sweden

^b Faculty of Science and Engineering, Southern Cross University, Australia

^c Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona, Bellaterra, Spain

^d Departament de Física, Universitat Autònoma de Barcelona, Barcelona, Spain

^e Instytut Oceanologii Polskiej Akademii Nauk, Sopot, Poland

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ABSTRACT

Subterranean estuaries modify nutrient transport to coastal waters through submarine groundwater discharge (SGD). In marginal seas with restricted circulation, both surface water and groundwater nutrient inputs may trigger and sustain eutrophication. Here, we use ^{224}Ra to quantify total SGD and related nutrient inputs from beaches across 5 Baltic countries. Groundwater sampled from 17 transects was brackish, hypoxic, and nutrient rich relative to river waters. Nutrient and radium concentrations were highest at the shoreline and rapidly decreased with distance offshore, indicating a terrestrial nutrient source at the land-ocean interface. Groundwater DIN and DIP concentrations were on average ~ 4 and ~ 21 times higher, respectively compared to nearby rivers. Overall, mean nutrient ratios across all river and groundwater samples deviated from the Redfield ratio, with elevated DIN:DIP ($>16:1$) and DSi:DIP ($>15:1$) but reduced DIN:DSi ($<16:15$). An SGD source was not needed to close the ^{224}Ra mass balance in $\sim 50\%$ of the transects. Total SGD inputs could be estimated using ^{224}Ra mass balances in $\sim 50\%$ of sampled transects resulting in mean total SGD of $6 \pm 10 \text{ m}^3/\text{day}$ per meter of shoreline across 8 beach-transects. Despite large natural variability and uncertainties, extrapolating beach-scale total SGD-derived fluxes to the 8000 km Baltic shoreline led to total SGD nutrient fluxes comparable to river inputs. Total SGD derived from ^{224}Ra budgets, but not fresh SGD derived from hydrological models, seems to be a relevant but still uncertain component of Baltic coastal nutrient budgets.

1. Introduction

Subterranean estuaries (STE) describe a subsurface area within the coastal zone where groundwater mixes with intruding seawater (Moore, 1999). STEs are characterized by sharp physicochemical gradients in salinity, redox potential and organic carbon content, making them effective biogeochemical reactors (Charette and Sholkovitz, 2006a). Groundwater flowing through STEs may release more nutrients than rivers to global coastal waters (Wilson et al., 2024). Redox and ion-exchange driven reactions are critical processes within STEs that can alter nutrient speciation and mobility (Kroeger et al., 2006; Moore, 2010; Wilson et al., 2023). As a result, nutrients associated with aquifer particulate organic matter are transformed into their

bioavailable and soluble forms, making STEs sources of nutrients contributing to coastal primary production (Chen et al., 2025).

The impact of coastal nutrient enrichment from submarine groundwater discharge (SGD) through STEs is amplified in semi-enclosed coastal ecosystems with long water residence times such as bays, gulfs, and marginal seas (Wilson et al., 2024). The vulnerability of these ecosystems, especially marginal seas, is due to limited water exchange resulting in accumulation of terrestrial inputs (Pratt and Spall, 2008). Thus, SGD-derived dissolved inorganic nitrogen (DIN) and phosphorus (DIP) can exacerbate eutrophication and promote the expansion of hypoxic conditions in marginal seas (Moore et al., 2024). While fresh-SGD is often a minor nutrient source, total SGD has previously been reported as a major source of nutrients to global coastal waters (Tait

* Corresponding author.

E-mail address: aprajita.singh.tomer@gu.se (A.S. Tomer).

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et al., 2023). Separating the role of fresh and total SGD in nutrient budgets remains challenging (Böttcher et al., 2024; Robinson et al., 2017; Taniguchi et al., 2019). Despite decades of monitoring and management efforts resulting in reduction of surface nutrient inputs, delayed recovery from eutrophication has been observed in topographically restricted coastal ecosystems (Duarte et al., 2015; McCrackin et al., 2017). Discrepancies between expected and observed ecosystem recovery could be due to the exclusion of legacy SGD nutrient inputs from management and monitoring frameworks.

Radium isotopes are an effective tool for tracing total SGD because they are biologically conservative in seawater and are naturally enriched in groundwater (García-Orellana et al., 2021). Short-lived radium isotopes have been efficient in quantifying SGD-derived nutrient loads in the northeastern Gulf of Mexico (Moore, 2003), Monterey Bay (Lecher et al., 2015), and many other coastal ecosystems globally (García-Orellana et al., 2021; Moore, 2010). Specifically, ^{224}Ra is a powerful indicator of recent nearshore discharge due to its short half-life of 3.6 days. By balancing the sources and sinks of radium isotopes in dynamic coastal environments, total SGD rates can be quantified at the nearshore scale off beaches (Bratton, 2010).

In this study, we hypothesize that STEs are an overlooked nutrient source that may contribute to eutrophication in the Baltic Sea. While previous studies have primarily focused on localized SGD hotspots, the present study provides the first spatially integrated tracer-based assessment of total SGD and associated nutrient inputs across 10 Baltic Sea coastal regions. We apply an uncertainty-resolved ^{224}Ra mass balance model along each beach transect to quantify total SGD and associated nutrient loads to coastal waters. The primary objective of this study is to use a regional-scale approach to quantify groundwater-derived nutrient fluxes across contrasting hydrogeological settings, contextualize the results through comparison with riverine nutrient inputs, and provide a first-order assessment of the basin-scale significance of SGD in the Baltic Sea.

2. Material and methods

2.1. Study site

The Baltic Sea is the second largest brackish water basin in the world (Leppäranta and Myrberg, 2009a). It is a shallow semi-enclosed sea with a mean depth of about 54 m and a coastline length of 8000 km (Snoeijs-Leijonmalm et al., 2017). Water exchange between the Baltic Sea and the North Sea is restricted, occurring through the narrow Danish straits. Consequently, the limited water exchange and circulation lead to long water and pollutant residence times, of ~37 years (Reusch et al., 2018). This limited water flushing along with a catchment population of 85 million make the Baltic Sea highly vulnerable to anthropogenic pressures and climate stressors (Andersen and Laamanen, 2009; Philip Axe et al., 2023).

Despite extensive nutrient monitoring, the Baltic Sea remains as one of the most eutrophic marginal seas in the world (Kuliński et al., 2022a; Reusch et al., 2018). While surface nutrient inputs have decreased in recent decades, ~94% of the Baltic sea surface water is subject to eutrophication (Philip Axe et al., 2023). About 70% of total nitrogen loading comes from agricultural runoff through unmonitored catchment sources (Andersen and Laamanen, 2009). Phosphorus concentrations in central and northern areas of the Baltic Sea have increased despite managing discharge from wastewater treatment plants which is a major point source of phosphorus (Cloern, 2001; Preisner et al., 2021). Large scale monitoring frameworks retain the focus on riverine and atmospheric nutrient inputs with little insight into groundwater sources (Philip Axe et al., 2023).

Local scale studies have investigated STEs and SGD to the southern and central coastal Baltic. For example, SGD to the southern Baltic coast has led to nutrient enrichment in coastal waters (Hinsby et al., 2025). Several approaches such as use of seepage meters and porewater lances

in Hütelmoor coastal peatland (Germany) (Racasa et al., 2025; Saban et al., 2025), hydrological modelling in Pomeranian Bay in south-western Baltic Sea (Kaleris et al., 2002), geochemical tracing in Bay of Puck (Poland) and Eckernförde Bay (Germany) (Klostowska et al., 2020; Kreuzburg et al., 2023; Purkl and Eisenhauer, 2004; Szymczycha et al., 2020b), and geophysical surveys in the Gulf of Finland (Schlüter et al., 2004; Virtasalo et al., 2019) have assessed SGD both qualitatively and quantitatively. Multiple studies conducted in the Polish Bay of Puck identify SGD as a major source of mercury, carbon, nutrients, and pharmaceuticals (Szymczycha et al., 2023; Von Ahn et al., 2024). Eckernförde Bay and Hanko in Finland are other SGD hotspots based on naturally occurring geochemical tracers and geophysical surveys (Luoma et al., 2021; Purkamo et al., 2022; Schlüter et al., 2004). Combined, these studies have identified SGD as an important driver of local biogeochemistry in the Baltic Sea.

2.2. Sampling and analytical methods

Sampling was done between May and August 2024 along the Baltic Sea shoreline. 17 shore-perpendicular transects were sampled in 10 coastal regions, with each transect including beach groundwater and nearshore Baltic surface water (Fig. 1). Multiple transects within one coastal region were generally ~3–7 km apart. The nearshore surface water was collected within 200 m of the shoreline from a depth of 0.5–1.5 m. Riverine endmembers were also collected from rivers representing the drainage area of all beach groundwater transects. On average 3 surface water samples and 5 groundwater samples were collected at each transect site (Fig. 1B). In total, 45 rivers were sampled accounting for more than 50% of the total riverine discharge into the Baltic Sea. Salinity, pH, and dissolved oxygen saturation levels were measured for each groundwater and surface water sample using a calibrated YSI probe in the field.

To sample for radium isotope analysis, 60 L of nearshore surface water and 5 L of groundwater were filtered through MnO_2 -coated acrylic fibers. Then fibers were analyzed using a Radium Delayed Coincidence Counter (RaDeCC) for quantification of ^{223}Ra and ^{224}Ra activities (Moore and Arnold, 1996). ^{223}Ra data were discarded for nine samples due to elevated ^{224}Ra activities that caused interference in the ^{223}Ra channel during RaDeCC measurements, thereby compromising data reliability (Scholten et al., 2010). Sediment samples were also collected along 13 shoreline transects within the intertidal zone. Diffusion experiments were conducted by covering sediment samples with 3 to 5 L of overlying radium-free water under oxic conditions. The samples were subsequently analyzed after >60 days, when diffusion sources were assumed to be in equilibrium with decay within the container (Stewart et al., 2018).

For nutrient analysis, discrete water samples were collected and filtered through 0.45 μm cellulose acetate filters and then frozen (DIN and DIP) or stored at ~4 °C (DSi) until analysis. DIN was defined as the sum of NO_2^- , NO_3^- , and NH_4^+ . The concentrations of nutrients were determined by colorimetric methods using an automated photometric analyzer (SEAL AA500) (Salley et al., 1987; Strickland, 1972). To ensure quality control of measurements the certified reference materials (QC3179, Sigma Aldrich; HAMIL-20.2, Environment Canada) were regularly analyzed. The accuracy of measurements was ~99% with a precision better than 1.1%. Detection limits of the applied method were 0.33 $\mu\text{mol L}^{-1}$ for NO_3^- , 0.05 $\mu\text{mol L}^{-1}$ for NO_2^- , 0.27 $\mu\text{mol L}^{-1}$ for NH_4^+ , 0.1 $\mu\text{mol L}^{-1}$ for phosphate, and 0.1 $\mu\text{mol L}^{-1}$ for silicate. All the data are published in our companion data descriptor paper following FAIR principles (McKenzie et al., 2025).

