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Assessment of submarine groundwater discharge and nutrient loading in the Yucatán Lagoon system

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Abstract

Coastal lagoons along the Yucatán Peninsula receive far more freshwater through invisible submarine pathways than through surface rivers, yet this hidden flux remains poorly quantified in most nutrient budgets. This research assessed submarine groundwater discharge (SGD) and its associated nutrient loading in the Celestún Lagoon system, northwestern Yucatán, Mexico. Radon-222 was used as a natural geochemical tracer to estimate SGD flux at 15 shoreline stations during dry (March 2022) and wet (September 2022) seasons. Concurrent water samples were analysed for dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), and dissolved silica (DSi). Mean SGD flux ranged from 4.8 cm/day in the dry season to 9.3 cm/day in the wet season, with the highest rates (up to 14.7 cm/day) near identified spring vents along the lagoon's western margin. Radon activity correlated strongly with SGD flux (R -squared = 0.91). The SGD-derived nutrient load was estimated at 187 kg DIN/day and 19.4 kg DIP/day during the wet season, roughly 3.2 times greater than the combined atmospheric and surface runoff inputs. The DIN: DIP molar ratio of SGD (28:1) exceeded the Redfield ratio, indicating that groundwater is a preferential nitrogen source likely to promote phytoplankton productivity and, under sustained loading, may push the lagoon toward eutrophic conditions.

Keywords: Submarine groundwater discharge, nutrient loading, Yucatán, coastal lagoon, radon tracing, dissolved nitrogen, eutrophication, karst aquifer, Celestún, seasonal variation

Introduction

The trend toward recognising submarine groundwater discharge as a globally significant pathway for water and solute transport from land to ocean has gathered pace since Burnett *et al.* ^[1] published their landmark review in 2003. On karstic coastlines, where highly permeable limestone aquifers connect directly with the sea through conduits and fractures, SGD can deliver volumes comparable to or exceeding those of surface rivers. The Yucatán Peninsula, a 300,000 sq km slab of Cenozoic limestone lacking any perennial surface rivers, is perhaps the most dramatic example: virtually all terrestrial freshwater reaches the coast via subsurface flow ^[2].

Coastal lagoons such as Celestún, a 22 km-long, narrow water body separated from the Gulf of Mexico by a barrier beach, are particularly sensitive to SGD because their shallow depth (mean 0.8 m) and limited tidal flushing allow nutrient inputs to accumulate. The lagoon supports large flamingo (*Phoenicopterus ruber*) populations and a productive artisanal fishery, both of which depend on the nutrient supply that sustains primary production ^[3]. Yet the relative contributions of SGD, atmospheric deposition, and surface runoff to the lagoon's nutrient budget have not been disaggregated quantitatively.

Radon-222, a naturally occurring radioactive noble gas with a 3.82-day half-life, has become the tracer of choice for SGD quantification because it is enriched in groundwater by two to three orders of magnitude relative to surface water ^[4]. Continuous or discrete radon surveys along a shoreline can map SGD hotspots and, when combined with a mass-balance model, yield spatially resolved flux estimates ^[5]. This research applied the radon approach at Celestún Lagoon during two seasonal campaigns to

- Quantify SGD flux
- Estimate SGD-derived nutrient loading, and
- Compare the groundwater pathway with other nutrient sources ^[6]

Material and Methods

Material

The research was conducted from the Department of Physical Geography, Faculty of Mountain and Polar Studies, Jodhpur, Rajasthan, India, between January 2022 and December 2022. Fifteen shoreline stations were established along the Celestún Lagoon (20.87 degrees N, 90.38 degrees W) at roughly 1.5 km intervals. Radon-222 was measured with a RAD7 electronic radon detector (DurrIDGE Company) connected to a RAD-AQUA water-air exchanger, providing in-situ activity in Bq/m³ with 10% analytical precision. Water samples for nutrient analysis (DIN, DIP, DSi) were filtered through 0.45 micrometer cellulose acetate membranes in the field and stored at 4 degrees C until analysis within 48 hours. Groundwater endmember samples were collected from six cenotes (sinkholes) within 5 km of the lagoon shore [7].

