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Assessing Spatio-temporal Patterns of Groundwater Salinity in Small Coral Islands in the Western Indian Ocean

Jean-Lambert Join[1], Olivier Banton[2], Jean-Christophe Comte[3], Julie Leze[1], Frederick Massin[1], Eric Nicolini[1]

[1]UMR IPGP 7154 Laboratoire GéoSciences Réunion, Université de La Réunion, France ; [2]UMR EMMAH, Laboratoire d'Hydrogéologie, Université d'Avignon, France ; [3]Groundwater Group - EERC - SPACE, Queen's University Belfast, Northern Ireland.

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Abstract—We investigated groundwater salinity as a key element in both the short and long-term evolution of the island of Grande Glorieuse. Firstly, we demonstrated that its evolution involved the integration of the whole range of variables forcing climate change. Piezometric surveys designed to sample the salinity of the subsoil waters of Grande Glorieuse could therefore provide an objective indicator of the environment's evolution. Then, based on information from geoelectrical investigations, we proved that the spatial distribution of salinity is strongly dependent on the geological structure of the island. Structural heterogeneities can influence vulnerability of the island environment to salinization of the freshwater lens. Thus, characterization and monitoring of the freshwater lens will provide a reliable means of observing and managing anticipated climate changes on small islands.

INTRODUCTION

Many small islands, in particular coral atolls, lie within three metres of current sea level. This is where the effects of a rise in sea level will first be felt, and these islands are likely to suffer disproportionately from the negative impacts of climate change (Patel, 2006; Tompkins *et al.*, 2005, Burns, 2003; Hoegh-Guldberg, 2009; White *et al.*, 2007). In the tropics and the subtropics, the impacts of climate change are likely to be further compounded by the environmental sensitivity of coral reefs (Bates *et al.*, 2008). Providing

Corresponding author: JL Join
E-mail: join@univ-reunion.fr

accurate environmental indicators of the effects of climate change on small coral islands is a challenge. Like most environmental systems, small islands are characterised by a multitude of non-linear interactions and external forcing. Consequently, the effects of ongoing climate change on these ecosystems remain difficult to measure on a local scale and over short periods of time. These difficulties are due to the natural variability of the climatic system, the initial heterogeneity of the environment and complexities in differentiating anthropogenic from natural impacts (Barry *et al.*, 2008; Camoins *et al.*, 1997; Jones, 2003; Michael *et al.*, 2005; Oberdorfer & Buddemeier, 1986; Oberdorfer *et al.*, 1990; Wegehenkel, 2009). This becomes even more difficult when studying reef environments. Therefore, improved vulnerability assessment requires indicators that both facilitate monitoring but also reflect the complexity of reef ecosystem interactions.

Objectives

In response to this problem, the research programme INTERFACE was proposed to the French National Research Agency (ANR) within a call for proposals on the study of "Vulnerability of ecosystems to climate changes". The programme proposed a three-year monitoring of environmental indicators on very small coral reef islands, situated in protected areas (both circumstantial and thanks to policies) isolated from human activity.

It was proposed to monitor environmental indicators that would help to characterise the effects of climate change at these sites, on a small island, groundwater salinity is a major factor that maintains and develops the terrestrial ecosystem. We therefore proposed to test the adequacy of monitoring of groundwater salinity as an indicator of the vulnerability of a small reef island subject to climate change. In such a case, the value of this parameter as an indicator of the effects of climate change would be based on the theoretical link between changes in groundwater salinity and the evolution of the main variables of climate and ocean level. Thus, Schneider and Kruse (2003, 2006) proposed a detailed analysis of the factors that regulate the morphology (size and shape) of the freshwater lens on small islands. Among these factors, they distinguished between parameters such as aquifer salinity (i.e. horizontal and vertical hydraulic conductivity) and temporal variations associated with the boundary condition (i.e. recharge by rainfall and sea level). Factors controlling the system's long-term evolution correspond mainly to transient phenomena in boundary condition such as seasonal variability (precipitation and evaporation), changes in the island's structure (accretion and erosion), and anthropogenic factors, such as groundwater pumping and alterations in vegetation and elevation (Vacher, 1997).