2.3. Total SGD estimates and extrapolations

A radium mass balance model constituting four terms was applied along each transect to estimate total SGD (García-Orellana et al., 2014; Moore, 2000b) (Fig. 2-A):

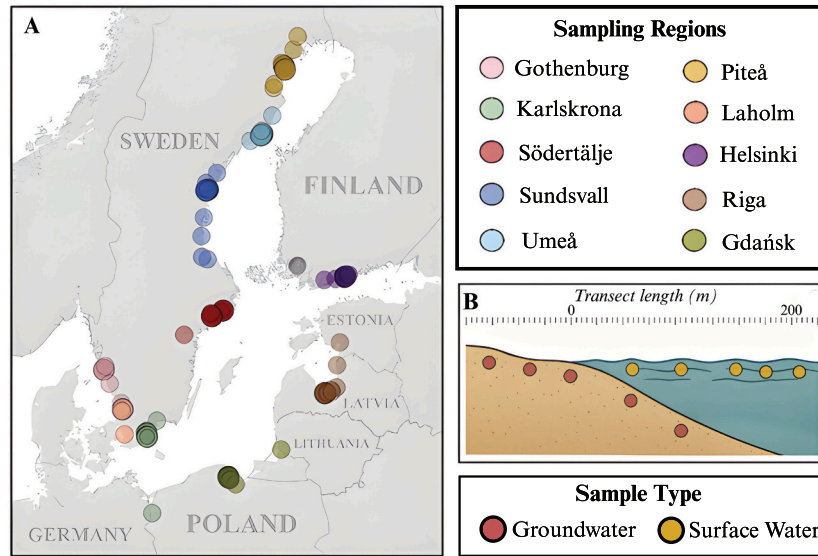


Fig. 1. Sampling locations and strategy used to quantify radium and nutrient dynamics along the Baltic Sea coastline: (A) map showing coastal transects in Sweden, Finland, Estonia, Latvia, Lithuania, Poland, and Germany, colored by sampling regions. The Differences in colour intensity result from overlapping markers and do not represent an additional variable. (B) schematic cross-section depicting sampling methodology by illustrating positions of groundwater (red) and surface-water (yellow) samples along each transect. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$f_{SGD} + f_{Diffusion} = f_{Decay} + f_{Mixing} \quad (1)$$

where flux contributions, denoted by f , of radium sources (SGD and sediment diffusion) are equated with those of radium sinks (radioactive decay and offshore mixing) under the assumption of steady state sources and sinks with timescales that are comparable to the half-life of ^{224}Ra (3.6 days). Beach transects were largely conducted away from rivers. The criteria for inclusion of a transect were groundwater endmember tracer activities exceeding that of surface water samples and at least 3 surface water samples collected within 200 m off the shoreline to capture nearshore tracer gradients.

$f_{Diffusion}$ was calculated using radium activities obtained from diffusion experiments in which sediment samples from each transect were incubated with radium free water matching the local salinity for two months (longer than 6 half-lives of the isotopes of interest) (Garcia-Solsona et al., 2008):

$$f_{Diffusion} = C_{^{224}\text{Ra}} \times h \times \lambda_{^{224}\text{Ra}} \times x \quad (2)$$

where $C_{^{224}\text{Ra}}$ denotes ^{224}Ra activities obtained from diffusion experiments in dpm m^{-3} , h is the height of water column in m overlying above the sediment in m, $\lambda_{^{224}\text{Ra}}$ represents the decay constant for ^{224}Ra with a value of 0.189 day^{-1} , and x is for the transect length in m. f_{Decay} represents the radium flux removed from the system due to radioactive decay:

$$f_{Decay} = I_{^{224}\text{Ra}} \times \lambda_{^{224}\text{Ra}} \times x \quad (3)$$

where $I_{^{224}\text{Ra}}$ denotes the inventory of ^{224}Ra in seawater (dpm m^{-2}). f_{Mixing} signifies fraction of radium removed due to offshore coastal mixing and is calculated as follows (Moore, 2000b):

$$f_{Mixing} = \left(I_{^{224}\text{Ra}} \times x \right) / t \quad (4)$$

where t is the flushing time in days derived from isotopic ratios (Moore, 2000a):

$$t = \ln \left(\frac{AR_{obs}}{AR_i} \right) / \left(\lambda_{^{223}\text{Ra}} - \lambda_{^{224}\text{Ra}} \right) \quad (5)$$

where AR denotes activity ratio of concentrations of ^{224}Ra to ^{223}Ra . AR_{obs} denotes observed activity ratio of individual surface water sample while AR_i denotes activity ratio of the surface water sample collected closest to the shoreline. $\lambda_{^{223}\text{Ra}}$ is the decay constant for ^{223}Ra and is equal to 0.06 day^{-1} . ^{223}Ra isotope activities of 9 samples with unreliable RaDeCC measurements were excluded from further analysis since they did not satisfy analytical procedures (Scholten et al., 2010). Upon obtaining each of these mass balance terms, we calculated the total SGD rate:

$$SGD = f_{SGD} / C_{^{224}\text{Ra}}^{gw} \quad (6)$$

where, $C_{^{224}\text{Ra}}^{gw}$ is the activity levels of ^{224}Ra (dpm m^{-3}) in the groundwater endmember, and f_{SGD} is the radium-derived contribution from SGD. Fresh SGD rates were obtained by applying the hydrological model developed by (Luijendijk et al., 2020) to individual transect locations. Model-derived fresh SGD estimates were subsequently combined with radium-derived total SGD estimates to quantify the relative contribution of fresh groundwater to total discharge.

To account for spatial heterogeneity in aquifer properties, groundwater endmembers were determined independently for each transect. This ensured that local hydrogeological conditions specific to each aquifer system were represented, rather than assuming uniform hydrogeological characteristics across the ~8000-km Baltic Sea coastline. For each transect, the groundwater sample with the highest ^{224}Ra activity was selected as the potential groundwater endmember. Since SGD discharge rates are inversely proportional to ^{224}Ra activities (Eq. 6), this approach yielded the most conservative discharge rate and prevented overestimation of SGD fluxes (Cho and Kim, 2016; Luo et al., 2024).

The SGD rate can then be used to calculate nutrient fluxes as follows:

$$f_{Nut} = SGD \times (C_{gw} - C_{sw}) \quad (7)$$

where f_{Nut} denotes resultant nutrient flux (mol day^{-1}), SGD is the discharge rate of groundwater ($\text{m}^2 \text{ day}^{-1}$ per m of shoreline) and C_{gw} is the nutrient concentration in groundwater end member (mmol m^{-3}), and C_{sw} is the concentration in the adjacent surface water (mmol m^{-3}). This approach assumes that nutrients in beach groundwater are a mixture of seawater nutrients penetrating the beach and terrestrial

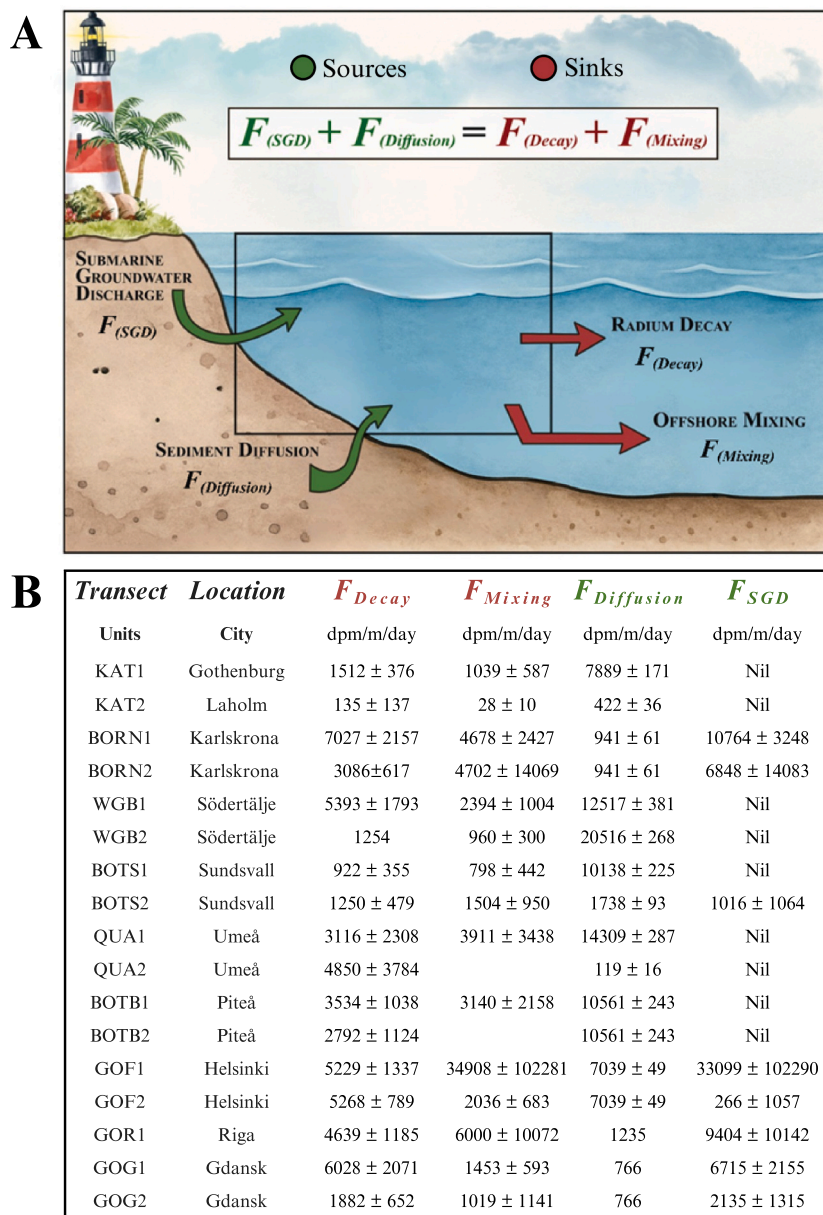


Fig. 2. Schematic representation and transect-specific results of the ^{224}Ra mass balance used to quantify submarine groundwater discharge (SGD) along the Baltic Sea coastline: (A) conceptual model of the radium budget showing sources (SGD and sediment diffusion) and sinks (radium decay and offshore mixing), and (B) table summarizing the calculated ^{224}Ra fluxes associated with decay, offshore mixing, sediment diffusion, and the residual advective SGD term for each coastal transect.

nutrients. By removing the background surface seawater concentrations and using the groundwater sample with highest ^{224}Ra activities, we produce the minimum possible SGD flux and minimize the risk of overstating the contribution of SGD to Baltic Sea nutrient budgets. River fluxes were quantified by using the following formula:

$$f_{rNut} = Q_r \times C_{rNut}. \quad (8)$$

where f_{rNut} denotes resultant riverine nutrient flux (mol day^{-1}), Q_r is the flow rate of the river obtained from monitoring databases ($\text{m}^3 \text{day}^{-1}$) and C_{rNut} is nutrient concentration in the sampled river (mmol m^{-3}).

2.4. Uncertainties

Transect-scale uncertainties for measured hydro-chemical parameters such as salinity, temperature, dissolved oxygen, nutrient concentrations, and radium activities are reported as mean ± standard

deviation of readings from all sampled points along each transect (Taylor, 2022). For radium mass balance calculations, uncertainties associated with radioactive decay, sediment diffusion, and coastal mixing fluxes were calculated using standard error propagation methods (Garcia-Solsona et al., 2008). The propagated uncertainty of SGD-derived radium fluxes was obtained by combining the absolute uncertainties of diffusive, mixing, and decay fluxes in quadrature without scaling by flux magnitude (García-Orellana et al., 2021). Representative regional uncertainties were subsequently derived from the propagated uncertainties of individual transects within each region.

