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### Evaluation of effective groundwater recharge of freshwater lens in small islands by the combined modeling of geoelectrical data and water heads

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[1] In small islands, a freshwater lens can develop due to the recharge induced by rain. Magnitude and spatial distribution of this recharge control the elevation of freshwater and the depth of its interface with salt water. Therefore, the study of lens morphology gives useful information on both the recharge and water uptake due to evapotranspiration by vegetation. Electrical resistivity tomography was applied on a small coral reef island, giving relevant information on the lens structure. Variable density groundwater flow models were then applied to simulate freshwater behavior. Cross validation of the geoelectrical model and the groundwater model showed that recharge exceeds water uptake in dunes with little vegetated sectors, where water uptake exceeds recharge, the lens cannot develop and seawater intrusion occurs. This combined modeling method constitutes an original approach to evaluate effective groundwater recharge in such environments.

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#### 1. Introduction

[2] On low coral islands, the groundwater lens is a vital source of freshwater for terrestrial ecosystems and domestic or agricultural consumption [Falkland, 1999; White et al., 2007a]. In these islands, fresh groundwater is replenished exclusively from precipitation while significant groundwater uptake through evapotranspiration can occur in low-lying and/or vegetation-covered areas [Falkland and Custodio, 1991; Vacher and Wallis, 1992; White, 1996; White et al., 2007b]. Evaluating groundwater recharge is of crucial importance for understanding and modeling groundwater behavior in order to better manage water resources [Wallis et al., 1991; Vacher and Wallis, 1992]. But evaluating recharge and water uptake by direct methods in the field remains difficult and involves many uncertainties [Jocson et al., 2002; Sanford, 2002; Bauer et al., 2004; van der Velde et al., 2006; Wanke et al., 2007].

[3] Model calibration or inversion can be used to predict both rate and distribution of recharge [*Sanford*, 2002]. However, because recharge and hydraulic conductivity are numerically highly correlated, the estimated recharge by

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calibration on groundwater levels only is often nonunique [*Scanlon et al.*, 2002]. Furthermore, at regional scale, because hydraulic conductivity may range over several orders of magnitude, estimation of recharge rates using model calibration may not be very accurate.

[4] Complementary data, such as the distribution of salt concentrations through aquifer, could be used to constrain the models [*Wallis et al.*, 1991; *Comte and Banton*, 2007]. To this end, electrical resistivity methods (in a broad sense, i.e., both direct current (DC) electrical and electromagnetic methods) can be used to image freshwater lens morphology [see, e.g., *Stewart*, 1982; *Ayers and Vacher*, 1986; *Ruppel et al.*, 2000; *Schneider and Kruse*, 2005; *Wilson et al.*, 2006].

[5] In the present study, an approach coupling twodimensional DC geoelectrical and two-dimensional/threedimensional groundwater modeling was used to evaluate the influence of effective groundwater recharge (i.e., recharge minus water uptake, with recharge equals infiltration minus evapotranspiration in the unsaturated zone) on the geometry and renewal of freshwater lens in a small coral reef island of the Noumea lagoon (New Caledonia). This study gives an added value in constituting a successful application for the approach combining hydrogeological modeling with geoelectrical imaging, whose relevance has been shown by *Comte and Banton* [2007]. Moreover, this application focuses on an example of coral islet particularly sensitive to the climate changes in tropical area.

# 2. Hydrogeological Setting (Coral Reef Islands in the Noumea Lagoon, New Caledonia)

[6] The study was carried out on Mba Island, a small coral reef island located in the Noumea lagoon in the southwestern region of New Caledonia (Figure 1). Mean

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**Figure 1.** Location of Mba Island in the Noumea lagoon, New Caledonia (modified after *Migon et al.* [2007]; aerial photography after Google Earth). Red lines are ERT profiles, and green dots are observation wells.

seawater salinity of lagoon water is 35.9 g/L, and the temperature averages 25°C [*Ouillon et al.*, 2005]. This elliptically shaped islet extends NW–SE, is restricted to an area of about 0.33 km<sup>2</sup> (the island length is about 3 times the width), and is characterized by a well-marked sand dune system along its shoreline.