The easiest way to investigate links between salt water intrusions and variations in climate change is the application of the Dupuits and Ghyben-Herzberg model (Herzberg, 1901). When applied to a small circular island, this model assumes that rainwater infiltrates and forms a freshwater lens of maximum thickness at the centre of the island. In this case, the depth of the freshwater-salt water interface (Hi) is directly proportional to the elevation of the water table (h=hydraulic head) above average sea level (Bobba, 1993; Reilly & Goodman, 1985):

$$\rho_f * (Hi + h) = \rho_s * Hi$$

$$Hi = \left(\frac{\rho_f}{(\rho_s - \rho_f)}\right) * h$$

where ρf and ρs are respectively the densities of fresh and salt water.

Moreover, the distribution of hydraulic heads in a phreatic aquifer consisting of only freshwater is given by the equation of conservation of mass of groundwater flow (Bear, 1979; Kiro *et al.*, 2008). This equation can be simplified by linearization, yielding a one-dimensional diffusion equation:

$$\frac{\partial h}{\partial t} = \frac{T}{n} \times \frac{\partial^2 h}{\partial x^2}$$

$$T = K\,(Hi + h)$$

where h [m] is the hydraulic head, a function of the distance from the shore x [m] and time t [s], T [m^2 s^{-1}] is the freshwater transmissivity, n is the porosity and K the hydraulic conductivity (m s^{-1}).

From this equation, it is possible to ascertain the main parameters determining the development of the freshwater lens (Lee, 2003). This simple model constitutes a reference used in several recent studies on the potential impact of global changes on coastal groundwater (Ranjan *et al.*, 2006; Ranjan *et al.*, 2009; Wegehenkel, 2009).

In order to evaluate the efficiency of monitoring of brackish groundwater as an indicator of climate change on small islands, we investigated the temporal and spatial evolution of salinity on the very small island of Grande Glorieuse.

Hydrogeological setting of Grande Glorieuse

The programme was implemented on the small reef island of Grande Glorieuse (11° 33’ 20”S; 47° 20’ 33”E), which is part of the French Iles Eparses, located north of Madagascar in the Mozambique Channel in the western Indian Ocean. The island has no permanent population and has been classified as a nature reserve (Quod *et al.*, 2007; UICN, 2009).

Grande Glorieuse is the largest in a group of five small islands forming a bench reef. It is round and has a maximum diameter of 3 km. The island is covered with holocene aeolian sand, forming dunes which reach an altitude of 12 m in the east, and limestone sub-outcrops correspond to a Pleistocene reef in the south. The island is surrounded by a reef flat that dries out at low tide. The tidal range is particularly high, attaining over 3 m during spring tides. On land, the flora consists mainly of coconut palms and casuarina trees.

The climate corresponds to the southern boundary of the equatorial low-pressure zone and primarily comprises two seasons:

- A cool season that lasts from May to October when the wind blows from the east to the south-east. Mean temperatures range between 24.5-26.5°C and the humidity lies between 75 and 78%.
- A hot season that lasts from November to April, corresponding to the north-west monsoon regime with substantial precipitation, 100-210 mm per month, peaking in January. Average temperatures are ~28°C and the humidity is between 81 and 84%.

During the hot season, the island can be affected by tropical cyclones (UICN, 2009).

MATERIAL AND METHODS

Investigations of groundwater on Grande Glorieuse have led to the implementation of direct and indirect methods of prospection, involving drilling and geophysical surveys respectively.

Drilling and monitoring of boreholes

During the dry season, five boreholes (GW1, GW2, GW3, GW4 and GW5) were drilled to the water table to monitor and sample the groundwater (Table 1). A sixth observation point comprised an earlier well dug (Pts) in the centre of the island (Fig. 1).

Boreholes were drilled manually. Each one was dug to a depth of 0.5 m below the lowest level of the water table. A piezometric pipe equipped with a one-metre well screen, was inserted in the aquifer. A “CTD Diver”type probe was installed in each piezometer as shown in Figure 2. These sensors allow continuous recording of water heads (expressed in metres), electrical conductivity (µS/cm) of the water and its temperature (°C). This design enabled measurement and water sampling at the top of the water table, anticipating the upper zone to be the least contaminated by the underlying salt wedge, thus facilitating the interpretation of hydraulic heads not influenced by density effects