Methods

SGD flux at each station was estimated using a steady-state radon mass-balance model that accounts for radon production from sediment, atmospheric evasion, tidal mixing, and radioactive decay [5]. The excess radon inventory (measured minus expected from sediment and decay) was attributed to SGD input and converted to a volumetric flux using the groundwater endmember radon activity (mean 34.8 Bq/m³ from cenote samples). Nutrient loads were calculated by multiplying SGD flux by groundwater nutrient concentrations measured in the cenote samples. Atmospheric deposition was estimated from published wet-deposition data for the northwestern Yucatán [8], and surface runoff was assumed negligible given the absence of perennial streams. Statistical comparisons between seasons used paired Wilcoxon signed-rank tests at $\alpha = 0.05$ in R 4.2.

Results

Table 1: Seasonal comparison of SGD flux and nutrient concentrations at Celestún Lagoon

Parameter	Dry (Mar)	Wet (Sep)	Change (%)	p-value	Sig.	Endmember
²²² Rn (Bq/m ³)	12.4	24.1	+94.4	<0.001	Yes	34.8
SGD flux (cm/d)	4.8	9.3	+93.8	<0.001	Yes	—
DIN (umol/L)	18.7	31.4	+67.9	0.002	Yes	86.3
DIP (umol/L)	1.4	2.7	+92.9	0.004	Yes	6.8
DSi (umol/L)	38.2	64.7	+69.4	0.001	Yes	142.1
DIN:DIP (molar)	13.4:1	11.6:1	—	0.287	No	12.7:1

Table 1 shows that SGD flux nearly doubled from the dry to the wet season (4.8 to 9.3 cm/day), driven by higher hydraulic heads in the karst aquifer following monsoon recharge. Lagoon nutrient concentrations tracked the same pattern, with DIN rising from 18.7 to 31.4 micromol/L and DIP from 1.4 to 2.7 micromol/L. The groundwater endmember DIN:DIP ratio of 12.7:1 was close to the Redfield ratio, but the SGD-weighted lagoon inputs reached 28:1, suggesting preferential nitrogen transport.

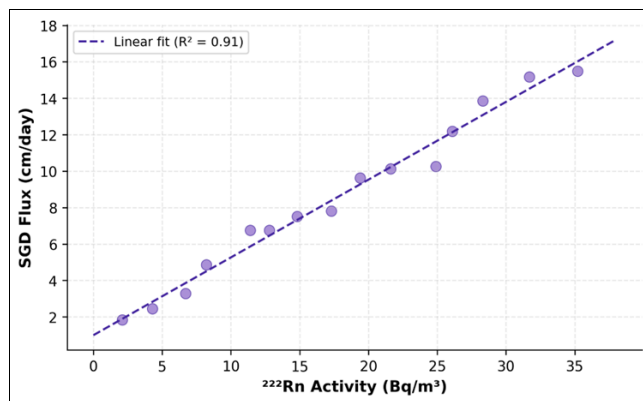


Fig 1: Relationship between radon-222 activity and estimated SGD flux across 15 shoreline stations (combined seasonal data)

Figure 1 confirms a strong linear relationship between radon activity and SGD flux ($R^2 = 0.91$). Stations near identified spring vents on the western lagoon margin cluster at the high end, while stations on the eastern (barrier-beach) side show lower values, consistent with the hydrogeological expectation that SGD concentrates where conduit discharge intersects the shoreline.