[7] Mba Island, as well as other similar islets in this lagoon, is composed of modern and Holocene carbonate sediments lying on a Pleistocene reef unit [*Castellaro*, 1999]. The Holocene sediments are made of 3 m to more than 6 m thick layers of carbonate sands of fine- to medium-sized grains combined with rare coral debris and sometimes discontinuous relicts of beach rock. Just below the sand layers, the Pleistocene basement, found to be more than 26 m deep [*Castellaro*, 1999; *Andréfouët et al.*, 2009], is characterized by a succession of coral buildups, layers of skeletal, and algal debris, sands, and cavities. The Pleistocene reef sequence is generally more lithified than the Holocene sediments.

[8] The hydraulic conductivity (m/d) in Holocene sediments is about one order of magnitude lower than in Pleistocene limestone, i.e., tens m/d in the former versus hundreds m/d in the latter [*Buddemeier and Oberdorfer*, 1988; *Ghassemi et al.*, 2000]. Total porosity ranges from 10% to 30% in Holocene sediments and from 10% to 50% in Pleistocene limestone; effective porosity is about 20% in both formations [*Buddemeier and Oberdorfer*, 1988; Ghassemi et al., 2000; Jones and Banner, 2003]. Homogeneous lithology and hydraulic conductivity of Holocene sediments at the scale of the islet are evidenced by all the core samples collected from the five 3.3–5.1 m depth piezometers (Figure 1) and the eight 1 m depth distributed soundings drilled (this study) plus the previous long cores [Castellaro, 1999]. Sedimentological analyses of eight sand samples also provide evidence of a very homogeneous grain size distribution ranging from 0.125 to 1 mm. These data are consistent with the data from the three 23-26.5 m long cores drilled in 1985 on Mba [Castellaro, 1999] and are also similar to the results acquired in numerous sand cays in Indian and Pacific oceans, which support the homogeneity of such Holocene sands [Maxwell et al., 1961; Woodroffe et al., 2004, 2007; Kench et al., 2005; Barry et al., 2007, 2008; Woodroffe, 2008].

[9] Neglecting tide effects beyond the beach zone and considering homogeneous hydraulic conductivity, the spatial and temporal variability of the effective groundwater recharge, in the absence of pumping wells, is the only factor that controls the morphology of the lens.

#### 3. Geoelectrical Data Acquisition and Modeling

[10] Electrical resistivity tomography (ERT) is a DC geoelectrical prospecting technique that provides a continuous characterization of subsurface electrical resistivity



Figure 2. Apparent resistivity pseudosections and corresponding inverse model resistivity sections of the three ERT profiles acquired on Mba Island.

 Table 1. Hydrogeological Parameter Values Used in the Groundwater Models

Hydrogeological Parameter	Holocene Carbonate Sediments	Pleistocene Coral Limestone	Data Source
Horizontal hydraulic conductivity (m/d)	10	900	Buddemeier and Oberdorfer, 1988; Ghassemi et al., 2000
Vertical hydraulic conductivity (m/d)	7	180	Buddemeier and Oberdorfer, 1988; Ghassemi et al., 2000
Horizontal longitudinal dispersivity (m)	0.7	0.7	Calibrated on ERT results
Vertical longitudinal dispersivity (m)	0.1	0.1	Calibrated on ERT results
Isotropic transversal dispersivity (m)	0.02	0.02	Calibrated on ERT results
Total porosity (%)	20	30	Buddemeier and Oberdorfer, 1988; Ghassemi et al., 2000; Jones and Banner, 2003

using a multielectrode array driven into the soil and an automatic data acquisition system [*Dahlin*, 1993]. To represent the true subsurface resistivity distribution, measured apparent resistivities need to be deconvolved by geoelectrical modeling.

[11] On Mba Island, ERT was applied from coast to coast along three geoelectrical profiles (Figure 1), among them a 405 m long, NW–SE axis perpendicular to the dune systems (profile 2, Figure 1) and a 880 m long, NE–SW axis (profile 3, Figure 1). The survey was conducted using an ABEM Lund System 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/noise ratio [*Dahlin and Zhou*, 2004] and is sufficiently sensitive to the geometrical features of the seawater interface in coastal groundwater [*Comte*, 2008]. As defined by *Edwards* [1977], the maximum investigation depth with this protocol, corresponding to the maximum electrode spacing, was around 40 m.