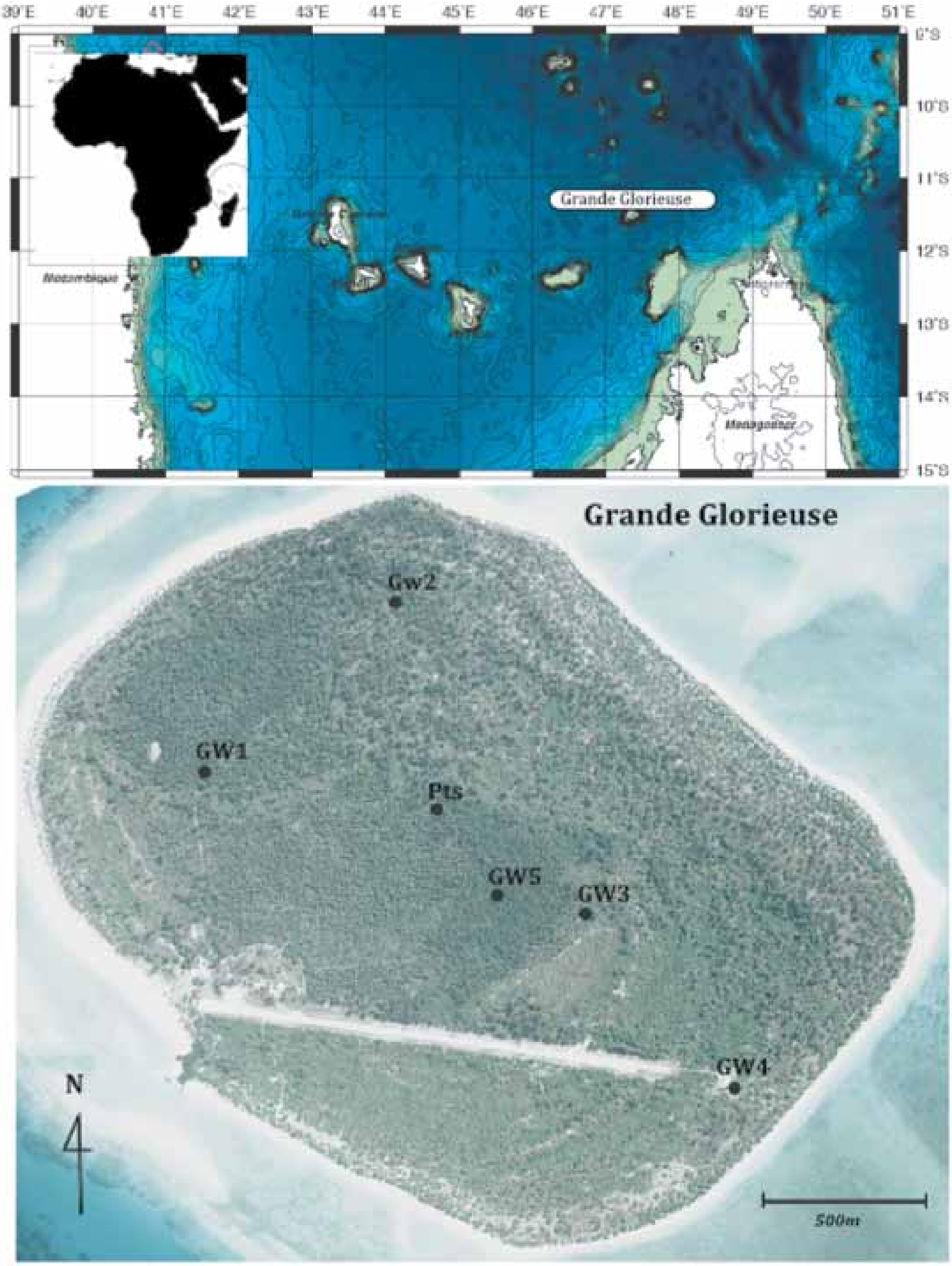

Figure 1. Location of the Grande Glorieuse island in the Indian Ocean and map of borehole monitoring stations.

attributable to dissolved salt. The boreholes were levelled with a theodolite relative to mean sea level (MSL).

This methodology was previously tested on a similar atoll in the Pacific Ocean within the INTERFACE programme (Comte *et al.* 2010).

