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Terrestrial groundwater and nutrient discharge along the 240-km-long Aquitanian coast

Pierre Anschutz *, Céline Charbonnier, Jonathan Deborde, Loris Deirmendjian, Dominique Poirier, Aurélia Mouret [1], Damien Buquet, Pascal Lecroart

Université de Bordeaux, CNRS, UMR 5805 Environnements Paléoenvironnements Océaniques et Continentaux (EPOC), 33615 Pessac, France

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ABSTRACT

We collected samples from sea water, runnel water, beach pore waters, water from the unconfined surficial aquifer discharging at the beach face, groundwater, and rainwater from the Aquitanian coast in order to determine the flux of dissolved inorganic nitrogen (DIN), phosphorus and silica from terrestrial submarine groundwater discharge (SGD). The flux of fresh groundwater was obtained from a water balance calculation based on precipitation and evapotranspiration and assessment of the coastal watershed from hydrograph separation. Waters with intermediate salinities between sea water and freshwaters are found all along the 240-km-long coast, indicating that SGD is ubiquitous. The estimated fresh water flux is 2.25 $m^3\ d^{-1}\ m^{-1}$ longshore. Terrestrial SGD provides a DIN flux of $9 \cdot 10^6$ mol each year to the adjacent coastal zone. This flux is about four times lower than the release of DIN due to tidally driven saline SGD. The freshwater DIN flux is low because the upland land use consists almost exclusively of pine forest. Dissolved organic nitrogen represents more than 60% of the total dissolved nitrogen flux. Dissolved iron, phosphorus and silica have much higher concentrations in the anoxic forest aquifer than in the fresh-water end-member of the subterranean estuary sampled in the upper beach aquifer. This suggests that the salinity gradient of the estuary does not correspond to a redox gradient. The redox front between anoxic groundwater and fresh oxic waters occurs below the soil-depleted foredune/yellow dune. Anoxic P- and Si-rich waters seep directly on the beach face only in the north Gironde, where the foredunes are eroded. This study reveals the role of the sandy foredune aquifer in biogeochemical fluxes from SGD, which is to dilute and oxidize waters from the unconfined surficial upland aquifer.

1. Introduction

Submarine Groundwater Discharge (SGD) plays a significant role in freshwater and biogeochemical fluxes of some coastal zones (Moore, 2010) and the global ocean (Kwon et al., 2014). Direct SGD might be responsible for up to 10% of the total terrestrial water input to estuaries and to the ocean (Garrels and MacKenzie, 1971). It may represent 2400 $km^3\ y^{-1}$ (Zektser and Loaiciga, 1993) compared to total runoff, which is estimated at 37,400 $km^3\ y^{-1}$ (Berner and Berner, 1987).

The world's coastlines are dominated by sandy shores (McLachlan and Brown, 2006). The intertidal zone of permeable sandy sediments represents an environment where nutrient dynamics is governed by diagenitic recycling of biogenic compounds (e.g. Billerbeck et al., 2006), recirculation of pore waters (Deborde et al., 2008; Anschutz et al., 2009), or seepage of terrestrial groundwaters (e.g. Ullman et al., 2003; Charette and Sholkovitz, 2002). Seepage of terrestrial groundwater through coastal permeable sediments occurs where aquifers have a positive head relative to sea level; almost all coastal zones are subject to such flow (Burnett et al., 2006). Therefore, freshwater discharge through coastal sandy sediments has been recognized as a widespread phenomenon. Fluid circulation in tidal permeable sediment has received increasing attention due to its potential importance in the transport of chemical constituents to the sea. Freshwater inputs have effects on the carbon and nutrient cycles (Kroeger and Charette, 2008; Spiteri et al., 2008; Bowen et al., 2007), but estimated fluxes of terrestrial groundwater are highly variable and quantification remains problematic. That is why very few data exist on the direct contribution of groundwater to nutrient input to coastal zones. On a local scale, groundwater-borne nutrient loads may be important in maintaining primary production (Zimmermann et al., 1985; Lee et al., 2010). But when coastal pore water is mixed with terrestrial groundwater, it becomes difficult to determine the proportion of nutrient input caused by in situ mineralization of organic matter (e.g. Charbonnier et al., 2013a) and that originating from freshwater seepage.