[12] Measured resistivities were interpreted using the two-dimensional inverse modeling software RES2DINV (ver. 3.55) [*Loke*, 2006] incorporating topographical data. The inversion method used here was the default least squares ( $L_2$  norm) inversion, with the inverse Schwartz-Christoffel transformation method for the topographical distortion of the mesh and a vertical to horizontal flatness filter ratio of 0.3 so as to enhance horizontal anomalies (freshwater lens).

[13] Geoelectrical imaging shows resistivities ranging from less than 5  $\Omega$  m to more than 300  $\Omega$  m (Figure 2). Resistivities greater than 50  $\Omega$  m correspond to the unsaturated coral sands above the aquifer water table. Toward each coast, there is a zone with resistivity ranging from 2 to 50  $\Omega$  m, inferred to reflect brackish water above conductive seawater (around 1  $\Omega$  m). Between these zones lies a central zone with higher conductivity (around 1  $\Omega$  m) presumed to represent a seawater dome. On the longitudinal profile (profile 3, Figure 1), a resistive layer (more than 50  $\Omega$  m) can also be identified around 35 m below modern mean sea level, inferred to reflect Pleistocene limestone. For better comparison with groundwater model results (see next sections; Figures 4 and 6), deepest geoelectrical data (beyond approximately 20 m pseudodepth, nonrelevant for lens imagery) were then excluded from the inversion process so as to improve both the convergence (stopped to the third iteration) and associated RMS errors of inverse models.

[14] The geoelectrical profiles 2 and 3 indicate the presence of two freshwater zones located below the main system of dunes extending along the coasts. These freshwater zones are separated by a depressed zone where supposed high water uptake due to evapotranspiration prevents the formation of a freshwater lens. However, the uncertainty related to the nonuniqueness of the inversion results implies that the results of the geoelectrical model must be compared with geological and hydrogeological data to validate the recharge pattern.

#### 4. Groundwater Modeling

[15] Simulating the dynamics and mixing processes of the freshwater/saltwater interface requires a numerical model that solves the flow and transport equations simultaneously, taking into account the effect of density in relation to salt concentrations. The three-dimensional finite difference code SEAWAT [*Langevin et al.*, 2003] was applied to simulate the flow and saltwater interface on Mba Island. The three-dimensional model included the whole island and reef flat, was extended to several hundred meters toward the lagoon (1400 m × 800 m horizontally), and was vertically extended to 50 m below modern mean sea level. The model was structured in two layers according to the lithological features: (1) sands from the surface to -35 m and (2) coral limestone from -35 to -50 m.

[16] The two-dimensional finite element numerical code SUTRA [Voss and Provost, 2003] was then applied to compare at higher resolution both heads and salinity with geoelectrical data measured on the transverse profile (profile 3; wells E, C, and W). Orientation of this transect was perpendicular to the geomorphological structures and divided the elliptically shaped island in half. Flow and transport are assumed to be two-dimensional along this section, as confirmed by the results of the three-dimensional model. The two-dimensional model corresponded to the ERT profile but was also extended several hundred meters toward the lagoon from both NE and SW coastlines. In accordance with the three-dimensional model, the twodimensional model extended vertically to 50 m below modern mean sea level and was structured in two layers of similar extension.

[17] Hydrogeological parameters (Table 1) were synthesized from similar island contexts reported in literature (see section 2). Vertical anisotropy was applied to both hydraulic conductivities and dispersivities to reflect the horizontal layering of both the top and bottom layers. Two types of boundary conditions were applied (Table 2): fixed pressure/ concentration condition (seawater edges and seafloor) and surface fluid/solute flow condition (freshwater recharge and groundwater uptake).

