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Groundwater-driven nutrient inputs to coastal lagoons: The relevance of lagoon water recirculation as a conveyor of dissolved nutrients

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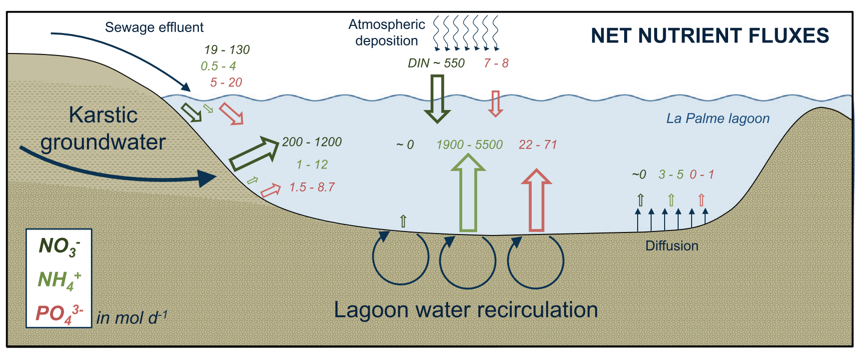
HIGHLIGHTS

- Nutrient inputs from groundwater and recirculation to La Palme lagoon are evaluated.
- Water recirculation through sediments is a NH_4^+ and PO_4^{3-} source, but a NO_3^- sink.
- Recirculation is the main source of dissolved inorganic nitrogen and phosphorous.
- Need to evaluate recirculation-driven nutrient fluxes for coastal lagoon management

GRAPHICAL ABSTRACT



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ABSTRACT

Evaluating the sources of nutrient inputs to coastal lagoons is required to understand the functioning of these ecosystems and their vulnerability to eutrophication. Whereas terrestrial groundwater processes are increasingly recognized as relevant sources of nutrients to coastal lagoons, there are still limited studies evaluating separately nutrient fluxes driven by terrestrial groundwater discharge and lagoon water recirculation through sediments. In this study, we assess the relative significance of these sources in conveying dissolved inorganic nutrients (NO_3^-, NH_4^+ and PO_4^{3-}) to a coastal lagoon (La Palme lagoon; France, Mediterranean Sea) using concurrent water and radon mass balances. The recirculation of lagoon water through sediments represents a source of NH_4^+ (1900–5500 mol d^{-1}) and PO_4^{3-} (22–71 mol d^{-1}), but acts as a sink of NO_3^-. Estimated karstic groundwater-driven inputs of NO_3^-, NH_4^+ and PO_4^{3-} to the lagoon are on the order of 200–1200, 1–12 and 1.5–8.7 mol d^{-1}, respectively. A comparison between the main nutrient sources to the lagoon (karstic groundwater, recirculation, diffusion from sediments, inputs from a sewage treatment plant and atmospheric deposition) reveals that the recirculation of lagoon water through sediments is the main source of both dissolved inorganic nitrogen (DIN) and phosphorous (DIP) to La Palme lagoon. These results are in contrast with several studies conducted in systems influenced by terrestrial groundwater inputs, where groundwater is often assumed to be the main pathway for dissolved inorganic nutrient loads. This work highlights the important role of lagoon water recirculation through

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permeable sediments as a major conveyor of dissolved nutrients to coastal lagoons and, thus, the need for a sound understanding of the recirculation-driven nutrient fluxes and their ecological implications to sustainably manage lagoonal ecosystems.

1. Introduction

Coastal lagoons host some of the most dynamic, diverse and productive ecosystems on Earth, and provide a wide range of goods and services of a great socio-economic value to coastal communities (Beer and Joyce, 2013; Kjerfve, 1994; Newton et al., 2014). These ecosystems are threatened by anthropogenic and climatic disturbances that lead to land reclamation, loss of habitats and vegetation and significant pressure on biological and ecological resources (de Jonge et al., 2002; Jennerjahn and Mitchell, 2013). These semi-enclosed coastal ecosystems are characterized by a restricted water exchange with the ocean that favors the accumulation of chemical compounds, and they are thus strongly dependent on watershed inputs. This results in systems extremely vulnerable to eutrophication, mainly driven by increasing nutrient inputs from untreated domestic or industrial sewage and/or the use of fertilizers for agriculture in the surrounding watershed (Brito et al., 2012; Cloern, 2001; Howarth et al., 2011; Lloret et al., 2008). Eutrophication of coastal surface waters may lead to recurrent toxic algal blooms, hypoxia, changes in aquatic species community structure and losses of biodiversity (Garcés et al., 2011; Gobler and Sañudo-Wilhelmy, 2001; Lee and Kim, 2007; Valiela et al., 1992). Understanding the origin and pathways of nutrient inputs to coastal lagoons is thus as an essential step towards the mitigation of the negative effects of eutrophication in these coastal ecosystems.