Different approaches have been used to improve estimates of groundwater flow and nutrient load to coastal ocean (Burnett et al., 2006). Groundwater temperature can be used to estimate groundwater

* Corresponding author.
E-mail address: pierre.anschutz@u-bordeaux.fr (P. Anschutz).

[1] Present address: UMR-CNRS 6112 Université d'Angers LPG-BIAF 49045 Angers, France.

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discharge rates. A temperature difference in the groundwater–surface-water system is a qualitative signal of groundwater seepage that can be detected using remote sensing infrared signal (Fischer et al., 1964; Lévêque et al., 1972; Roxburgh, 1985; Banks et al., 1996). The use of remote sensing technologies to quantify groundwater seepage requires intensive field calibration, which has never been performed. Seepage meters are a direct technique that can be used in a relatively calm environment (Taniguchi and Fukuo, 1993). Recent developments of radium and radon isotopic techniques have permitted evaluations of groundwater flows at local, regional, and global scales (Moore, 2010; Kwon et al., 2014). These techniques may discriminate terrestrial water seepage fluxes from recirculating sea water in permeable marine sediments. Radium and radon are commonly used as tracers of saline and total SGD, respectively. The difference between them is the fresh part (Knee and Paytan, 2011). But radon is subject to exchange with the atmosphere, which may be difficult to model under some circumstances (e.g., waves breaking along a shoreline). Another approach is the water balance calculation. This approach simply links the terrestrial aquifer with the beach through the discharge of groundwater, which is set by precipitation, evapotranspiration, runoff, and groundwater pumping over an extended period in the catchment area that drains the coastal zone directly. Estimates of nutrient load obtained from this approach may be based on measured nutrient concentrations from upland monitoring wells. However, groundwater nutrient concentrations are generally transient because of biologically and chemically mediated reactions (e.g., Ullman et al., 2003; Slomp and Van Cappellen, 2004; Kroeger and Charette, 2008; Santos et al., 2008). To account for such non-conservative behaviour in an aquifer, groundwater load estimates can be based on nutrient concentrations measured at the seepage zone (Charette et al., 2001; Michael et al., 2003; Loveless and Oldham, 2010).

Discharging groundwater flux and its nutrient contribution are much easier to estimate in regions where fluids may seep into a body of water having limited circulation, such as a semi-enclosed basin. Identification of terrestrial groundwater nutrient flux on an open ocean reflective beach with tidal currents and breaking waves remains a challenge. The 240-km-long Aquitanian coast is a sandy coast where nutrient recycling due to sea water circulation and tidal pumping has been recognized from the study of saline ($S > 34$) interstitial and seeping waters (Anschutz et al., 2009; Charbonnier et al., 2013a). Organic matter supplied by the sea water entering the pore spaces during floods is trapped long enough to be mineralized. This efficient recycling process supplies 600 tonnes of N-nitrate to the adjacent coastal zone annually. These studies also showed that some brackish waters could be sampled on the beach at low tide, suggesting that terrestrial water seepage occurred. To study the impacts of terrestrial groundwater on a large-scale high-energy coastal environment, we have made an estimate of the quantity of nutrients that are discharged to the coastal zone of the Aquitanian beach using a water balance calculation and spatial monitoring of groundwater in upland wells and seeping on the beach at low tide.