Boundary Condition	Value	Data Source
Seawater pressure gradient (N/m <sup>3</sup> )	10,055.25	Voss and
		Provost, 2003
Seawater salinity (g/L)	35.9	Ouillon et al., 2005
NE–SW mean sea level difference (m)	0.10	Kench, 1998
Recharge in the three-dimensional model (mm/y)	50 to 300	Calibrated
Maximum groundwater uptake in the three-dimensional model (mm/y)	400	Calibrated
Water uptake extinction depth in the three-dimensional model (m)	3.5	Calibrated
Effective recharge in the two-dimensional model (mm/y)	-200 to 300	Calibrated
Recharge water salinity (g/L)	0	Fixed

[18] In the three-dimensional model, recharge (infiltration minus evapotranspiration in the soil layer) was spatially distributed in conformity with the vegetation cover of the islet, which is typically staged, as observed on the field and on the aerial photo (Figure 1). On beaches and dunes with sparse vegetation, the soils are not significantly developed and the recharge was calibrated to 300 mm/y. This is mainly located to the periphery of the island and in a number of well-defined inner zones (Figure 1). In the inner sectors with weakly developed soils under shrubby cover (dominated by Acacia spirorbis and Acropogon bullatus), recharge was calibrated to 150 mm/y, whereas in sectors with strongly developed soils under both shrubby and arboreal cover (dominated by Acacia spirorbis and Casuarina equisetifolia), recharge was calibrated to 50 mm/y. Water uptake by roots was then applied in the three-dimensional model as a

linear function of the water table depth, ranging from 600 mm/y when theoretically water table reaches the ground surface to 0 mm/y at 3.5 m below the ground surface. As the minimum depth of water table is about 2.5 m in the center of the island, maximum groundwater uptake reaches 400 mm/y there. Because of the lack of topographical data for the overall surface of the island, water uptake remains spatially submit to uncertainties.

[19] In the two-dimensional model, recharge and water uptake were applied as a single "effective recharge" parameter, which is positive in the case of net recharge (water entering in the system) and negative when water uptake exceeds recharge. The values applied in the twodimensional model were recalibrated from both recharge and water uptake values applied in the three-dimensional model.

[20] As the lens volume tend to reflect recharge averaged over longer times, seasonal variability in rainfall, recharge (infiltration minus evapotranspiration in the soil zone), and water uptake has not been taken into account and was thus applied as averaged values over years. Modern sea level variations and modern sea surface salinity data were provided by the French Hydrographic and Oceanographic Service of the Marine (http://www.shom.fr/). Dominant east to southeast winds and related seawater currents are considered to be responsible for an average sea level that is 10 cm higher in the northeastern region of the island than in the southwestern sector, as observed by *Kench* [1998] on a similar atoll in the Indian Ocean. As for the recharge, sea levels and salinities were applied as averaged values to reflect the long-term behavior of the lenses.

[21] Both two-dimensional and three-dimensional variable density flow models provided groundwater heads and



**Figure 3.** Three-dimensional view of the groundwater salinity distribution (transition levels between freshwater and seawater) simulated with the three-dimensional model showing seawater intrusion in the low-lying central area of the island. Vertical exaggeration is 10 times.



**Figure 4.** Comparison between two-dimensional geoelectrical inverse models and corresponding twodimensional sections from the three-dimensional groundwater model. For better comparisons of the lens structure in the saturated zone, both geoelectrical and groundwater model results have been graphically truncated at 10 m below sea level, so as the unsaturated zone (displaying relatively homogeneous resistivities and salinities), which is not represented.

salt concentrations throughout the saturated zone. The threedimensional groundwater model correctly reproduced the brackish lenses as observed by ERT (see Figures 3 and 4). However, both the coarse meshing of the model and the weakness of topographical data outward the geophysical transects (which strongly conditions the water uptake as a function of the water table depth) do not allow comparing the accurately measured groundwater heads with those simulated by the three-dimensional model. With higher resolution, the two-dimensional groundwater model correctly reproduced both the measured groundwater heads (Figure 5) and the brackish lenses as observed by ERT on the transverse profile (see Figure 6 and section 5). In the best two-dimensional model (model b with nonuniform recharge), simulated water levels ranged from 0 to 0.16 m above seawater level, and lens salinities ranged from about 1 g/L to more than 10 g/L over the seawater-saturated aquifer (35.9 g/L).