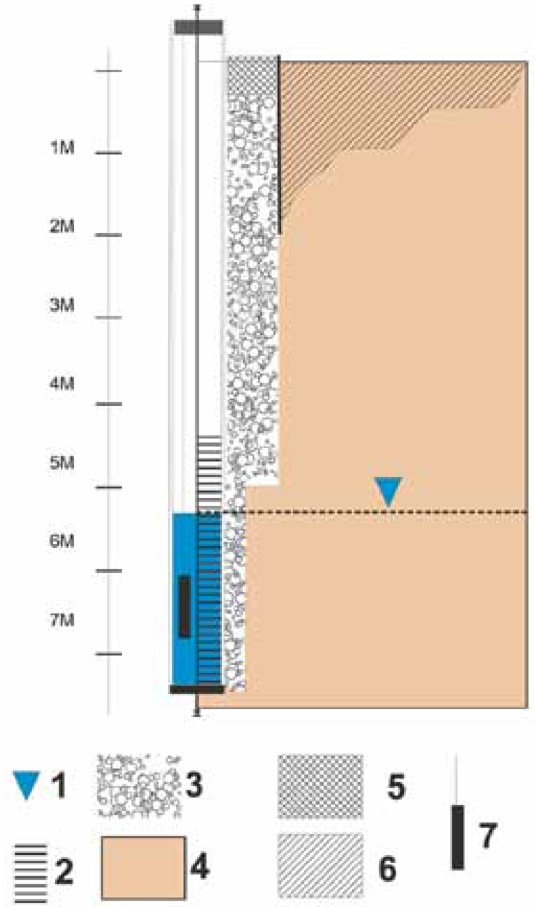

Figure 2. Typical borehole design employed on Grande Glorieuse. 1, water level; 2, well screen; 3, sand pack; 4, terrain; 5, cement grout; 6, backfill with clay ; 7, CTD Diver (datalogger).

Geophysical prospecting

A geo-electrical prospecting technique was applied on Grande Glorieuse to investigate seawater distribution into the island. For this purpose, electrical resistance tomography (ERT) was implemented along a transect across the island. The method uses a multi-electrode array driven into the soil and an automatic data acquisition system (Dahlin, 1993). As resistance readings cannot be interpreted directly as a true subsurface distribution of resistances, measured data needed to be deconvolved by geo-electrical modelling.

In order to protect the vegetation cover on Grande Glorieuse, the profile was carried out along existing paths. The longest path corresponded to the axis of the airport runway (Fig. 1). The survey was conducted using an ABEM Lund System from ABEM Instrument AB, Sweden, with a 5-m electrode spacing and a maximum AB spacing of 210 m. Measurements were taken with the Wenner-Schlumberger array (a=5-30 m; n=1-3), which has a relatively good signal-to-noise ratio (Dahlin & Zhou, 2004) and was sufficiently sensitive to the geometrical features of seawater intrusion in the coastal groundwater (Comte & Banton, 2007). The maximum investigation depth achievable with this protocol was 40 m below MSL. Measured resistances were interpreted using the 2-D inverse modelling software RES2DINV (ver. 3.55) (Loke, 2006).

Hydrological data

A weather station has been maintained on Grande Glorieuse since 1955. Precipitation (P) temperature (T) data were provided by Meteo-France in hourly resolution via the Climatheque database server.

The MSL was estimated from tide gauge data. The tide gauge was equipped with a pressure sensor installed on a levelled benchmark, located below the level of the lowest tides.

RESULTS

The results obtained on Grande Glorieuse yielded information on both the structure of the freshwater lens and the spatio-temporal distribution of salinity.

Structural characteristics of the aquifer

Geo-electrical imaging yielded resistances ranging from <5 Ω.m to >300 Ω.m (Fig. 5a). Resistances >50 Ω.m correspond to unsaturated coral sands above the aquifer water table. Two zones of brackish water with resistances ranging from 2-50 Ω.m appear on each side of the profile above conductive seawater (~1 Ω.m). In the middle of the profile, conductive seawater reaches the unsaturated zone. On the longitudinal profile (Fig. 5), resistant Pleistocene limestone was also identified at ~35 m below sea level. These resistance values are consistent with previous studies on similar atolls (Lloyd *et al.*, 1981; Ajaykumar & Ramachandran, 1996; Comte *et al.*, 2010).