Uncertainty propagation was conducted hierarchically from transect-scale measurements to basin-scale nutrient flux estimates. Propagated uncertainties associated with SGD estimates were incorporated into groundwater-derived nutrient flux calculations together with uncertainties in groundwater nutrient concentrations, after correction for background seawater concentrations. These propagated transect-scale uncertainties were subsequently carried through regional

averaging and incorporated into Baltic-wide nutrient flux estimates. The dominant sources of uncertainty were associated with groundwater endmember selection, sediment diffusion estimates, offshore mixing calculations, and extrapolation of site-specific measurements to the broader Baltic Sea coastline. These uncertainties increase progressively from transect-scale SGD calculations to basin-scale nutrient flux estimates.

3. Results

3.1. Water characteristics

Groundwater and river samples exhibited a distinct physicochemical signature across 17 transects. Groundwater was often brackish and hypoxic with median salinity and dissolved oxygen values of 4 and 44%, respectively (Fig. 3). Contrastingly, riverine samples were more oxidic and fresher exhibiting median oxygen saturation of 89% and salinity of 2. Nearshore seawater samples were oxidic with a median oxygen saturation of 96%. Seawater samples had highest salinity (median = 5) consistent with large scale Baltic Sea salinity distributions. Median temperatures of the three water types were similar, ranging from 13.7 °C in seawater to 14.7 °C in groundwater.

3.2. Radium observations and mass balances

The short-lived radium isotopes, ^{223}Ra and ^{224}Ra , were utilized to trace groundwater inputs. Groundwater samples were enriched in short-lived radium isotopes with median concentrations of $25 \pm 30 \text{ dpm m}^{-3}$ for ^{223}Ra and $5340 \pm 12,000 \text{ dpm m}^{-3}$ for ^{224}Ra (Fig. 3). Concentrations in river and nearshore water samples were an order of magnitude lower

than groundwater for ^{223}Ra and ^{224}Ra (Table 1). The spatial gradient of isotope concentrations perpendicular to the shoreline exhibited a sharp nearshore peak, with ^{223}Ra concentrations dropping from $\sim 210 \text{ dpm m}^{-3}$ to $<30 \text{ dpm m}^{-3}$ off the beach (Fig. 4). A similar trend was observed for ^{224}Ra concentrations where shoreline concentrations exceeding $10,000 \text{ dpm m}^{-3}$ decreased off the beach.

^{224}Ra mass balance models revealed large spatial variability with SGD emerging as a major quantifiable source of radium in 8 out of 17 transects (Fig. 2B). Radium inventories within 200 m from the shoreline showed spatial variation. The lowest radium inventories were found along the coastlines of Sundsvall with a mean value of $24 \pm 9 \text{ dpm m}^{-2}$ and the highest observed at transects sampled in Karlskrona with a mean value of $190 \pm 60 \text{ dpm m}^{-2}$. The primary sink for ^{224}Ra was radioactive decay with a median contribution in mass balance models at $3116 \pm 3718 \text{ dpm m}^{-1} \text{ day}^{-1}$. Mixing had substantial spatial variation with rates ranging on an average from $28 \pm 10 \text{ dpm m}^{-1} \text{ day}^{-1}$ in Laholm to $(3.5 \pm 10.2) \times 10^4 \text{ dpm m}^{-1} \text{ day}^{-1}$ in Helsinki. Mean radium inputs via sediment diffusion exceeded the cumulative loss of ^{224}Ra by radioactive decay and offshore mixing in 9 out of 17 transects, ranging from $20,516 \pm 268 \text{ dpm m}^{-1} \text{ day}^{-1}$ in Södertälje to $119 \pm 16 \text{ dpm m}^{-1} \text{ day}^{-1}$ in Umeå. In these locations, non-SGD sources (i.e., diffusion) explained the radium losses in the mass balance, indicating that no substantial advective-SGD sources are required to achieve steady state in the mass balance model.

Out of the 8 transects with the presence of total SGD, 5 transects resulted in advective ^{224}Ra inputs via SGD with uncertainties significantly above zero. Here, the average contribution of SGD as a source of radium ranged from $1016 \pm 1064 \text{ dpm m}^{-1} \text{ day}^{-1}$ in Sundsvall to $10,764 \pm 3248 \text{ dpm m}^{-1} \text{ day}^{-1}$ in Karlskrona. Resolving the mass balance further in these locations provided total SGD rates with mean

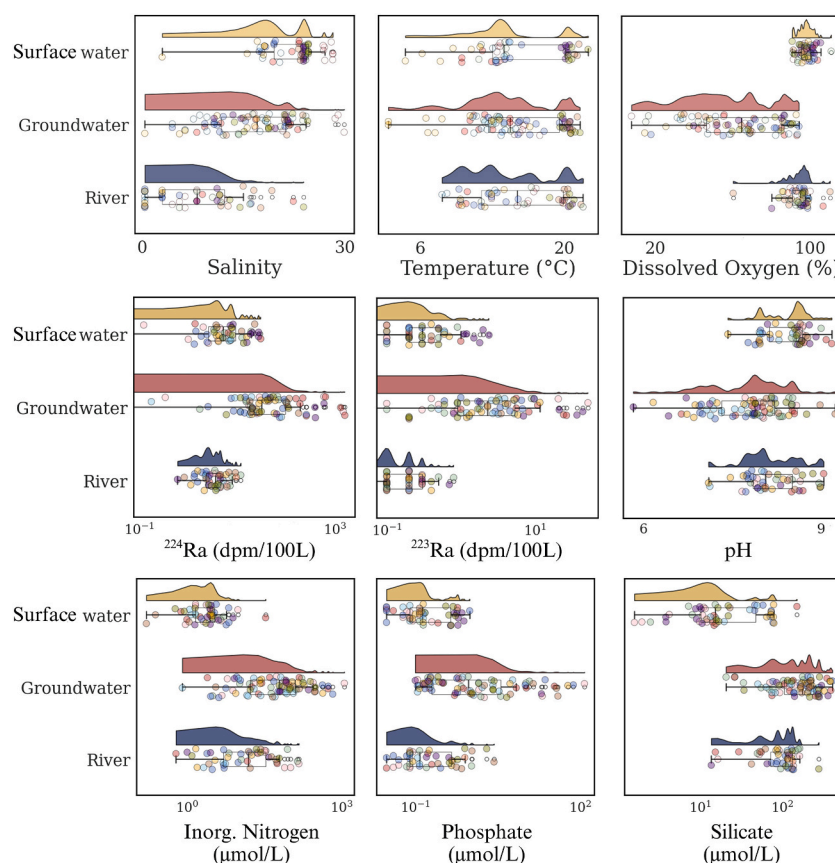


Fig. 3. Density distribution of general in-situ parameters and nutrient concentrations in surface water (yellow), groundwater (red), and river (blue) samples. The jitter below the distribution represents each individual sample that is colored based on the sampling region it was taken from (following the same scheme as shown in Fig. 1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

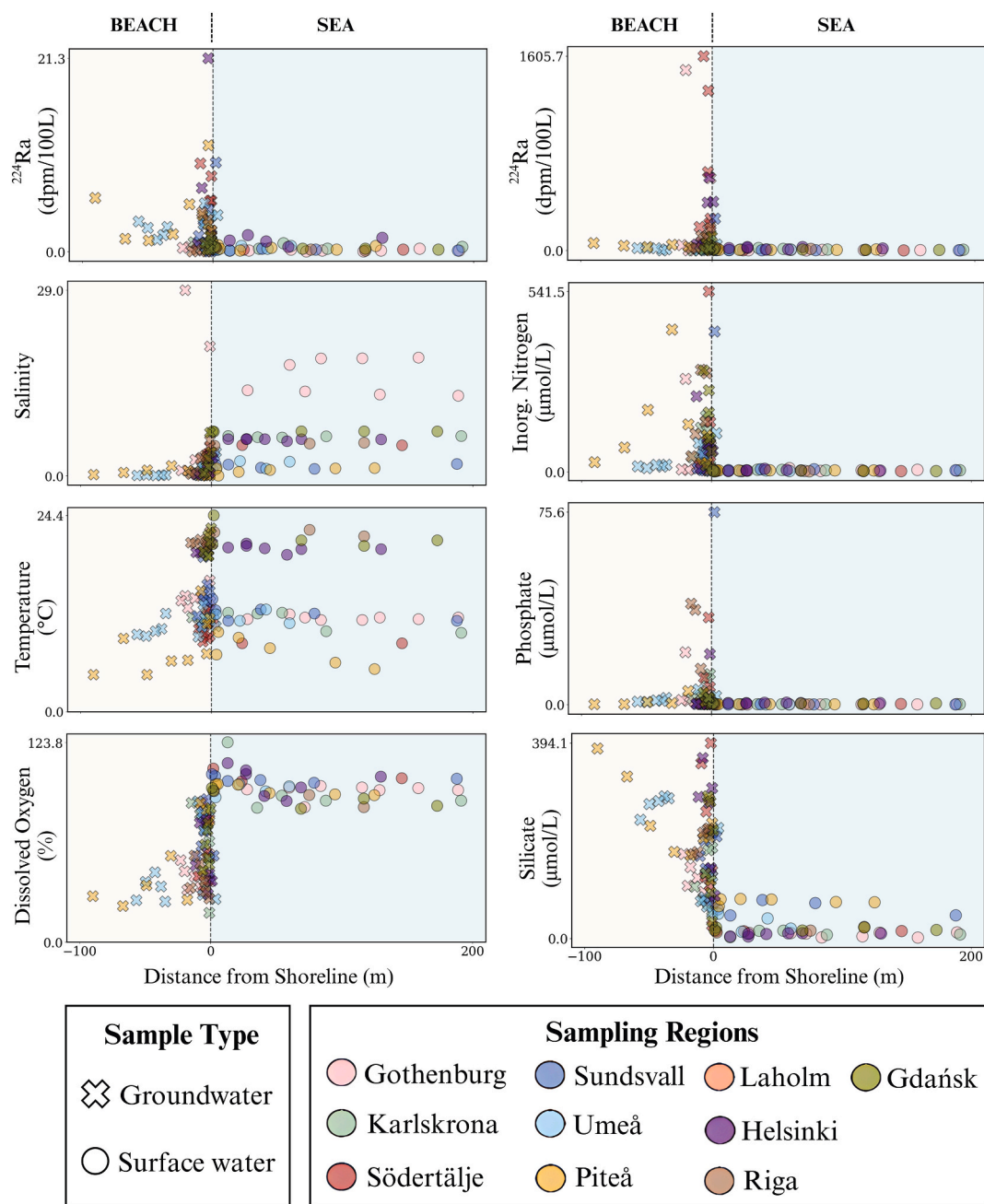


Fig. 4. Perpendicular gradients of ^{224}Ra activities, hydrographic properties, and nutrient concentrations in groundwater (crosses) and seawater (circles) along transects showing rapid changes and spikes precisely at the beach-ocean interface. The individual data points are colored based on the region where they were sampled. Values of ^{224}Ra activities in the unit dpm/100 L can be obtained by multiplying respective activities in units dpm/m³ by 10.

values of $10.2 \pm 3.1 \text{ m}^2 \text{ day}^{-1}$ (Karlskrona), $1.1 \pm 1.1 \text{ m}^2 \text{ day}^{-1}$ (Sundsvall), $5.1 \pm 5.5 \text{ m}^2 \text{ day}^{-1}$ (Riga), and $5.9 \pm 1.9 \text{ m}^2 \text{ day}^{-1}$ and $6.7 \pm 4.3 \text{ m}^2 \text{ day}^{-1}$ (Gdansk) (Fig. 5). Associated fresh SGD rates estimated from hydrological models (Luijendijk et al., 2020) at same locations were $0.1 \text{ m}^2 \text{ day}^{-1}$ in Karlskrona, $0.03 \text{ m}^2 \text{ day}^{-1}$ in Sundsvall, $0.001 \text{ m}^2 \text{ day}^{-1}$ in Riga, and $2.2 \text{ m}^2 \text{ day}^{-1}$ in Gdansk. Thus, fresh SGD on average made up only ~1% of total SGD rates derived from our ^{224}Ra mass balance models.