# 5. Cross Validation of Models and Effective Recharge Evaluation/Calibration

[22] In geological materials, bulk electrical resistivity ( $\rho$ ) is generally correlated with pore water resistivity ( $\rho_w$ ) (as is



**Figure 5.** Comparison between observed and simulated water heads with the two-dimensional model. Observed heads correspond for each well to both the mean value and the standard deviation from automatic and manual recordings made between February and June 2008, with a time step of 30 min (m/m.s. l = meters referred to the mean global sea level). Models a and b are illustrated in Figure 6.

electrical conductivity,  $\sigma = \rho^{-1}$ ;  $\sigma_w = \rho_w^{-1}$ ) using the model of *Waxman and Smits* [1968] or the more accurate and complete model of *Revil et al.* [1998]. In the case of the relatively clean and water-saturated carbonate sands outcropping on Mba Island, electrical properties of clays can be ignored because the clay fraction is negligible in relation to that of the carbonate grains and the high salinity of the pore water. Accordingly, both models reduce to Archie's law [*Archie*, 1942], expressed as follows:

$$\rho = \rho_w \cdot \frac{\alpha}{\phi^m}; \quad \sigma = \sigma_w \cdot \frac{\phi^m}{\alpha} \tag{1}$$

where  $\phi$ , *a*, and *m* are dimensionless parameters representing the microgeometry of the geomaterial:  $\phi$  is the total matrix porosity, *a* is the coefficient of pore tortuosity, and *m* is the coefficient of cementation, calibrated at 0.2, 1, and 1.3, respectively, on Mba Island. Archie parameters were calibrated according to typical values for unconsolidated carbonate sands [see *Archie*, 1942; *Adisoemarta et al.*, 2000; *Jones and Banner*, 2003].

[23] Additionally, for the ranges of concentration occurring in many natural waters, pore water electrical conductivity at 25°C (in  $\mu$ S/cm) is correlated to the concentration of total dissolved solids (TDS in mg/L) using the following simple linear approximation [*Hem*, 1985]:

$$TDS = A \cdot \sigma_w \tag{2}$$

[24] The calibration factor A is not constant over a wide range of concentrations or water chemistries. According to *Hem* [1985], for coastal systems dominated by sodium chloride, A ranges from 0.6 for seawater to 0.5 for fresh or slightly brackish water. We retained a mean A value of 0.55. Finally, since water temperature displays weak variations and is close to 25°C in both the New Caledonia lagoon and Mba Island groundwater, it was not necessary to correct for temperature in either Archie's law or in the ERT data. As an example, in well N, those among the five wells showing the maximum thermal amplitude in groundwater, temperature displays a seasonal amplitude of only 1.6°C over year and a diurnal amplitude around 0.2°C (Figure 7).

[25] The geoelectrical results (electrical resistivities) are consistent with those of both three-dimensional (Figure 4) and two-dimensional (Figure 6) groundwater models (TDS). All models show resistive/brackish zones surrounded by a homogeneous conductive/saline mass. These zones correspond to a unique ring-shaped freshwater zone in threedimensional sections (Figure 3) or two freshwater zones on two-dimensional sections (Figures 4 and 6) with bulk resistivities over 5  $\Omega$  m and groundwater salinities below 10 g/L that appear at each extremity of the geoelectrical transects, just beneath the sand dune system that forms the coastal fringe of the island. Conversely, the central, lowlying part of the island appears devoid of fresh/brackish groundwater, indicating that (1) recharge is annulled by water uptake (effective recharge = 0) or (2) groundwater uptake exceeds recharge (effective recharge <0).



#### **GEOELECTRICAL MODEL**





**Figure 7.** Evolution of groundwater temperature recorded at the top of groundwater in well N.

[26] These hypotheses about the spatial pattern of recharge and groundwater replenishment can be accurately tested through the combined use of two-dimensional geoelectrical and hydrogeological models (Figures 5 and 6). The use of a vertical two-dimensional groundwater model is justified by the results of the three-dimensional model that showed flow is negligible in the lateral direction for the transverse profile. Assuming no recharge in the center of the island (hypothesis 1: scenario a on Figures 5 and 6) leads to the development of a continuous fresh/brackish water lens in the aquifer that conflicts with geophysical observations. The lens in the central part of the profile is narrower than along the borders. In such a case, groundwater flows from the center of the island to the coastline, as with a unimodal freshwater lens. Postulating groundwater uptake by evapotranspiration (effective recharge ranging from 0 to -200 mm/y) in the central zone of the island (hypothesis 2: scenario b on Figures 5 and 6) leads to the development of two freshwater zones separated by a seawater dome (up to 0 m) like the one revealed in the geoelectrical profile. When water uptake occurs, freshwater flows from the dune areas to both the coastline and the inner island. Water head domes coincide roughly with the topographically high dunal coastal fringes, where effective recharge reaches 300 mm/y. Thus, the hypothesis 2 produces results more consistent with geophysical observations.