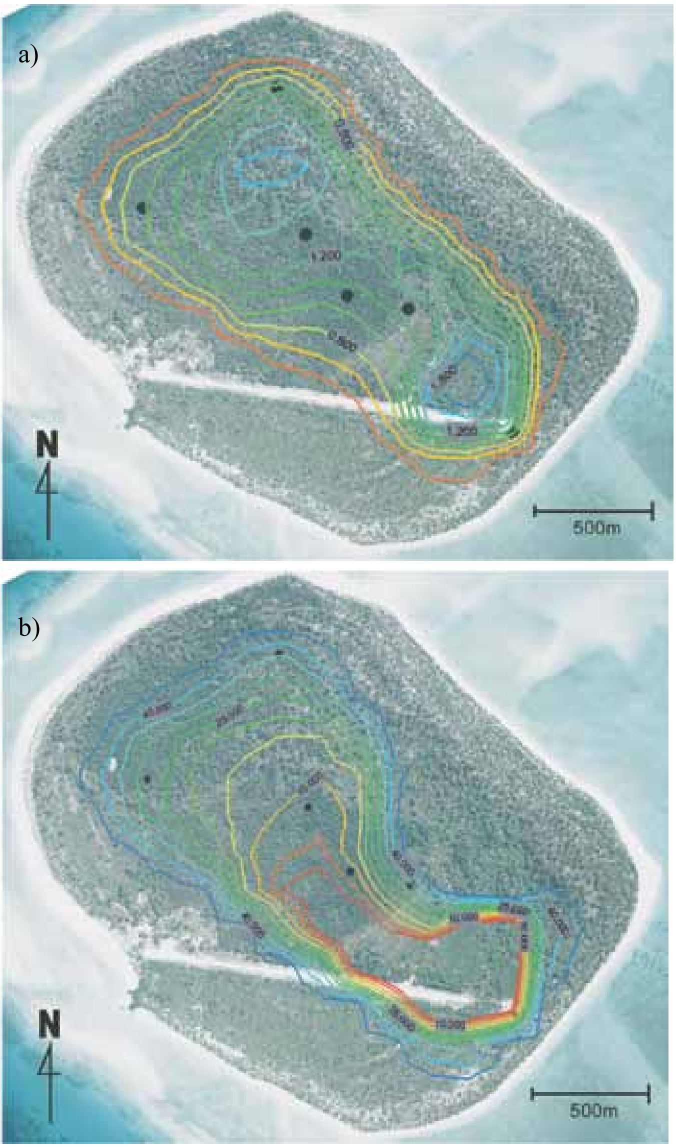

Figure 3. Piezometric (a) and electrical conductivity (b) contour maps of Grande Glorieuse groundwater. The former are presented as lines of equal potentiometric level (in meters above MSL), the latter as lines of equal electrical conductivity (in µS/cm).

Spatio-temporal pattern of groundwater table

Groundwater levels were measured in the piezometers. The measurements taken during 2008 were used to calculate an average depth of the water table in each borehole. These measurements were converted to the average level of the water table above MSL (Table 1). Spatial extrapolation was carried out by contouring the water table at 0.2 m intervals (Fig. 3.a).

Spatio-temporal pattern of groundwater salinity

The electrical conductivity of groundwater samples was indicative of the presence of brackish water throughout the island, with values higher than standards for safe drinking water. Some boreholes had a value close to that of seawater (56000 µS/cm). The iso-conductivity contours clearly pointed to a decrease in salinity towards the centre of the island (Fig. 3b). However, this map manifested major differences from what would be expected in a Ghyben-Herzberg model. For example, the northwest area showed a large inward salt-water intrusion, and in the eastern part there was a marked anomaly relative to borehole GW3. In these sectors, no correlation was evident between the piezometric level and salinity of the water, as confirmed by the results given in Table 1.

Sensitivity of groundwater to natural forcings

Monitoring of physical and chemical parameters (conductivity, water level) of the groundwater in borehole GW2 were compared with sea level

Table 1. Borehole location and characteristics on Grande Glorieuse island.