3.3. Nutrient dynamics

Nutrient concentrations had strong contrasts between different sample types. Groundwater emerged as the most nutrient-rich and chemically distinct source. The concentration of dissolved nutrients in

beach groundwater samples reached $173 \mu\text{mol L}^{-1}$ of DSi, $545 \mu\text{mol L}^{-1}$ of DIN and $76 \mu\text{mol L}^{-1}$ of DIP. On average, DIN in groundwater was constituted with 70.8% of NH_4 , 0.5% of NO_2 , and 28.8% of NO_3 . Seawater concentrations did not exceed $79 \mu\text{mol L}^{-1}$, $12 \mu\text{mol L}^{-1}$, and $1 \mu\text{mol L}^{-1}$ of DSi, DIN, and DIP, respectively. In riverine samples, observed nutrient concentrations were highly variable, often plotting between groundwater and seawater concentrations across all locations (Fig. 3).

Nutrient concentrations varied systematically with physicochemical parameters for each hydrological source (Fig. 6). Nutrient concentrations in groundwater and river samples exhibited a decreasing relationship with salinity. Higher variation was observed in DIP concentrations with groundwater samples being consistently enriched relative to sea and river water samples. Consistent production of

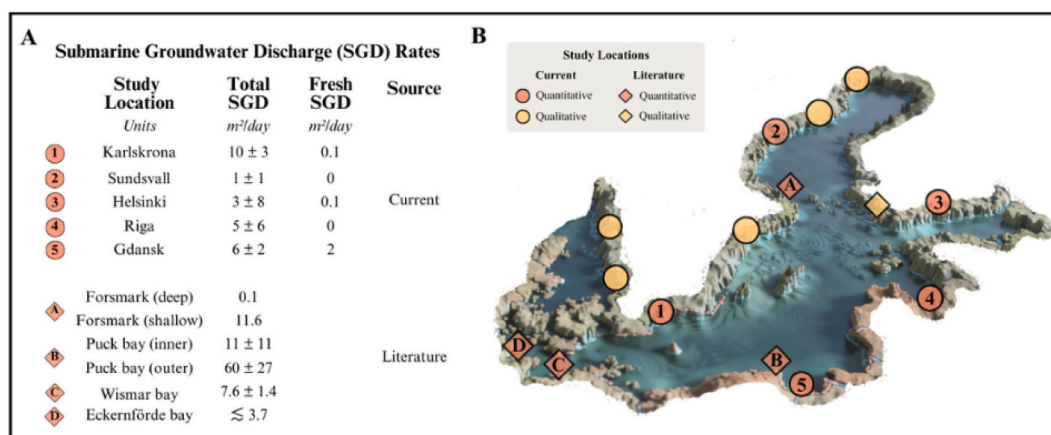


Fig. 5. Submarine groundwater discharge (SGD) rates along the Baltic Sea coastline: (A) Table summarizing Submarine groundwater Discharge (Total and Fresh) quantified in current study and previously published total SGD estimates from Forsmark (Krall et al., 2017), Puck Bay (Kłostowska et al., 2020), Wismar Bay, and Eckernförde Bay (Kreuzburg et al., 2023). (B) Conceptual rendering of Baltic Sea coastline illustrating the spatial distribution of tracer-derived total SGD from 8 transects sampled across 5 regions (circles 1–5) along the Baltic Sea coastline with previously published fresh and total SGD estimates (diamonds A–D) and distinguishing quantitative (red) versus qualitative (yellow) study locations. Base map is presented for spatial context only and is not to scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

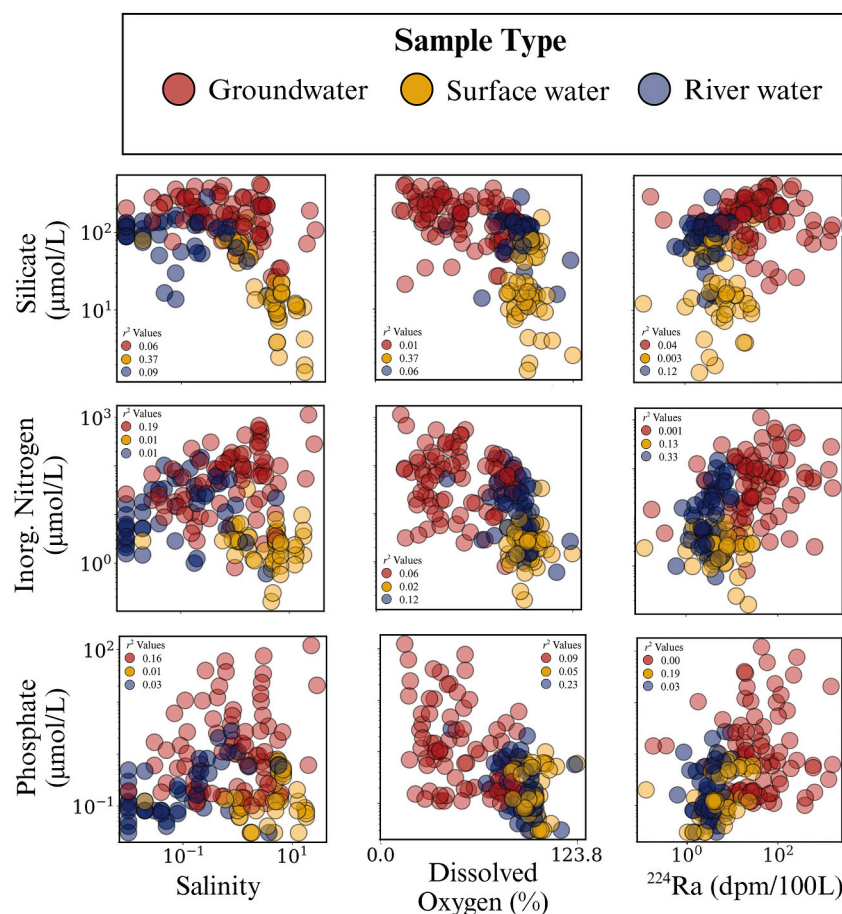


Fig. 6. Relationships between concentrations of inorganic nitrogen, phosphate, and silicate and physicochemical parameters for groundwater, seawater, and river water. Values of ^{224}Ra activities in the unit dpm/100 L can be obtained by multiplying respective activities in units dpm/ m^3 by 10.

inorganic nitrogen and silicate was observed across all hydrological sources with most pronounced non-conservative mixing observed within groundwater precisely at the beach-ocean interface. Nutrient enrichment was more pronounced in hypoxic groundwater than in oxic river and seawater samples. Nutrient concentrations (DSi, DIN, and DIP)

increased with increase in ^{224}Ra activities (Fig. 6). Additionally, nutrient concentrations and offshore distance exhibited a decreasing relationship, with a clear hotspot at the shoreline that faded offshore (Fig. 4).

A large proportion of groundwater, river and seawater samples exhibited elevated DIN:DIP (>16:1) and DSi:DIP (>15:1) but reduced

DIN:DSi (<16:15) ratios relative to the Redfield ratio (Fig. 7). Mean DIN:DIP ratios were 125 ± 202 and 260 ± 483 driven by high nitrogen concentrations, in groundwater and river samples, respectively. Groundwater and river samples were also enriched in silicate with mean DSi:DIP ratios of $\sim 450 \pm 690$ and $\sim 900 \pm 945$, respectively. While seawater samples exhibited a positive deviation from the Redfield ratio (N:Si:P = 16:15:1), the elevation in DIN:DIP ($\sim 30 \pm 30$) and DSi:DIP ($\sim 320 \pm 450$) ratios were not as profound as observed in groundwater and river samples. Additionally, consistently high variation in nutrient stoichiometric ratios was observed across all samples.

3.4. Nutrient fluxes

High spatial variation and large uncertainties were also observed in SGD-derived nutrient fluxes, with mean rates of $0.4 \pm 1.2 \text{ mol m}^{-1} \text{ day}^{-1}$ DSi, $0.3 \pm 0.5 \text{ mol m}^{-1} \text{ day}^{-1}$ DIN, and $0.01 \pm 0.04 \text{ mol m}^{-1} \text{ day}^{-1}$ DIP (m refers to meter of shoreline). The highest SGD-derived DSi flux occurred in Riga ($0.9 \pm 1.0 \text{ mol m}^{-1} \text{ day}^{-1}$), whereas the highest SGD-derived DIN ($0.8 \pm 0.5 \text{ mol m}^{-1} \text{ day}^{-1}$) and DIP ($0.01 \pm 0.01 \text{ mol m}^{-1} \text{ day}^{-1}$) fluxes were found in Bay of Puck within Gulf of Gdansk, a known SGD hotspot (Von Ahn et al., 2024) (Table 1). Sampled rivers released $2.2 \pm 0.5 \times 10^6 \text{ mol day}^{-1}$ of DSi, $0.3 \pm 0.1 \times 10^6 \text{ mol day}^{-1}$ of DIN, and $0.01 \pm 0.002 \times 10^6 \text{ mol day}^{-1}$ of DIP to Baltic coastal waters. Spatial variability was also observed in riverine nutrient fluxes, although these differences were primarily controlled by variations in river flow rates rather than nutrient concentrations.

4. Discussion

4.1. Baltic Sea subterranean estuaries

Previous Baltic Sea studies have identified subsurface mixing zones in the Bay of Puck and Eckernförde Bay beaches where groundwater discharge was brackish (Kreuzburg et al., 2023; Szymczycha et al., 2020b). Our observations imply that as fresh groundwater passes through STEs, dissolved oxygen is consumed by microbial respiration and redox reactions, resulting in oxygen deficient conditions relative to surface seawater and river samples (Charette and Sholkovitz, 2006b;

Moosdorf et al., 2021).

Prevalent benthic hypoxia and internal nutrient loading have been documented as a major concern in the deep Baltic Sea open waters (Carstensen et al., 2014). Hypoxic groundwater discharge acts as an additional overlooked source of reduced chemical species and regenerated nutrients to nearshore coastal waters (Moore et al., 2024). Overall, the brackish and hypoxic signature of groundwater discharge, against a thermally similar but fresher and oxic surface water, is consistent with previously documented mixing and redox transformations within subterranean estuaries along the Baltic coastline (Hinsby et al., 2025; Kłostowska et al., 2020; Kreuzburg et al., 2023).

In our study, groundwater consistently had the highest nutrient concentrations (Fig. 3) compared to river and seawater, and these maxima occurred in hypoxic samples. Between the western (Swedish) and eastern (Riga, Gdansk) coasts, more urbanized south-eastern sites tended to show higher DIN and DIP enrichment in groundwater and consequently larger SGD-derived nutrient fluxes. Along the Swedish coast, groundwater was enriched in DSi which resulted in high SGD-derived DSi fluxes, especially in Karlskrona. Together, these patterns suggest that the brackish and hypoxic groundwater is a nutrient source to nearshore Baltic waters.