#### 6. Conclusion

[27] The combined use of two-dimensional geoelectrical and two-dimensional/three-dimensional groundwater modeling to study freshwater lenses provides relevant knowledge of groundwater recharge. The results of the study show that the geometry and salinity of the freshwater lens are very much controlled by the magnitude and the spatial distribution of both groundwater recharge and uptake by roots. In the sectors with the highest dunes, recharge exceeds water uptake, resulting in a freshwater replenishment rate of 300 mm/y. Conversely, in the low-lying, central sectors, groundwater uptake through evapotranspiration produces a withdrawal rate of about 200 mm/y.

[28] Furthermore, the use of three-dimensional geoelectrical inverse models, when sufficient spatial geoelectrical measurements are possible, could provide more accurate results to compare with three-dimensional groundwater models, which is strongly relevant in the cases of dissymmetrical islands. Also, the computation of water uptake as a function of water table depth in the groundwater model, especially in the three-dimensional model, requires highresolution spatial topographical data that must be an integral part of the field investigation works.

[29] Combining a geoelectrical investigation with hydrogeological modeling appears to be a valid method of evaluating the groundwater budget and replenishment in small islands. Such studies also provide valuable information on evapotranspiration as well as pertinent knowledge of the dynamics of the vegetation in small ecosystems, which are generally not well known and are difficult to study.

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#### References

- Adisoemarta, P. S., G. A. Anderson, S. M. Frailey, and G. B. Asquith (2000), Historical use of *m* and *a* in well log interpretation: Is conventional wisdom backwards?, paper presented at 2000 SPE Permian Basin Oil and Gas Recovery Conference, Society of Petroleum Engineers, Midland, Tex., 21–23 March.
- Andréfouët, S., G. Cabioch, B. Flamand, and B. Pelletier (2009), A reappraisal of the diversity of geomorphological and genetic processes of New Caledonian coral reefs: A synthesis from optical remote sensing, coring and acoustic multibeam observations, *Coral Reefs*, 28, 691–707.
- Archie, G. E. (1942), The electrical resistivity log as an aid in determining some reservoir characteristics, *Trans. Am. Inst. Min. Metall. Pet. Eng.*, 146, 54–62.
- Ayers, J. F., and H. L. Vacher (1986), Hydrogeology of an atoll island: A conceptual model from detailed study of a Micronesian example, *Ground Water*, 24(2), 185–198, doi:10.1111/j.1745-6584.1986.tb00994.x.
- Barry, S. J., P. J. Cowell, and C. D. Woodroffe (2007), A morphodynamic model of reef-island development on atolls, *Sediment. Geol.*, 197, 47–63, doi:10.1016/j.sedgeo.2006.08.006.
- Barry, S. J., P. J. Cowell, and C. D. Woodroffe (2008), Growth-limiting size of atoll-islets: Morphodynamics in nature, *Mar. Geol.*, 247, 159–177, doi:10.1016/j.margeo.2007.09.004.
- Bauer, P., G. Thabeng, F. Stauffer and W. Kinzelbach (2004), Estimation of the evapotranspiration rate from diurnal groundwater level fluctuations in the Okavango Delta, Botswana, J. Hydrol., 288(3–4), 344–355, doi:10.1016/j.jhydrol.2003.10.011.
- Buddemeier, R. W., and J. A. Oberdorfer (1988), Hydrogeology and hydrodynamics of coral reef pore waters, paper presented at 6th International Coral Reef Symposium, James Cook Univ., Townsville, Queensland, Australia, 8–12 August.
- Castellaro, C. (1999), Reconstitutions paléoclimatiques et paléoenvironnementales à l'Holocène et au Pléistocène terminal en Nouvelle-Calédonie et aux Seychelles (région indo-pacifique): l'enregistrement par les coraux, Ph.D. thesis, Univ. of Provence, Marseille, France.
- Comte, J.-C. (2008), Apport de la tomographie électrique à la modélisation des écoulements densitaires dans les aquifères côtiers, Ph.D. thesis, 200 pp., Univ. of Avignon, Avignon, France.