Designation	X	Y	Depth of well (m)	Elevation of water table (m above MSL)	Electrical conductivity (10^3 µS/cm)
GW1	47.29031	11.576787	2.95	0.78	27.9
GW2	47.29554	11.572121	4.025	0.96	34.2
GW3	47.300728	11.580795	5.89	1.1	35
GW4	47.304852	11.585674	3.6	0.92	6.5
GW5	47.298328	11.580309	1	0.89	17.7
Pts	47.296669	11.57786	2.45	1.36	8.3

a)
b)
c)

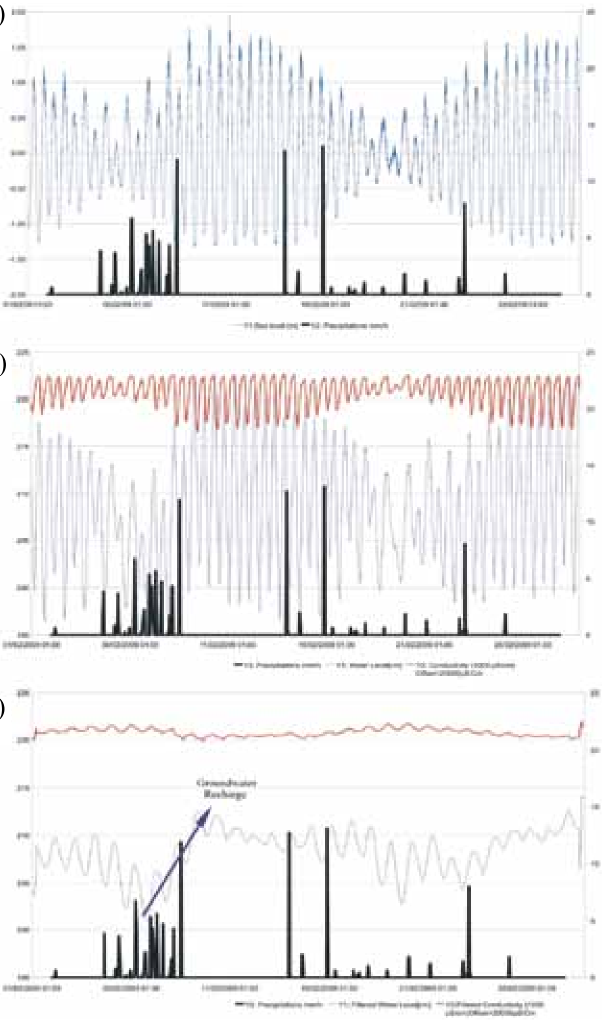

Figure 4. Sea level, rainfall, groundwater level and conductivity at borehole GW2 on Grande Glorieuse island.

a) The natural forcing of tide and precipitation (raw data).

b) Water level and conductivity in GW2.

c) Residual signal from moving average filter.

and precipitation recorded at Grande Glorieuse over the month of February 2009 (Fig. 4a, b, c). Results showed that the raw data of piezometer GW2 (Fig. 4b) were all strongly influenced by the ocean tide observed in tide gauge data (Fig. 4 a). Conductivity and water level changed with sea level, while the influence of no other natural force (i.e. precipitation) could be detected. However the minimum conductivity values varied with tidal range (Fig. 4b) and spring tides were responsible for the lowest conductivities in groundwater.

We applied a smoothing filter to the raw data of each parameter to reduce the preponderant influence of tide. The smoothing filter was based on a mean sliding-window filter, set at a width of 12 hours. In Figure 4c the residual signals of water level and conductivity were compared with meteorological data for the same period. Daily precipitation (mm) was plotted as a bar chart in Figure 4b and 4c. The filtered data of groundwater level in piezometer GW2 clearly show the influence of precipitation on the water table. A recharge of ~0.1 m over two days followed 60 mm of rainfall that fell during 6-8 February, 2009, and was extended by a discharge of 0.08 m over ten days. However, this rainfall had no major effect on the conductivity and the temperature.

DISCUSSION

The complexity of the spatial distribution of salinity in the groundwater was confirmed by geo-electrical imaging of the substratum. Despite the apparent homogeneity of this sandy island, geophysical exploration revealed stratified structuring in the aquifer. This is related to the presence of limestone bedrock reef encountered in boreholes at shallow depths in the south. The specific conditions of groundwater flow in these karstic terrains can locally modify the processes of salt wedge intrusion. The geo-electrical cross-section shown in Figure 5a confirms this substratum uplift in the southern sector of the island.