4.2. Radium-derived groundwater fluxes to nearshore waters

Substantial ^{223}Ra and ^{224}Ra enrichment in beach groundwater relative to river and seawater samples is consistent with radium desorption from particles within subterranean estuaries (Gonneea et al., 2008). Brackish conditions trigger radium desorption from sediments through ion exchange (García-Orellana et al., 2021; Gonneea et al., 2013; Vinson et al., 2013). The overall decreasing radium trend away from the beach indicates dilution or decay of the terrestrial radium source away from the shoreline over a time scale comparable to the isotope half-life (Moore, 2000b). The timescale of coastal mixing processes coincides with short half-lives of ^{223}Ra and ^{224}Ra isotopes which can be used to trace total (fresh + saline) groundwater discharge (García-Orellana et al., 2014).

The ^{224}Ra mass balance could not be closed with sediment diffusion, decay, and offshore mixing alone in 8 transects. In these transects, an additional source of ^{224}Ra was required to close the mass balance which was assumed to be SGD. Our interpretation is aligned with previous mass balance studies conducted in other semi-enclosed microtidal systems such as the Mediterranean Sea and Long Island Sound where SGD was the residual advective source of radium required to close mass balances (Rodellas et al., 2015a; Tamborski et al., 2020). Contrastingly, along 7 Swedish transects the radium released by sediment diffusion was enough to balance the cumulative removal of radium from its sinks. The absence of an identifiable SGD signal in these transects can be likely explained by the increased impact of benthic diffusion at the time of sampling (Rodellas et al., 2015a; Tamborski et al., 2020). This does not necessarily imply complete absence of groundwater discharge. The low permeability in these coastal-transects might result in weak groundwater flow relative to sedimentary radium diffusion causing it to be below detection level of mass balance approach (Rodellas et al., 2015b). Additionally, departures from the steady-state assumption of the model may contribute uncertainty to individual transect budgets (Kwon et al., 2014).

Substantial spatial variation in SGD flow rates ranging between 1 and $10 \text{ m}^2 \text{ day}^{-1}$ can be attributed to regional differences in hydrodynamics and hydrogeology along Baltic coastline. Groundwater discharge is highly sensitive to changes in hydraulic gradients, aquifer permeability, shoreline morphology, sea level oscillations, and hydrodynamic processes like coastal mixing and currents, that together control SGD in each transect location (Robinson et al., 2018; Taniguchi et al., 2019). SGD dynamics in the region are also influenced by the weak tidal regime and strong meteorological forcing that is characteristic of the Baltic Sea (Leppäranta and Myrberg, 2009b). These processes may substantially

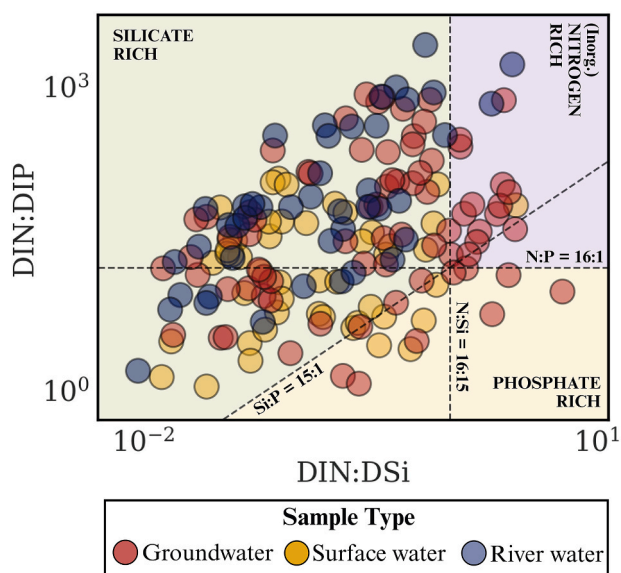


Fig. 7. Stoichiometric relationships between dissolved silicate (DSi), dissolved inorganic nitrogen (DIN), and dissolved inorganic phosphorus (DIP) in groundwater, seawater, and river water, shown as DIN:DIP versus DIN:DSi with Redfield reference lines (N:P = 16:1; N:Si = 16:15; Si:P = 15:1). The ratios are represented as log scale on both the axes.

influence hydraulic gradients and contribute to temporal variability in SGD fluxes across the coastline. Thus, seasonal and short-term hydrodynamic and meteorological variability may further increase spatial heterogeneity and uncertainties observed in tracer-derived SGD-fluxes (Burnett et al., 2006).

The observed differences in SGD rates between transects reflects these hydrogeological and hydrodynamic constraints. For instance, the highest groundwater discharge rate quantified was along a transect in Karlskrona ($\sim 10 \pm 3 \text{ m}^2 \text{ day}^{-1}$) while the lowest was in Sundsvall (Fig. 5A). In Karlskrona, the shoreline is dominated by crystalline bedrock with permeable coastal quaternary sediments that favor groundwater discharge (Giese and Barthel, 2021; Knutsson and Morfeldt, 1978; Kornfält and Larsson, 1987). In Sundsvall, the coastal sediments are dominated by more heterogeneous, fine grained glacial and post glacial deposits which are less permeable and hence restrict groundwater discharge (Grånäs, 2010). Additionally, low salinities and relatively modest coastal relief in Sundsvall imply weaker density and hydraulic gradients while less energetic waves and currents limit recirculation of coastal groundwater, resulting in a weak total SGD signal (Kuliński et al., 2022b; Lehmann et al., 2026; Roiha et al., 2018).

Dominant modes of groundwater discharge also contribute to the observed spatial variability in SGD rates. SGD is strongly influenced by local hydrological settings and hence vary across the Baltic Sea coastline (Von Ahn et al., 2024). While fractured crystalline bedrock along the Swedish coast of northern Baltic Proper promote more focused groundwater flow through the fractures (Krall et al., 2017), sandy coastal aquifers in the Gulf of Gdansk and Riga favor diffuse seepage through permeable beach sediments (Soomere et al., 2025). Further north, the Bothnian Bay coastline, dominated by glacial and post-glacial fine-grained sediments likely support lower intensity focused discharge through pockmarks (Ikonen et al., 2022; Luoma et al., 2021). While the mass balance approach used in this study is unable to distinguish point source springs from diffuse seepage faces, contrasting geological conditions along the Baltic will impact total SGD rates.

Earlier tracer-based SGD investigations in the Baltic Sea region have quantified local discharge rates at four coastal sites (Fig. 5). Among these, a Swedish study applied radium to estimate a discharge rate of $12 \text{ m}^2/\text{day}$ in shallow coastal waters off Forsmark (Krall et al., 2017). This is comparable to the total SGD rate of $10 \pm 3 \text{ m}^2 \text{ day}^{-1}$ that we calculated in Karlskrona, Sweden. Similarly, our total SGD rates of $6 \pm 2 \text{ m}^2 \text{ day}^{-1}$ in the Gulf of Gdansk and Riga also align closely with previous estimates of $11 \text{ m}^2 \text{ day}^{-1}$ quantified using ^{222}Rn in inner parts of Bay of Puck, Poland (Von Ahn et al., 2024). Groundwater discharge was also observed in sandy sediments of the Finnish Hanko peninsula, but discharge rates were not quantified (Ikonen et al., 2022). Our study builds on these earlier observations by calculating a total SGD rate of $3 \pm 8 \text{ m}^2 \text{ day}^{-1}$ in Helsinki, Finland. While we did not investigate sites along German coastline, previous estimates of $\sim 4 \text{ m}^2 \text{ day}^{-1}$ and $8 \text{ m}^2 \text{ day}^{-1}$ reported in Eckernförde Bay and Wismar Bay, respectively, fall within our total SGD range of 0 to $10 \text{ m}^2 \text{ day}^{-1}$ (Purkl and Eisenhauer, 2004; Von Ahn et al., 2024).

Multiple approaches including seepage meters, porewater salinity profiles, and hydroacoustic mapping, adopted in the Baltic Sea have primarily captured fresh SGD (Kaleris et al., 2002; Pempkowiak et al., 2010; Purkl and Eisenhauer, 2004). Numerical models and groundwater flow models like HYDRUS-2D often focus on estimating fresh SGD because they treat groundwater discharge as purely terrestrial flow (Racasa et al., 2021). While fresh SGD may be a vital conduit for transport of terrestrial solutes, it represents only 1–10% of total SGD (Luijendijk et al., 2020). Considering recirculated seawater often causes total SGD-derived total exchange to either exceed or be comparable to corresponding river discharge estimates (Kwon et al., 2014; Moore, 2010; Santos et al., 2021).

Although tracer studies capturing recirculated SGD remain rare in the Baltic Sea, existing investigations in Bay of Puck, Poland report fresh SGD inputs itself are a major source of mercury, nutrients, and

pharmaceuticals (Szymczycha et al., 2020a; Szymczycha et al., 2020b; Szymczycha et al., 2014; Szymczycha et al., 2013). The contrast between the flow rates of total and fresh SGD were highlighted in the Bothnian Sea where radium mass balance derived total SGD was about two orders of magnitude larger than numerically modelled fresh SGD (Krall et al., 2017). Similarly, in Eckernförde Bay, fresh SGD rates obtained using seepage meters and porewater chemistry were only 14–21% of the total SGD obtained from radium mass balance models (Kreuzburg et al., 2023). The present study quantified total SGD in 8 coastal transects of the Baltic Sea by applying ^{224}Ra mass balance models which explicitly include recirculated SGD component. Fresh SGD accounted for only $\sim 2\%$ (median) of our ^{224}Ra -derived total SGD rates at these 8 sites, providing additional evidence that fresh SGD is a small component of total SGD in the Baltic region.

4.3. Nutrient enrichment in groundwater

The Baltic coast is exposed to intense anthropogenic stressors which increase nutrient inputs via agricultural leaching, and sewage discharge from treatment plants (Auditors, 2016; Müller-Karulis et al., 2024). The long residence time of groundwater within STEs (Moore, 1999) allows for nutrient accumulation, making average DIN and DIP concentrations of groundwater samples ~ 4 times higher and ~ 21 times higher than sampled rivers, respectively. Under hypoxic and anoxic conditions, sediments become a significant internal source of phosphorus through the release of redox-sensitive, iron-bound P into the water column (Charette and Sholkovitz, 2002). This internal loading via recirculated SGD may reinforce eutrophication and prolong the persistence of hypoxia, even in the absence of continued external nutrient inputs.

The brackish nature of groundwater further enhances nutrient desorption and cation exchange of DIP and DIN from aquifer walls (Kroeger and Charette, 2008; Moore, 1999; Zhu et al., 2025). Brackish and hypoxic conditions promote remineralization of organic matter, coupled nitrification–denitrification, and ammonium accumulation which collectively drive nitrogen enrichment in groundwater (Seitzinger et al., 2006) observed precisely at the shoreline of our transects (Fig. 4). Oscillating oxic/hypoxic conditions within STEs promote reductive dissolution/precipitation of Fe-Mn oxides, occasionally releasing particle-bound phosphorus into transiting groundwater (Charette and Sholkovitz, 2002). This phosphorus-enriched groundwater may exert an oxygen demand which potentially amplifies benthic hypoxia, creating a positive feedback loop with internal phosphorus loading (Stigebrandt and Andersson, 2020).