- Comte, J.-C., and O. Banton (2007), Cross-validation of geo-electrical and hydrogeological models to evaluate seawater intrusion in coastal aquifers, *Geophys. Res. Lett.*, 34, L10402, doi:10.1029/2007GL029981.
- Dahlin, T. (1993), On the automation of 2D resistivity surveying for engineering and environmental applications, Ph.D. thesis, Dept. Eng. Geol., Lund Univ., Lund, Sweden.
- Dahlin, T., and B. Zhou (2004), A numerical comparison of 2D resistivity imaging with 10 electrode arrays, *Geophys. Prospect.*, 52(5), 379–398, doi:10.1111/j.1365-2478.2004.00423.x.
- Edwards, L. S. (1977), A modified pseudosection for resistivity and induced-polarization, *Geophysics*, 42, 1020–1036.
- Falkland, A. (1999), Tropical island hydrology and water resources: Current knowledge and future needs, paper presented at 2nd International Colloquium on Hydrology and Water Management in the Humid Tropics, UNESCO-IHP, Panama, Rep. of Panama, 22–26 March.
- Falkland, A., and E. Custodio (1991), Hydrology and water resources of small islands: A practical guide, *Studies and Reports in Hydrology*, 49, *IHP-III Project 4.6*, 453 pp., UNESCO-IHP, Paris.
- Ghassemi, F., K. Alam, and K. W. F. Howard (2000), Fresh-water lenses and practical limitations for their three-dimensional simulation, *Hydro*geol. J., 8(5), 521–537, doi:10.1007/s100400000087.
- Hem, J. D. (1985), Study and interpretation of the chemical characteristics of natural waters, 3rd ed., Water Supply Pap. 2254, 263 pp., U.S. Geological Survey, Alexandria, Va.
- Jocson, J. M. U., J. W. Jenson, and D. N. Contractor (2002), Recharge and aquifer response, Northern Guam Lens Aquifer, Guam, Mariana Islands, J. Hydrol., 260(1–4), 231–254, doi:10.1016/S0022-1694(01)00617-5.
- Jones, I. C., and J. L. Banner (2003), Hydrogeologic and climatic influences on spatial and interannual variation of recharge to a tropical karst island aquifer, *Water Resour. Res.*, 39(9), 1253, doi:10.1029/ 2002WR001543.
- Kench, P. S. (1998), Physical processes in an Indian Ocean atoll, *Coral Reefs*, 17(2), 155–168, doi:10.1007/s003380050110.
- Kench, P. S., R. F. McLean, and S. L. Nichol (2005), New model of reefisland evolution: Maldives, Indian Ocean, *Geology*, 33(2), 145–148, doi:10.1130/G21066.1.
- Langevin, C. D., W. B. Shoemaker, and W. Guo (2003), MODFLOW-2000, the U.S. Geological Survey modular ground-water model – Documentation of the SEAWAT-2000 version with the variable-density flow process (VDF) and the integrated MT3DMS transport process (IMT), *Open-File Report 03-426*, 43 pp., U.S. Geological Survey, Tallahassee, Fla.
- Loke, M. H. (2006), RES2DINV ver. 3.55, Rapid 2-D resistivity & IP inversion using the least-squares method, 139 pp., Geotomo Software, Penang, Malaysia, http://www.geoelectrical.com/download.html.
- Maxwell, W. G. H., R. W. Day, and P. J. G. Fleming (1961), Carbonate sedimentation on the Heron Island reef, Great Barrier Reef, J. Sediment. Petrol., 31(2), 215–230.
- Migon, C., S. Ouillon, X. Mari, and E. Nicolas (2007), Geochemical and hydrodynamic constraints on the distribution of trace metal concentrations in the lagoon of Nouméa, New Caledonia, Estuarine, *Coastal Shelf Sci.*, 74(4), 756–765, doi:10.1016/j.ecss.2007.05.048.
- Ouillon, S., P. Douillet, R. Fichez, and J.-Y. Panché (2005), Enhancement of regional variations in salinity and temperature in a coral reef lagoon, New Caledonia, C. R. Geosci., 337(16), 1509–1517, doi:10.1016/j. crte.2005.08.005.
- Revil, A., L. M. Cathles III, S. Losh, and J. A. Nunn (1998), Electrical conductivity in shaly sands with geophysical applications, *J. Geophys. Res.*, 103(B10), 23925–23936.
- Ruppel, C., G. Schultz, and S. Kruse (2000), Anomalous fresh water lens morphology on a strip barrier island, *Ground Water*, 38(6), 872–881, doi:10.1111/j.1745-6584.2000.tb00686.x.
- Sanford, W. (2002), Recharge and groundwater models: An overview, *Hydrogeol. J.*, *10*(1), 110–120, doi:10.1007/s10040-001-0173-5.
- Scanlon, B. R., R. W. Healy, and P. G. Cook (2002), Choosing appropriate techniques for quantifying groundwater recharge, *Hydrogeol. J.*, 10(1), 18–39, doi:10.1007/s10040-0010176-2.