2. Material and methods

2.1. Study site

The French Aquitanian coast forms a vast unique natural environment in Western Europe. This relatively protected milieu is a 240-km-long straight coast bordered by Aeolian dunes several tens of metres high and exposed to high-energy conditions in a meso-macrotidal setting. This coast is located between the Gironde and Adour estuaries (Fig. 1) and is interrupted by the Arcachon lagoon tidal inlet, which is approximately 5 km wide. The tide is of meso-macro type, with an average tidal range of 3.2 m, extending up to 5 m during spring tides. The Aquitanian coast commonly displays double bar beaches with very dynamic rhythmic features, such as the presence of ridge and runnel systems developed more or less in relation with meteorological conditions (Michel and Howa, 1999; Castelle et al., 2007). The coast is exposed to high energy North Atlantic swells travelling mainly from the W–NW sector (Butel et al., 2002). Beaches are mainly intermediate double-barred following the classification of Short (1991) and Short and Aagaard (1993).

A morphological analysis has subdivided the Aquitanian coast from north to south into two main groups with homogeneous dynamic behaviour: the coast north of the Arcachon bay with gentle slope beaches, which are subjected to erosion in the northernmost part; and the more stable coast south of the Arcachon bay, with beaches increasingly inclined toward the south. The beaches between the Verdon and Montalivet are in erosion. There, the beaches are flat and limited by cliffs made of Pleistocene cemented sands and palaeosoils. Terrestrial groundwater seeps directly out of the cliffs at the sand palaeosoils limit.

The beach catchment, that is, the land area that is not drained by a river or lakes and that is directly connected to the beach, has been delimited using the Geographic Information System (GIS) ArcGIS. It represents a 0 to 10 km wide strip of land along the coastlines, which covers 822 km^2. The coastal aquifer, composed of sand dunes, marine sands, and gravels of Plio-Quaternary period, is very permeable (Legigan, 1979). Foredune and cultivated pine forests located behind the foredune on Holocene dunes represent more than 90% of the total surface of the catchment area. Housing is confined to a few spots of the coastal zone.

The mean precipitation in the middle part of the studied beach at Cap Ferret was 810 mm y^{-1} between 1967 and 2014. In recent years, the values were 542, 744, 936, and 899 mm in 2011, 2012, 2013, and 2014 respectively, showing the large heterogeneity. The amount of water supplied by rainfall was compared to the stream flow in the neighbouring watershed of the Leyre river (Canton et al., 2012) so that an evaporation rate could be defined. The evaporation rate was between 40 and 80%, which is typical of a forested catchment (Bosch and Hewlett, 1982; Vertessy et al., 2003). The direct measurement of evapotranspiration in the dune forest located in the studied area gave a value of 51% (Pitaud, 1967), but this value was obtained from the measurements of transpiration of young pines during one year. It did not take into account the understory cover. A recent modelling approach that considered all the hydrological parameters and land covers indicated that evapotranspiration fluxes in pine forest of the Aquitanian coastal region were in the range of 234 to 570 mm y^{-1} (Govind et al., 2014), which represented 30 to 70% of the mean annual precipitation. Low values were obtained for young stands whereas high values were obtained for mature pine forest. The dune forest consists mostly of mature forest, suggesting that evapotranspiration represented close to 70% of precipitation. The excess rainfall would go to either surface runoff or groundwater recharge. In the case of the Aquitanian coastal watershed, surface runoff does not exist and we consider that the excess water feeds the aquifer.

2.2. Sampling

Several kinds of water samples were collected, including sea water, runnel water, beach pore waters, water from the unconfined surficial aquifer discharging at the beach face, groundwater, and rainwater (Fig. 2). Runnel waters are those sampled in large pools isolated at low tide on the lower beach. Water samples of the intertidal zone were collected at low tide in winter and spring 2007, 2008, and 2009 at several places accessible by car along the Aquitanian coast (Fig. 1) and during several periods between 2011 and 2013 on Truc Vert Beach. Samples were collected during periods of spring tide. Truc Vert beach is located a few kilometres north of the Cap Ferret sand spit (Fig. 1). It is representative of the Aquitanian coast and protected from human disturbance by difficult access. The boundary between the unsaturated and saturated zones defines the water table. The intersection of the water table and the beach face defines the seepage zone.