Silicate enrichment in groundwater can also be attributed to long residence times within STEs, which prolongs silicate mineral dissolution and enhances DSI accumulation in groundwater (Humborg et al., 2008; Rahman et al., 2019). Groundwater flow paths intersect extensive Quaternary silica-rich sands and glacial deposits that dominate large parts of the northern Baltic Sea and Swedish coastline (Schwarzer et al., 2008), providing a silicate source to discharging groundwater (Sverdrup et al., 2019). Contrastingly, because rivers flow at much faster rates, water–rock interaction times are shorter, which reduces silicate dissolution and leads to river waters containing only half the concentrations observed in beach groundwaters (Ameli et al., 2017; Maher, 2010).

Groundwater nutrient stoichiometry along the Baltic coastline reflects phosphorus limitation and nitrogen enrichment with potential impacts on the receiving coastal waters. The deviation from Redfield ratio observed in groundwater is likely due to preferential regeneration and mobilization of inorganic nitrogen and silicate within hypoxic STEs (Wilson et al., 2024; Zhu et al., 2025). Enhanced organic matter degradation, coupled nitrification–denitrification, and mineral dissolution within STEs promote nitrogen and silicate enrichment (Couturier et al., 2017; Moore, 1999), while phosphate is retained through adsorption, re-precipitation, and burial processes (Lenstra et al., 2018; Linkhorst et al., 2017; Rouxel et al., 2008). Consequently, nutrient ratios in groundwater departing from marine Redfield proportions may further

aggravate phosphorus limitation in Baltic coastal waters while favoring phytoplankton groups adapted to elevated nitrogen availability (Kroeger et al., 2006).

Additionally, SGD nutrient stoichiometry may influence phytoplankton community structure in coastal waters (Liang et al., 2025). Elevated DSi:DIP ratios indicate that SGD can supply substantial dissolved silica together with inorganic nitrogen which promotes diatomic productivity in nearshore regions (Sospedra et al., 2018). Since diatoms require silica for frustule formation high silica availability favors their productivity (Yool and Tyrrell, 2003). In contrast, reductions in silica relative to nitrogen promotes non-siliceous phytoplankton groups such as dinoflagellates, contributing to the documented diatom-to-dinoflagellate shift in the Baltic spring bloom (Klais et al., 2011).

4.4. Groundwater nutrient fluxes and their implications

The high spatial variability and uncertainties observed in SGD-derived nutrient fluxes (Fig. 5) are consistent with earlier studies conducted in the Baltic Sea, which report order-of-magnitude differences between groundwater derived nutrient fluxes between SGD hotspots such as the Bay of Puck and Eckernförde Bay (Kreuzburg et al., 2023; Schlüter et al., 2004; Szymczycha et al., 2020b). Studies from these regions also highlight how SGD-derived phosphate fluxes differed by an order-of-magnitude even between nearby embayments, thereby demonstrating strong spatial heterogeneity of subterranean estuarine nutrient delivery. Similarly, SGD-associated nutrient enrichment has also been observed in semi-enclosed coastal ecosystems, like the Mediterranean Sea (Rodellas et al., 2015a), Long Island Sound (Tamborski et al., 2020), and Monterey Bay (Lecher et al., 2015), where SGD rates commonly range between 1 and 15 m² day⁻¹. While SGD-derived fluxes quantified in this study broadly align with globally observed values, the Baltic Sea's unique combination of restricted flushing, brackish conditions, high spatial variability in coastal geology and long water residence times (Leppäranta and Myrberg, 2009b; Winsor et al., 2001) may amplify the ecological significance of SGD.

Despite having broadly similar coastal geology and anthropogenic nutrient exposure (Andersen et al., 2011), phosphate fluxes in the Gulf of Riga were substantially higher than those observed in the Gulf of Gdansk. The elevated phosphate fluxes observed in Riga are consistent with more efficient phosphorus mobilization, potentially associated with stronger reducing conditions within STEs that favor the release of sediment-bound phosphorus into groundwater prior to discharge (Slomp and Van Cappellen, 2004). In contrast, although groundwater nutrient concentrations were elevated along the coast of the Bothnian Bay, SGD-derived nutrient fluxes remained low. This indicates that while nutrient regeneration is occurring within these subterranean estuaries, the transport of regenerated nutrients to coastal waters via advective SGD is limited. Elevated dissolved silicate fluxes observed along several Swedish coastal transects further suggest the importance of prolonged groundwater–sediment interaction and silicate weathering in controlling regional differences in nutrient export (Rahman et al., 2019). Together, these observations demonstrate that nutrient flux variability across the Baltic Sea is controlled not only by groundwater discharge rates, but also by regional differences in nutrient regeneration, mobilization, and transport within subterranean estuaries.

To obtain initial insight into the potential impact of SGD on Baltic Sea nutrient budgets, we performed a first-order basin-level estimate for SGD derived nutrient inputs. Earlier regional upscaling exercises assumed Baltic-wide SGD derived nutrient fluxes were equivalent to SGD inputs in the Bay of Puck, part of Gulf of Gdansk (Szymczycha et al., 2012). Most local SGD studies in the Baltic do not report uncertainties but highlight the influence of SGD on biogeochemical cycles and the need for increased spatial coverage. We extrapolate the SGD rate of all coastal transects along the 8000 km Baltic coastline under the assumption of negligible SGD fluxes when radium budgets are dominated by diffusion as observed in 9 out of 17 transects, and using propagated

uncertainties of individual transects. Our first-order upscaling indicates that SGD-derived inorganic nitrogen load may exceed fluvial loads even though uncertainties remain greater than 100% (Table 2). This is consistent with local studies done in Bay of Puck, Eckernförde Bay, and Forsmark that identify total SGD as a major source of dissolved nutrients comparable to local rivers (Kłostowska et al., 2020; Krall et al., 2017; Kreuzburg et al., 2023). The SGD-derived DIP and DSi loads in this study are also large and estimated to be within the same order of magnitude as river inputs.

4.5. Limitations

Despite expanding the spatial coverage, we highlight that the upscaled estimates in current study remain highly uncertain. Our analysis is restricted to summertime sampling when river fluxes are the highest in the Baltic Sea (Rasmussen and Gustafsson, 2003). Results from the sediment incubation experiments used to estimate diffusion fractions ($f_{\text{Diffusion}}$) might not reflect in-situ dynamics since the experiments were conducted under controlled oxic conditions and assumed diffusion–decay equilibrium after >60 days. Therefore, the differences between laboratory and field conditions can introduce unquantified uncertainties into the mass balance model.

Our large-scale special survey represents summer conditions only. The SGD-derived nutrient fluxes quantified in this study are expected to vary seasonally due to changes in both hydrological forcing and subterranean estuary biogeochemistry. Seasonal variations in precipitation, snowmelt, sea-level and evapotranspiration alters the hydraulic gradients controlling SGD (Michael et al., 2005). Also, seasonal changes in physicochemical conditions within STEs influence nutrient regeneration (Kroeger and Charette, 2008; Sun et al., 2024). The basin-wide influence of local sea-level variability caused by winds on SGD inputs remains unresolved in the Baltic Sea (Racasa et al., 2021). Since no seasonal estimates of SGD are currently available for the Baltic Sea (Reckermann et al., 2022), the summertime estimates presented in this study should be interpreted as first-order assessment of the magnitude of SGD-derived nutrient loads rather than direct annual averages.

While the sampled transects were distributed across multiple Baltic sub-basins and encompass diverse hydrogeological settings including crystalline bedrock coastlines, sandy aquifers, and fine-grained glacial sediments, the sampling coverage does not represent the complete geological and hydrological diversity of the ~8000 km Baltic coastline. Nevertheless, our results consistently indicate substantial nutrient delivery via SGD and its potential role in promoting eutrophication in Baltic coastal waters. Coastal hypoxia and anoxia alter biogeochemical functioning of nearshore sediments which potentially modifies pore-water transport pathways, and benthic exchange dynamics (Villnäs et al., 2012). Enhanced accumulation of organic-rich fine sediments coupled with reduced oxygen penetration may further change pore structure and decrease flushing of STEs (Fox and Trefry, 2023; Santos et al., 2012). Thus, reduced porewater flushing and prolonged groundwater residence times under reducing conditions may intensify nutrient regeneration, thereby modifying both magnitude and chemical composition of SGD fluxes over longer timescales.

5. Conclusions

This study provides the first spatially integrated tracer-based

Table 2

Central estimates for nutrient fluxes associated with total SGD and river inputs extrapolated along the 8000 km long Baltic coastline.

Nutrient	Total SGD Loads X 10 ⁶ (mol/day)	River Loads X 10 ⁶ (mol/day)
DSi	2.9 ± 9.9	2.2 ± 0.5
DIN	2.1 ± 4.3	0.3 ± 0.1
DIP	0.1 ± 0.3	0.01 ± 0.002

assessment of total SGD-linked nutrient dynamics along 17 transects located across 10 coastal regions of the Baltic Sea. Subterranean estuaries are brackish, hypoxic, and highly enriched in nutrients relative to river and seawater samples. ^{224}Ra mass balance models identified active groundwater discharge in about half the transects while sediment diffusion dominated as a radium source along most of the Swedish coastline. Total SGD rates quantified in 8 coastal transects ranged from $\sim 1\text{--}10\text{ m}^2\text{ day}^{-1}$. Extrapolation of SGD-derived nutrient fluxes along the Baltic coastline yielded central estimates with values of $2.9 \pm 9.9 \times 10^6\text{ mol day}^{-1}$, $2.1 \pm 4.3 \times 10^6\text{ mol day}^{-1}$, and $0.1 \pm 0.3 \times 10^6\text{ mol day}^{-1}$ for DSi, DIN and DIP, respectively (Table 2). While the large uncertainties exceeding 100% of the central estimate require further constraints, the potentially large total SGD fluxes may be comparable or exceed regional river nutrient loads and imply that subterranean estuaries may be a major source of nutrients to the Baltic Sea.

CRedit authorship contribution statement

Apajita S. Tomer: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tristan McKenzie:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Claudia Majtényi-Hill:** Writing – review & editing, Validation, Project administration, Methodology, Investigation. **Ceylena Holloway:** Writing – review & editing, Validation, Investigation. **Júlia Rodríguez-Puig:** Writing – review & editing, Validation, Investigation. **Gloria Reithmaier:** Writing – review & editing, Validation, Investigation. **Línea Henriksson:** Writing – review & editing, Validation, Investigation. **Beata Szymczycha:** Writing – review & editing, Validation, Investigation. **Isaac R. Santos:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marchem.2026.104674>.

Data availability

Research Link Provided

References

Ameli, A.A., et al., 2017. Primary weathering rates, water transit times, and concentration-discharge relations: A theoretical analysis for the critical zone. *Water Resour. Res.* 53 (1), 942–960.