Geo-electrical imaging shows resistances ranging from <0.1 Ω.m to >800 Ω.m. Resistances >50 Ω.m appear at the top and bottom of the water table. On the surface, they correspond to unsaturated coral sand, whereas at the bottom, high resistances are interpreted as originating from the limestone bedrock. Despite the presence of salt water, the low porosity of the carbonates increases resistance. Between these two layers, the low resistances are associated with brackish waters with resistances ranging from 0.1-50 Ω.m.

The hydrogeological interpretation of the geo-electrical cross-section is consistent with the salinity data measured in the boreholes. In accordance with the iso-salinity map, the cross-section reveals a very wide brackish coastal area in the northern part. To the south, the less salty groundwater is related to the apparent uprise of bedrock. The geo-electrical section also suggests new elements in terms of the island's geological structure.

On the one hand the bedrock rises sharply in the middle of the cross-section, while, on the other, vertical structures show very localised intrusion of salt water. These structures are characteristic of a faults system conducive to sinking of the substratum and favouring karst processes. We can assume that the presence of such structures in the reef bedrock promotes spatial heterogeneity of salinity in the upper levels of the water table.

Figure 5b shows the hydrogeological interpretation of the geophysical cross-section.

a)

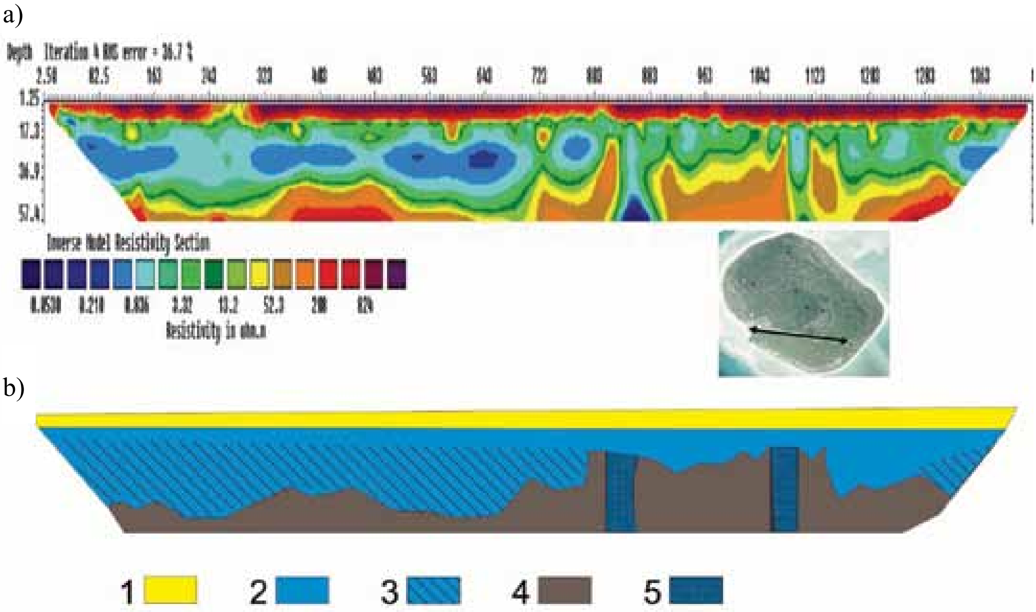

Figure 5. Geophysical cross-section of Grande Glorieuse island.

a) Geophysical cross-section.

b) Hydrogeological interpretation. **1**) Unsaturated coral sands; **2**) Aquifer in coral sands; **3**) Saltwater intrusion; **4**) Pleistocene limestone; **5**) Karstified fractures.

Complexity of saltwater mixing processes in groundwater related to coastal hydrology

The saltwater interface is therefore far more complex than assumed in the theoretical model that is based on the assumption of a distinct interface between two immiscible liquids, freshwater of density 1 and seawater of density 1.25. Henry (1959, 1964) showed that, for confined groundwater, the mixing zone of fresh and salt water depends on the kinematic dispersion coefficient, variable according to the nature of the aquifers. This has subsequently been confirmed in unconfined aquifers (Frind, 1982; Huyakorn P. *et al.*, 1987).

More recently, different authors (Ataie-Ashtiani *et al.*, 1999; Cartwright *et al.*, 2004; Li *et al.*, 1997; Maji & Smith, 2009; Urish & McKenna, 2004) have shown that the oceanic tide is a factor that effectively increases the dispersion of salt in groundwater. The tide in Grande Glorieuse has a range of over 3.4 m and is undoubtedly a fundamental factor in such a significant dispersion of salinity in the water.