While the role of surface water discharge as a source of dissolved nutrients to coastal ecosystems has been well documented for decades, groundwater processes have only recently been recognized as important contributors to their hydrological and biogeochemical budgets (Moore, 2010; Slomp and Van Cappellen, 2004; Windom et al., 2006). Several studies provide increasing evidence for groundwater as an important source of nutrients to coastal wetlands and lagoons, bays and coves, salt marshes, coral reefs or entire ocean basins, sometimes rivaling loads from riverine inputs (e.g. Adyasari et al., 2018; Beusen et al., 2013; Rodellas et al., 2015; Sadat-Noori et al., 2016; Slomp and Van Cappellen, 2004; Szymczycha et al., 2012). These evaluations usually incorporate nutrient inputs associated with the discharge of fresh terrestrial groundwater from coastal aquifers, but also to the recirculation of seawater (or lagoon water) through permeable sediments. These two disparate processes are commonly incorporated within the definition of Submarine Groundwater Discharge (SGD), mainly because both processes represent advective water flows across the sediment-water interface that can supply chemical loads to coastal and lagoonal waters (Burnett et al., 2006; Moore, 2010). Terrestrial groundwater discharge is a source of new nutrients to coastal systems, derived from natural (e.g. vegetation, rocks, microorganisms) and anthropogenic (e.g. agriculture, industrial and domestic wastewaters) sources to coastal aquifers (Knee and Paytan, 2011; Slomp and Van Cappellen, 2004). While seawater recirculation does not represent a net input of water, it can also result in a significant net flux of nutrients to coastal waters mainly as a consequence of i) the biogeochemical transformations occurring when fresh groundwater mixes with seawater in coastal aquifers and permeable coastal sediments (Moore, 1999; Santos et al., 2008); ii) the continuous supply of oxidants and fine particulate and dissolved matter into sediment porewaters that fuel biological and chemical reactions within sediments (Anschutz et al., 2009; Huettel et al., 2014); and iii) the remobilization of nutrients stored in sediments as a consequence of past regimes or anthropogenic activities (Martínez-Soto et al., 2016; Trezzi et al., 2016). Therefore, the biogeochemical composition of terrestrial groundwater discharge and saline recirculation flows may be considerably different, requiring the separation of both processes to better understand and characterize fluxes of dissolved nutrients to coastal lagoons and their ecological implications (Sadat-Noori et al., 2016; Weinstein et al., 2011). However, there are still limited studies that have attempted to distinguish nutrient fluxes driven by terrestrial groundwater and recirculation inputs (e.g. Kroeger and Charette, 2008a; Sadat-Noori et al., 2016; Santos et al., 2009; Tamborski et al., 2017; Weinstein et al., 2011), and these are rarely focused on lagoonal ecosystems. Most studies conducted in coastal lagoons are based on nutrient fluxes supplied by terrestrial groundwater (e.g. Ji et al., 2013; Malta et al., 2017; Tait et al., 2014) and neglect the potential role of water recirculation through sediments as a pathway for dissolved nutrients loads.

In this study, we assess the relative significance of terrestrial groundwater discharge from a karst origin (referred hereinafter as karstic groundwater) and saline water recirculation through sediments in conveying dissolved nutrients to a coastal lagoon. This study was conducted in La Palme lagoon (France, Mediterranean Sea), a small shallow coastal lagoon where both the discharge of karstic groundwater and the recirculation of lagoon water through permeable sediments have been documented previously (Bejannin et al., 2017; Stieglitz et al., 2013a). In this paper, detailed estimations of fluxes of dissolved inorganic nutrients (NO_3^-, NH_4^+ and PO_4^{3-}) driven by karstic groundwater discharge and lagoon water recirculation are conducted via concurrent water and radon mass balances.

1.1. Terminology

Advective fluxes occurring over small spatial scales (mm to cm) are often excluded from the current definition of SGD and referred to as "porewater exchange" (Moore, 2010; Santos et al., 2012). For the purpose of this study, we prefer distinguishing exchange processes depending on their origin, composition and driving force, rather than differentiating them according to their length-scale. Therefore, the term karstic groundwater discharge is used for low-salinity groundwater driven by the terrestrial hydraulic gradient, whereas recirculation fluxes refer to both short- and long-scale recirculation of saline water through sediments, which is driven by pressure gradients forced by tides, waves, bottom currents, benthic organisms, or bottom water/porewater density changes (Huettel et al., 2014; Santos et al., 2012).

2. Study site

La Palme lagoon lies on the western French Mediterranean coastline and is well recognized for its high conservation value and its high biodiversity (it is included under the international Ramsar Convention and the environmental protection program Natura2000) (Fig. 1). The lagoon has a surface area of 500 ha and mean and maximum water depths of ~0.7 and ~2 m, respectively. It is partially connected with the Mediterranean Sea through a small opening in the coastal sand spit (usually <10 m width and <1 m depth), which is seasonally closed (particularly during summer months). A road dike and a railway dike separate the lagoon into three basins (northern, central and southern) and further restrict the exchange between lagoon waters and the sea, allowing exchange between sections only through one small bridge in each dike (Fig. 1). The study site experiences rainfall during fall and spring and little rain during summer (total precipitation of 310 and 440 mm in 2016 and 2017, respectively) (Fig. 2).