- Andersen, J., Laamanen, M., 2009. Eutrophication in the Baltic Sea—an Integrated Assessment of the Effects of Nutrient Enrichment in the Baltic Sea Region. Baltic Marine Environment Protection Commission—Helsinki Commission.
- Andersen, J.H., et al., 2011. Getting the measure of eutrophication in the Baltic Sea: towards improved assessment principles and methods. *Biogeochemistry* 106 (2), 137–156.
- Auditors, E.C.O., 2016. Combating Eutrophication in the Baltic Sea: Further and More Effective Action Needed. Publications Office of the European Union Luxembourg.
- Philip Axe, J.C., Fleming, Vivi, Heyden, Birgit, Hoikkala, Laura, Hüttel, Theodor, Kaikkonen, Laura, Leujak, Wera, Lips, Urmars, Markager, Stig, Nielsen, Lasse Tor, Stoicescu, Stella-Theresa, (2023). HELCOM Thematic assessment of Eutrophication 2016–2021. Baltic Sea Environ. Proc. No.192, holas 3, Available at: https://helcom.fi/post_type/publ/holas3_eut, 9–41.
- Böttcher, M.E., et al., 2024. Coastal–groundwater interfaces (Submarine groundwater discharge). *Ecohydrol. Interfaces* 123–147.
- Bratton, J.F., 2010. The three scales of submarine groundwater flow and discharge across passive continental margins. *J. Geol.* 118 (5), 565–575.
- Burnett, W., et al., 2006. Quantifying submarine groundwater discharge in the coastal zone via multiple methods. *Sci. Total Environ.* 367 (2–3), 498–543.
- Carstensen, J., et al., 2014. Hypoxia in the Baltic Sea: biogeochemical cycles, benthic fauna, and management. *Ambio* 43 (1), 26–36.
- Charette, M., Sholkovitz, E., 2006. Trace element cycling in a subterranean estuary: Part 2. Geochemistry of the pore water. *Geochimica et Cosmochimica Acta* 70, 811–826.
- Charette, M.A., Sholkovitz, E.R., 2002. Oxidative precipitation of groundwater-derived ferrous iron in the subterranean estuary of a coastal bay. *Geophys. Res. Lett.* 29 (10), 85–1–85–4.
- Chen, X., et al., 2025. Sandy Subterranean Estuaries Minimize Groundwater Nitrogen Pollution Impacts on Coastal Waters. *Geophys. Res. Lett.* 52.
- Cho, H.-M., Kim, G., 2016. Determining groundwater Ra end-member values for the estimation of the magnitude of submarine groundwater discharge using Ra isotope tracers. *Geophys. Res. Lett.* 43 (8), 3865–3871.
- Cloern, J.E., 2001. Our evolving conceptual model of the coastal eutrophication problem. *Marine Ecol. Progr. Series* 210, 223–253.
- Couturier, M., et al., 2017. Nitrogen transformations along a shallow subterranean estuary. *Biogeochemistry* 14 (13), 3321–3336.
- Duarte, C., et al., 2015. Paradigms in the recovery of estuarine and coastal ecosystems. *Estuaries Coasts* 38, 1202–1212.
- Fox, A.L., Trefry, J.H., 2023. Nutrient fluxes from recent deposits of fine-grained, organic-rich sediments in a Florida estuary. *Front. Marine Sci.* 10–2023.
- García-Orellana, J., et al., 2014. Evaluation of ^{224}Ra as a tracer for submarine groundwater discharge in Long Island Sound (NY). *Geochimica et Cosmochimica Acta* 141, 314–330.
- García-Orellana, J., et al., 2021. Radium isotopes as submarine groundwater discharge (SGD) tracers: Review and recommendations. *Earth-Sci. Rev.* 220, 103681.
- García-Solsona, E., et al., 2008. Estimating submarine groundwater discharge around Isola La Cura, northern Venice Lagoon (Italy), by using the radium quartet. *Marine Chem.* 109 (3–4), 292–306.
- Giese, M., Barthel, R., 2021. Saltwater intrusion in fractured crystalline bedrock. *Hydrogeol. J.* 29 (7), 2313–2328.
- Gonneea, M.E., Morris, P.J., Dulaiova, H., Charette, M.A., 2008. New perspectives on radium behavior within a subterranean estuary. *Marine Chem.* 109 (3–4), 250–267.
- Gonneea, M.E., Mulligan, A.E., Charette, M.A., 2013. Seasonal cycles in radium and barium within a subterranean estuary: Implications for groundwater derived chemical fluxes to surface waters. *Geochimica et Cosmochimica Acta* 119, 164–177.
- Grånäs, K., 2010. Beskrivning till jordartskartan delar av. Sundsvalls kommun, Sveriges Geologiska Undersökning (SGU), Uppsala.
- Hinsby, K., et al., 2025. Towards a digital information platform for locating and assessing environmental impacts of submarine groundwater discharge: examples from the Baltic Sea. *J. Marine Sci. Eng.* 13 (3), 614.
- Humborg, C., Smedberg, E., Medina, M.R., Mörtz, C.-M., 2008. Changes in dissolved silicate loads to the Baltic Sea—the effects of lakes and reservoirs. *J. Marine Syst.* 73 (3–4), 223–235.
- Ikonen, J., Hendriksson, N., Luoma, S., Lahaye, Y., Virtasalo, J.J., 2022. Behavior of Li, S and Sr isotopes in the subterranean estuary and seafloor pockmarks of the Hanko submarine groundwater discharge site in Finland, northern Baltic Sea. *Appl. Geochem.* 147, 105471.
- Kaleris, V., Lagas, G., Marcinek, S., Piotrowski, J.A., 2002. Modelling submarine groundwater discharge: an example from the western Baltic Sea. *J. Hydrol.* 265 (1), 76–99.
- Klais, R., Tamminen, T., Kremp, A., Spilling, K., Olli, K., 2011. Decadal-scale changes of dinoflagellates and diatoms in the anomalous Baltic Sea spring bloom. *PLoS One* 6 (6), e21567.
- Kłostowska, Ż., Szymczycha, B., Lengier, M., Zarzeczańska, D., Dzierżbicka-Głowacka, L., 2020. Hydrogeochemistry and magnitude of SGD in the Bay of Puck, southern Baltic Sea. *Oceanologia* 62 (1), 1–11.
- Knutsson, G., Morfeldt, C.-O., 1978. Vatten i jord och berg. Ingenjöröförel., Stockholm.
- Kornfält, K.-A., Larsson, K., 1987. Geological maps and cross-sections of Southern Sweden. Swedish Nuclear Fuel and Waste Management Co., Stockholm.
- Krall, L., et al., 2017. Submarine groundwater discharge at Forsmark, Gulf of Bothnia, provided by Ra isotopes. *Marine Chem.* 196, 162–172.
- Kreuzburg, M., et al., 2023. Submarine groundwater discharge-derived nutrient fluxes in Eckernförde Bay (Western Baltic Sea). *Estuaries Coasts* 46 (5), 1190–1207.
- Kroeger, K., Charette, M., 2008. Nitrogen biogeochemistry of submarine groundwater discharge. *Limnol. Oceanogr.* 53 (3), 1025–1039.
- Kroeger, K., Swarzenski, P., Crusius, J., Bratton, J., Charette, M., 2006. Submarine Ground-Water Discharge: Nutrient Loading and Nitrogen Transformations.