Winds and currents act as additional marine influences in the interior of the island. On a small atoll in the Indian Ocean, Kench (1998) showed that the mean level of the sea could vary from 0.1 m from one side of the island to the other. Moreover, Nielsen (1990) and Turner, (1996) showed that the morphology of beaches also contributes significantly in defining the conditions of penetration of salt inland. On Grande Glorieuse, Cordier *et al.* (2009) showed that repeated seasonal beach profiles manifested significant changes in the morphology of the coastal strip.

All these marine influences could be smoothed by the presence of reef around the island. In fact, Bailey *et al.* (2009), Join *et al.* (1988) and Li *et al.* (2009) have shown that reefs may act as a key regulator of all marine influence. However, this effect actually depends on the variable extension of the reef around the island.

Complexity of saltwater mixing processes in groundwater related to recharge processes

On land, the processes of groundwater recharge and evapotranspiration are additional causes of variability in the salinity of groundwater (White *et al.*, 2007a; Comte & al., 2010). Among the factors involved, some are relatively stable, whereas others vary on different time scales. The structural factors are more stable and essentially related to land elevation, which controls the thickness of the unsaturated zone above groundwater. The low-lying areas might be subject to major evaporation by capillary rise. Other factors, such as rainfall interception and transpiration by plants, are less stable over time. White (1996) showed that evapotranspiration was a forcing factor of the freshwater lens and was particularly difficult to evaluate Depending on the status of vegetation, this factor is likely to evolve over all time scales.

The initial salinity of soils is partly attributable to the marine origin of sand and coral debris, but salt introduced by wind and sea spray also become permanently concentrated in the soil. Both phenomena contribute to contamination of the percolating water. On Grande Glorieuse, samples of rain and soil water have a mean conductivity of 210 µS/cm and 1600 µS/cm respectively, prior to percolation into the groundwater. Groundwater withdrawal by evaporation can also constitute a significant factor that increases salinity, especially when the groundwater is already brackish.

These combined factors account for the very high surface salinity of the water in the northern area. Thus the spatial distribution of salinity on Grande Glorieuse will remain difficult to determine in view of the numerous interactions that control its evolution.

However, monitoring of the groundwater head in each piezometer during the rainy period in February 2009 gave clear evidence of the effect of forcing variables on both water level and conductivity. Hence, the tidal range influences the groundwater conductivity and precipitation clearly impacted the groundwater level, although this signal was barely perceptible in changes in water conductivity in the borehole. The piezometric equipment also probably introduced a bias in in situ measurements of instantaneous change in the groundwater contents.

Finally, although salinity is the most spectacular indicator of the vulnerability of a coral island's water resources, its spatio-temporal evolution is difficult to forecast. In this context, the long-term evolution of a hydraulic head in a piezometric survey may provide an ideal indicator of environmental change.

CONCLUSION

Terrestrial water resources are subject to pervasive influences of the marine environment in the archipelago of the Iles Glorieuses. Salinity values measured in boreholes on the island were close to the survival limits of the island's flora and fauna. This environment is therefore critically vulnerable to oceanic and climatic factors, providing an opportunity to observe the effects of climate change on the region's water resources. The precarious balance in water salinity is likely to alter rapidly as a result of changes in external regulatory parameters. Among these, expected increases in MSL may reduce the overall size of the fresh water lens and higher temperatures will affect the ground water recharge (through changes in evapotranspiration and precipitation). In this regard, island environments such as Grande Glorieuse provide excellent sites to set up climate change observatories through monitoring of groundwater. We have shown that such hydrogeological monitoring will emphasize a large number of interacting factors involved in the vulnerability of these environments. However, while salinity is eminently suitable as an indicator of this vulnerability, we have demonstrated that its spatial and temporal distribution is complex and does not reflect a simple relationship based on the hydraulic head according to the Ghyben-Herzberg model. There is a relationship nonetheless, and, consequently, if we accept its complexity, direct monitoring of the hydraulic head and indirect monitoring of groundwater salinity through resistance imaging may well provide valuable indicators of changes in the state of the water table and the evolution of salinity.

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