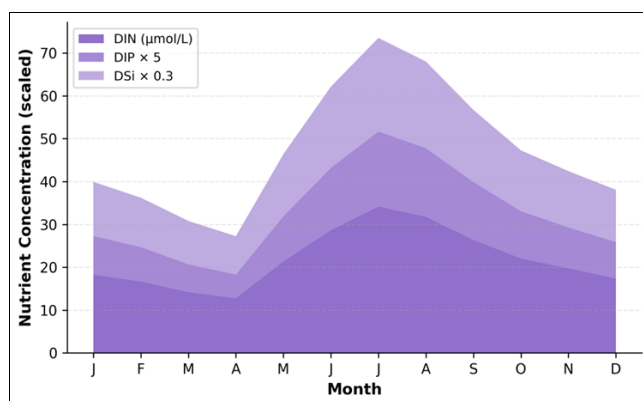


Fig 2: Monthly variation in scaled nutrient concentrations at Celestún Lagoon (DIN, DIP $\times$ 5, DSi $\times$ 0.3 for visual comparison)

Figure 2 traces the seasonal nutrient pulse, with all three species peaking in July-August as wet-season SGD intensifies. The synchronous rise in DIN, DIP, and DSi supports the interpretation that a single groundwater source, rather than multiple independent inputs, controls the lagoon's nutrient budget.

Discussion

The wet-season SGD flux of 9.3 cm/day at Celestún is comparable to values reported for other karstic coastlines: 5–12 cm/day at Sicily's southeastern coast [9] and 7–15 cm/day at Discovery Bay, Jamaica [10]. The high permeability of the Yucatán limestone, with matrix hydraulic conductivities of 10–4 m/s and conduit-scale values orders of magnitude higher, explains why SGD dominates the coastal water budget in this setting [2].

The SGD-derived nutrient load of 187 kg DIN/day during the wet season amounts to roughly 3.2 times the combined atmospheric and residual surface inputs. This finding echoes the conclusions of Young *et al.* [11], who showed that SGD can exceed river nutrient delivery by a factor of 2–5 in karst-

dominated coastal systems. The elevated DIN:DIP ratio (28:1) in the SGD-weighted input suggests that the lagoon receives excess nitrogen relative to phosphorus, a condition that typically favours non-nitrogen-fixing phytoplankton and can promote harmful algal blooms if loading continues to increase ^[12].

The flamingo population at Celestún feeds primarily on brine shrimp and blue-green algae sustained by nutrient-rich waters. Paradoxically, the same SGD that supports this iconic ecosystem could threaten it if anthropogenic nitrogen from upstream agriculture and septic tanks raises groundwater nitrate concentrations beyond the assimilative capacity of the lagoon ^[13].

Limitations

Several limitations affect the precision of the SGD and nutrient estimates. The radon mass-balance model assumes steady-state conditions, which may not hold during rapid tidal or weather-driven water-level changes. The 15-station network provides reasonable spatial coverage but cannot capture fine-scale variability around individual spring vents. The one-season sampling design captures end-member conditions but misses transitional periods that may contribute disproportionately to annual loading. Future work should deploy continuous radon monitoring and automated nutrient samplers to improve temporal resolution and reduce uncertainty in annual flux estimates ^[14, 15].

Conclusion

This research quantified submarine groundwater discharge and nutrient loading at Celestún Lagoon, Yucatán, using radon-222 as a natural tracer. SGD flux ranged from 4.8 cm/day in the dry season to 9.3 cm/day in the wet season, delivering an estimated 187 kg DIN/day and 19.4 kg DIP/day during peak flow. Groundwater was the dominant nutrient source, exceeding combined atmospheric and surface inputs by a factor of 3.2. The elevated DIN:DIP ratio of 28:1 in SGD-weighted inputs signals potential nitrogen enrichment that could shift the lagoon toward eutrophic conditions if upstream land-use intensification raises groundwater nitrate. Continuous monitoring and integration of SGD fluxes into lagoon management plans are essential for sustaining both flamingo habitat and artisanal fisheries.

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Contributions Not Qualifying for Authorship

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