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Baseline geochemical characterisation of a vulnerable tropical karstic aquifer; Lifou, New Caledonia

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ABSTRACT

Study region: Lifou Island, near the main island of New Caledonia.
Study focus: Stable oxygen and hydrogen isotopes of groundwater and rainfall were used to characterise baseline values for the main fresh water aquifer of Lifou Island and describe its recharge. Other stable isotope parameters (nitrates and DIC) were used to investigate the interaction between surface water (rainfall) and groundwater, including anthropogenic effects from human activities.
New hydrological insights for the region: This study represents the first baseline isotopic characterisation of Lifou Island's groundwater aquifer composition and provides a reference for future investigative studies on groundwater quality and security. Groundwater sampled in June and October 2012 had nearly identical isotopic composition. Tap water sampled monthly between February 2012 and January 2014 also had a constant isotopic composition similar to the groundwater. Groundwater recharge was found to occur when monthly precipitation exceeded 140 mm, with the recharge cycle representing 20–30% of the annual rainfall. Relationships between HCO_3^{2-} content, pH, soil $\delta^{13}C$ DIC and satellite photo interpretation suggests a variance of soil pCO_2, which is explained by different vegetation cover and higher water use efficiencies in forested areas (high pCO_2, more negative $\delta^{13}C$ isotope values). The $\delta^{15}N_{NO3}$ values for most groundwater indicate they are uncontaminated with anthropogenic nitrates, although some samples taken in October (dry season) showed a slight denitrification, possibly of natural origin.

1. Introduction

Climate change, urbanisation, increasing agricultural practices and human activities threaten the quality and security of drinking water resources of small tropical islands. We present the first hydrogeological karstic aquifer study of Lifou Island, near New Caledonia, and use stable isotopes to provide an initial assessment of precipitation (oxygen and hydrogen) and groundwater (oxygen and hydrogen in water, dissolved inorganic carbon (DIC), and oxygen and nitrogen in nitrates). This baseline study describes and characterises the initial isotopic state of the hydrological sheet and determines the interaction between surface vegetation, human activity, the freshwater lens and sea water to provide a starting point for protecting Lifou's groundwater.

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Karst aquifers are important water resources that supply fresh water to about 25% of the world's population (Ford and Williams, 1989) and are found mainly in large sedimentary basins and mountain ridges although they also cover many uplifted reef islands. Both continental and island karstic aquifers have the same vertical structure: the epikarst, or "skin" of the karst (Williams, 2008) is the weathered zone of enhanced porosity on, or near, the surface (Jones et al., 2004). Water percolates down through the vadose zone which, in turn, recharges the saturated or phreatic zone. Large island karstic aquifers (e.g. Puerto Rico, Jamaica) are indistinguishable from tropical continental karstic aquifers as they have no freshwater/seawater mixing and therefore are not affected by sea-level change. In contrast, small carbonates islands affected by tectonic uplift and subsidence overprinted by glacio-eustasy display specific characteristics which influence the circulation of groundwaters.

A key karstic aquifer characteristic is its porosity, and the development of carbonate island karst is partly controlled by meteoric diagenisis and dissolution of the host rock (Mylroie and Vacher, 1999). The perculating fresh water infiltrating fissures is predominantly diffuse, obviating surface flow and subsurface conduit transport, typical of classical karsts (Taborosi et al., 2004). Large dissolution voids called flank margin caves form preferentially in the discharging margin of the freshwater lens resulting from freshwater/salt-water mixing dissolution. Similarly, smaller dissolution voids also develop at the top of the lens where vadose and phreatic fresh-waters mix (Mylroie and Carew, 2003).

It is difficult to exhaustively classify hydrogeological characteristics of tropical islands due to their physical diversity, changing climatic patterns and past geological events; however, Mylroie et al. (2001) integrated a systematic geomorphic description of small carbonate islands located in the Atlantic–Caribbean to propose a Carbonate Island Karst Model (CIKM) which they used to describe these unique small carbonate island karsts.

Freshwater springs (commonly found in massive continental karst formations) are not usually found on karstic islands so it can be difficult to correlate small karstic island aquifer recharges with rainfall events which recharge these aquifers through diffuse infiltration caused by high porosity (~45%). Instead, coral reef carbonate islands such as Barbados Islands rely on the vadose zone for recharge, where the flow can be distinguished by two modes: minutes to days for water seeping through sinkholes, and days to several months for diffuse infiltration (Senn, 1946; Bakalowicz, 1995, 2013; Mwansa and Barker, 1996; Smart and Ketterling, 1997).

The fresh groundwater lens under karstic island aquifers is highly vulnerable to urban and agricultural pollution due to high permeability and little or no surface runoff. Currently the environmental pressures on Lifou's drinking water resources are low due to a small, well dispersed population across the island, smaller family-run farms, and virtually no industrial activity. However, there is a growing need to survey drinking water quality and recharge, in order to understand baseline characteristics and monitor changes due to these increasing anthropogenic stressors and climate change events in the future.

In the past, the water recharge in karstic island environments was usually estimated by various conventional methods such as changes in groundwater chlorine and tritium, estimation of coastal discharges, and soil moisture measurements using lysimeters and seepage meters. More recently, water and environmental isotopes have been used as a valuable tool to provide more detailed information regarding water quality, infiltration and recharge timing (Tarhule-Lips, 1999; Jones and Banner, 2003), although integrated rainfall, drinking water and aquifer isotope studies including nitrate assessments, particularly of South Pacific tropical islands, are still rare.

2. Study area

2.1. Geology

Lifou Island (part of the Loyalty Islands) is located in the southwestern Pacific Ocean, (Fig. 1). Situated on the western edge of the Australian plate, it is part of a series of raised atolls arranged parallel to the main island of New Caledonia and separated by the Loyalty Trench. The Loyalty Islands were uplifted during the Pleistocene by a lithostatic fore bulge created by the Australian plate as it approached the New Hebrides subduction zone (Dubois et al., 1974).

Lifou, the largest of these atolls with an area of 1150 km^2, consists of an external band of uplifted corals (up to a maximum of 100 m asl.), and its interior is dominated by a carbonate platform of up to 40 m asl. consisting mainly of limestone and rhodolites associated with Miocene to Pliocene biodetritic sediments (Maurizot and Lafoy, 2003). The central part of the erosion platform is karstified while the outer part of the reef contains biodetritic formations bordering both sides of the reef crown. The island has also undergone Quaternary eustatic sea-level change.

2.2. Climate and vegetation

The Loyalty Islands are subject to tropical and temperate influences from two key seasons driven by the ITCZ (Inter Tropical Convergence Zone) and SPCZ (South Pacific Convergence Zone) with minimum and maximum annual temperatures of 19.7 and 27.1 °C respectively (Météo-France Atlas Climatique de la Nouvelle-Calédonie, 2007). A warm season occurs in the first trimester where a tropical influence dominates and maximum rainfall is around 40% of total annual rainfall. A cool season occurs from June to September when polar disturbances move northwards. The average rainfall is 1742 mm per year, with 1011 mm falling in the rainy season (January–April, Fig. 2) and 731 mm falling in the dry season (May–December, Fig. 2). High spatial variability in precipitation may explain irregular rainfall data across the island (Hapetra: 210 mm and Mu: 411 mm in March 2012) and inter-annual variations (Wanaham: 55.9 mm in November 2011 and 188.6 mm in November