- Kuliński, K., Rehder, G., Asmala, E., Bartosova, A., Carstensen, J., Gustafsson, B., Hall, P., O.J., Humborg, C., Jilbert, T., Jürgens, K., Meier, H.E.M., Müller-Karulis, B., Naumann, M., Olesen, J.E., Savchuk, O., Schramm, A., Slomp, C.P., Sofiev, M., Sobek, A., Szymczycha, B., Undeman, E., 2022. Biogeochemical functioning of the Baltic Sea. *Earth Syst. Dynam.* 13, 633–685. <https://doi.org/10.5194/esd-13-633-2022>.
- Kwon, E.Y., et al., 2014. Global estimate of submarine groundwater discharge based on an observationally constrained radium isotope model. *Geophys. Res. Lett.* 41 (23), 8438–8444.
- Lecher, A., et al., 2015. Nutrient loading through submarine groundwater discharge and phytoplankton growth in Monterey Bay, CA. *Environ. Sci. Technol.* 49 (11), 6665–6673.
- Lehmann, A., et al., 2026. Salinity dynamics of the Baltic Sea. *Earth Syst. Dyn.* 13, 373–392.
- Lenstra, W.K., et al., 2018. Large variations in iron input to an oligotrophic Baltic Sea estuary: impact on sedimentary phosphorus burial. *Biogeochemistry* 15 (22), 6979–6996.
- Leppäranta, M., Myrberg, K., 2009a. Future of the Baltic Sea.
- Leppäranta, M., Myrberg, K., 2009b. *Physical Oceanography of the Baltic Sea*. Springer.
- Liang, W., et al., 2025. Distinguishing the impact of river discharge and submarine groundwater discharge on phytoplankton community in coastal water. *Water Res.* 124355.
- Linkhorst, A., Dittmar, T., Waska, H., 2017. Molecular fractionation of dissolved organic matter in a shallow subterranean estuary: the role of the iron curtain. *Environ. Sci. Technol.* 51 (3), 1312–1320.
- Luijendijk, E., Gleeson, T., Moosdorf, N., 2020. Fresh groundwater discharge insignificant for the world's oceans but important for coastal ecosystems. *Nature Commun.* 11 (1), 1260.
- Luo, M., et al., 2024. Optimizing groundwater radium end-members in submarine groundwater discharge estimation by incorporating groundwater flow information. *J. Hydrol.* 630, 130786.
- Luoma, S., Majaniemi, J., Pullinen, A., Mursu, J., Virtasalo, J., 2021. Geological and groundwater flow model of a submarine groundwater discharge site at Hanko (Finland), northern Baltic Sea. *Hydrogeol. J.* 29, 1279–1297.
- Maier, K., 2010. The dependence of chemical weathering rates on fluid residence time. *Earth Planet. Sci. Lett.* 294 (1–2), 101–110.
- McCrackin, M.L., Jones, H.P., Jones, P.C., Moreno-Mateos, D., 2017. Recovery of lakes and coastal marine ecosystems from eutrophication: A global meta-analysis. *Limnol. Oceanogr.* 62 (2), 507–518.
- McKenzie, T., et al., 2025. Large scale hydrogeochemical and isotopic observations in the Baltic Sea system. *Scientific data* 12 (1), 1757.
- Michael, H.A., Mulligan, A.E., Harvey, C.F., 2005. Seasonal oscillations in water exchange between aquifers and the coastal ocean. *Nature* 436 (7054), 1145–1148.
- Moore, W., 1999. The subterranean estuary: a reaction zone of ground water and sea water. *Marine Chem.* 65, 111–125.
- Moore, W., 2010. The effect of submarine groundwater discharge on the ocean. *Ann. Rev. Marine Sci.* 2, 59–88.
- Moore, W.S., 2000a. Ages of continental shelf waters determined from ^{223}Ra and ^{224}Ra . *J. Geophys. Res.: Oceans* 105 (C9), 22117–22122.
- Moore, W.S., 2000b. Determining coastal mixing rates using radium isotopes. *Continental Shelf Res.* 20 (15), 1993–2007.
- Moore, W.S., 2003. Sources and fluxes of submarine groundwater discharge delineated by radium isotopes. *Biogeochemistry* 66 (1), 75–93.
- Moore, W.S., Arnold, R., 1996. Measurement of ^{223}Ra and ^{224}Ra in coastal waters using a delayed coincidence counter. *J. Geophys. Res.: Oceans* 101 (C1), 1321–1329.
- Moore, W.S., et al., 2024. SGD-OD: investigating the potential oxygen demand of submarine groundwater discharge in coastal systems. *Scientific Reports* 14 (1), 9249.
- Moosdorf, N., et al., 2021. A state-of-the-art perspective on the characterization of subterranean estuaries at the regional scale. *Front. Earth Sci.* 9, 601293.
- Müller-Karulis, B., Gustafsson, B., Durkin, M., 2024. Fact Sheet: Effects of the new UWWTD on Nutrient Inputs to the Baltic Sea. Stockholm University.
- Pempkowiak, J., Szymczycha, B., Kotwicki, L., 2010. Submarine groundwater discharge (SGD) to the Baltic Sea. *Rocznik Ochrona Środowiska* 12, 17–32.
- Pratt, L., Spall, M., 2008. Circulation and exchange in choked marginal seas. *J. Phys. Oceanogr.* 38, 2639–2661.
- Preisner, M., Smol, M., Szoldrowska, D., 2021. Trends, insights and effects of the Urban Wastewater Treatment Directive (91/271/EEC) implementation in the light of the Polish coastal zone eutrophication. *Environ. Manage.* 67, 342–354.
- Purkamo, L., et al., 2022. Impact of submarine groundwater discharge on biogeochemistry and microbial communities in pockmarks. *Geochimica et Cosmochimica Acta* 334, 14–44.
- Purki, S., Eisenhauer, A., 2004. Determination of radium isotopes and ^{222}Rn in a groundwater affected coastal area of the Baltic Sea and the underlying sub-sea floor aquifer. *Marine Chem.* 87 (3), 137–149.
- Racasa, E.D., Lennartz, B., Toro, M., Janssen, M., 2021. Submarine groundwater discharge from non-tidal coastal peatlands along the Baltic Sea. *Front. Earth Sci.* 9, 665802.
- Racasa, E.D., et al., 2025. Characterization of submarine groundwater discharge in front of a rewetted coastal Peatland. *Estuaries Coasts* 49 (1), 12.
- Rahman, S., Tamborski, J.J., Charette, M.A., Cochran, J.K., 2019. Dissolved silica in the subterranean estuary and the impact of submarine groundwater discharge on the global marine silica budget. *Marine Chem.* 208, 29–42.
- Rasmussen, B., Gustafsson, B., 2003. Computation of nutrient pools and fluxes at the entrance to the Baltic Sea, 1974–1999. *Continental Shelf Res.* 23 (5), 483–500.
- Reckermann, M., et al., 2022. Human impacts and their interactions in the Baltic Sea region. *Earth Syst. Dyn.* 13 (1), 1–80.
- Reusch, T.B.H., et al., 2018. The Baltic Sea as a time machine for the future coastal ocean. *Sci. Adv.* 4 (5), eaar8195.
- Robinson, C., et al., 2017. Groundwater dynamics in subterranean estuaries of coastal unconfined aquifers: Controls on submarine groundwater discharge and chemical inputs to the ocean. *Adv. Water Resour.* 115, 315–331.
- Robinson, C.E., et al., 2018. Groundwater dynamics in subterranean estuaries of coastal unconfined aquifers: Controls on submarine groundwater discharge and chemical inputs to the ocean. *Adv. Water Resour.* 115, 315–331.
- Rodellas, V., Garcia-Orellana, J., Masqué, P., Feldman, M., Weinstein, Y., 2015a. Submarine groundwater discharge as a major source of nutrients to the Mediterranean Sea. *Proc. Natl. Acad. Sci.* 112 (13), 3926–3930.
- Rodellas, V., Garcia-Orellana, J., Masqué, P., Font-Muñoz, J.S., 2015b. The influence of sediment sources on radium-derived estimates of Submarine Groundwater Discharge. *Marine Chem.* 171, 107–117.
- Roiha, P., et al., 2018. Estimating currents from argo trajectories in the bothnian sea, baltic sea. *Front. Marine Sci.* 5, 308.
- Rouxel, O., Sholkovitz, E., Charette, M., Edwards, K.J., 2008. Iron isotope fractionation in subterranean estuaries. *Geochimica et Cosmochimica Acta* 72 (14), 3413–3430.
- Saban, R.C., Jenner, A.-K., Janssen, M., Schmiedinger, I., Böttcher, M.E., 2025. A multi-isotope hydrobiogeochemical characterization of a subterranean estuary before and after changes in coastal protection. *Estuaries Coasts* 48 (6), 174.
- Salley, B.A., Bradshaw, J.G., Neilson, B.J., 1987. Results of Comparative Studies of Preservation Techniques for Nutrient Analysis of Water Samples.
- Santos, I.R., Eyre, B.D., Huettel, M., 2012. The driving forces of porewater and groundwater flow in permeable coastal sediments: a review. *Estuarine Coastal Shelf Sci.* 98, 1–15.
- Santos, I.R., et al., 2021. Submarine groundwater discharge impacts on coastal nutrient biogeochemistry. *Nature Rev. Earth Environ.* 2 (5), 307–323.
- Schlüter, M., Sauter, E.J., Andersen, C.E., Dahlgard, H., Dando, P.R., 2004. Spatial distribution and budget for submarine groundwater discharge in Eckernförde Bay (Western Baltic Sea). *Limnol. Oceanogr.* 49 (1), 157–167.
- Scholten, J.C., et al., 2010. Preparation of Mn-fiber standards for the efficiency calibration of the delayed coincidence counting system (RaDeCC). *Marine Chem.* 121 (1–4), 206–214.
- Schwarzer, K., Ricklefs, K., Bartholomä, A., Zeiler, M., 2008. Geological development of the North Sea and the Baltic Sea. *Die Küste* 74 (74), 1–17.
- Seitzinger, S., et al., 2006. Denitrification across landscapes and waterscapes: a synthesis. *Ecol. Appl.* 16 (6), 2064–2090.
- Slomp, C.P., Van Cappellen, P., 2004. Nutrient inputs to the coastal ocean through submarine groundwater discharge: controls and potential impact. *J. Hydrol.* 295 (1–4), 64–86.
- Snoeijs-Leijonmalm, P., Schubert, H., Radziejewska, T., 2017. *Biological Oceanography of the Baltic Sea*. Springer Science & Business Media.
- Soomere, T., Jankowski, M.Z., Eelsalu, M., Parnell, K.E., Viška, M., 2025. Alongshore sediment transport analysis for a semi-enclosed basin: a case study of the Gulf of Riga, the Baltic Sea. *Ocean Sci.* 21 (2), 619–641.
- Sospedra, J., et al., 2018. Identifying the main sources of silicate in coastal waters of the Southern Gulf of Valencia (Western Mediterranean Sea). *Oceanologia* 60 (1), 52–64.
- Stewart, B.T., Bryan, K.R., Pilditch, C.A., Santos, I.R., 2018. Submarine groundwater discharge estimates using radium isotopes and related nutrient inputs into Tauranga Harbour (New Zealand). *Estuaries Coasts* 41 (2), 384–403.
- Stigebrandt, A., Andersson, A., 2020. The Eutrophication of the Baltic Sea has been Boosted and Perpetuated by a Major Internal Phosphorus Source. *Front. Marine Sci.* 7–2020.
- Strickland, J., 1972. *A practical handbook of seawater analysis*. Fisher. Res. Board Canada 310.
- Sun, D., Ibáñez, J.S.P., Zhang, J., Zhang, G., Jiang, S., 2024. Phosphorus cycling in a subterranean estuary seepage face: a seasonal view on inventory composition and linkage with nitrate transformations. *Sci. Total Environ.* 924, 171473.
- Sverdrup, H.U., et al., 2019. Reviews and syntheses: Weathering of silicate minerals in soils and watersheds: Parameterization of the weathering kinetics module in the PROFILE and ForSAFE models. *Biogeochem. Discuss.* 2019, 1–58.
- Szymczycha, B., Vogler, S., Pempkowiak, J., 2012. Nutrient fluxes via submarine groundwater discharge to the Bay of Puck, southern Baltic Sea. *Sci. Total Environ.* 438, 86–93.
- Szymczycha, B., Miotk, M., Pempkowiak, J., 2013. Submarine groundwater discharge as a source of mercury in the bay of puck, the Southern Baltic Sea. *Water Air Soil Pollut.* 224 (6), 1542.
- Szymczycha, B., Maciejewska, A., Winogrodow, A., Pempkowiak, J., 2014. Could submarine groundwater discharge be a significant carbon source to the southern Baltic Sea? The study reports the results obtained within the framework of the following projects: the statutory activities of the Institute of Oceanology Polish Academy of Sciences theme 2.2, research project No. 2012/05/N/ST10/02761 sponsored by the National Science Centre, and AMBER, the BONUS+EU FP6 Project. *Oceanologia* 56 (2), 327–347.
- Szymczycha, B., Borecka, M., Białk-Bielińska, A., Siedlewicz, G., Pazdro, K., 2020a. Submarine groundwater discharge as a source of pharmaceutical and caffeine residues in coastal ecosystem: Bay of Puck, southern Baltic Sea case study. *Sci. Total Environ.* 713, 136522.
- Szymczycha, B., Kłostowska, Ż., Lengier, M., Dzierżbicka-Głowacka, L., 2020b. Significance of nutrient fluxes via submarine groundwater discharge in the Bay of Puck, southern Baltic Sea. *Oceanologia* 62, 117–125.
- Szymczycha, B., et al., 2023. The benthic-pelagic coupling affects the surface water carbonate system above groundwater-charged coastal sediments. *Front. Marine Sci.* 10, 1218245.

- Tait, D.R., et al., 2023. Submarine groundwater discharge exceeds river inputs as a source of nutrients to the great barrier Reef. *Environ. Sci. Technol.* 57 (41), 15627–15634.
- Tamborski, J., et al., 2020. Radium mass balance sensitivity analysis for submarine groundwater discharge estimation in semi-enclosed basins: the case study of Long Island Sound. *Front. Environ. Sci.* 8, 108.
- Taniguchi, M., et al., 2019. Submarine groundwater discharge: updates on its measurement techniques, geophysical drivers, magnitudes, and effects. *Front. Environ. Sci.* 7, 141.
- Taylor, J.R., 2022. *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements*. MIT Press.
- Villnäs, A., Norkko, J., Lukkari, K., Hewitt, J., Norkko, A., 2012. Consequences of Increasing Hypoxic Disturbance on Benthic Communities and Ecosystem Functioning.
- Vinson, D.S., et al., 2013. Occurrence and mobilization of radium in fresh to saline coastal groundwater inferred from geochemical and isotopic tracers (Sr, S, O, H, Ra, Rn). *Appl. Geochem.* 38, 161–175.
- Virtasalo, J.J., et al., 2019. Submarine groundwater discharge site in the First Salpausselkä ice-marginal formation, south Finland. *Solid Earth* 10 (2), 405–423.
- Von Ahn, C.M.E., et al., 2024. Submarine groundwater discharge into a semi-enclosed coastal bay of the southern Baltic Sea: A multi-method approach. *Oceanologia* 66 (1), 111–138.
- Wilson, S., Anderson, I., Song, B., Tobias, C., 2023. Temporal and spatial variations in subterranean estuary geochemical gradients and nutrient cycling rates: impacts on groundwater nutrient export to estuaries. *J. Geophys. Res. Biogeosci.* 128.
- Wilson, S., et al., 2024. Global subterranean estuaries modify groundwater nutrient loading to the ocean. *Limnol. Oceanogr. Lett.* 9.
- Winsor, P., Rodhe, J., Omstedt, A., 2001. Baltic Sea ocean climate: an analysis of 100 yr of hydrographic data with focus on the freshwater budget. *Climate Res.* 18 (1–2), 5–15.
- Yool, A., Tyrrell, T., 2003. Role of diatoms in regulating the ocean's silicon cycle. *Global Biogeochem. Cycles* 17 (4).
- Zhu, T., et al., 2025. Large scale submarine groundwater discharge dominates nutrient inputs to China's coast. *Nat. Commun.* 16 (1), 2932.