- Schneider, J. A., and S. E. Kruse (2005), Assessing natural and anthropogenic impacts on freshwater lens morphology on small barrier islands: Dog Island and St. George Island, Florida, *Hydrogeol. J.*, 14(1–2), 131–145, doi:10.1007/s10040-005-0442-9.
- Stewart, M. T. (1982), Evaluation of electromagnetic methods for rapid mapping of salt-water interfaces in coastal aquifers, *Ground Water*, 20(5), 538–545, doi:10.1111/j.1745-6584.1982.tb01367.x.
- Vacher, H. L., and T. N. Wallis (1992), Comparative hydrogeology of Bermuda and Great Exuma Island, Bahamas, *Ground Water*, 30(1), 15–20, doi:10.1111/j.1745-6584.1992.tb00806.x.
- van der Velde, M., M. Javaux, M. Vanclooster, and B. E. Clothier (2006), El Niño-Southern Oscillation determines the salinity of the freshwater lens under a coral atoll in the Pacific Ocean, *Geophys. Res. Lett.*, *33*, L21403, doi:10.1029/2006GL027748.
- Voss, C. I., and A. M. Provost (2003), SUTRA: A model for saturatedunsaturated variable-density ground-water flow with solute or energy transport, *Water Resources Invest. Rep. 02-4231*, 250 pp., U.S. Geological Survey, Reston, Virginia, 21 June.
- Wallis, T. N., H. L. Vacher, and M. T. Stewart (1991), Hydrogeology of freshwater lens beneath a Holocene strandplain, Great Exuma, Bahamas, J. Hydrol., 125(1–2), 93–109, doi:10.1016/0022-1694(91)90085-V.
- Wanke, H., A. Dünkeloh, and P. Udluft (2007), Groundwater recharge assessment for the Kalahari catchment of north-eastern Namibia and north-western Botswana with a regional-scale water balance model, *Water Resour. Manage.*, 22, doi:10.1007/s11269-007-9217-5.
- Waxman, M. H., and L. J. M. Smits (1968), Electrical conductivities in oil-bearing shaly sands, Soc. Pet. Eng. J., 8(2), 107–122, doi:10.2118/ 1863-A.
- White, I. (1996), Fresh groundwater lens recharge, Bonriki, Kiribati: Preliminary Report, *Rep. IHP-V Project 6.1*, 38 pp., UNESCO-IHP, Paris.
- White, I., T. Falkland, T. Metutera, E. Metai, M. Overmars, P. Perez, and A. Dray (2007a), Climatic and human influences on groundwater in low atolls, VZJ, 6, 581–590, doi:10.2136/vzj2006.0092.
- White, I., T. Falkland, P. Perez, A. Dray, T. Metutera, E. Metai, and M. Overmars (2007b), Challenges in freshwater management in low coral atolls, *J. Cleaner Prod.*, 15(16), 1522–1528, doi:10.1016/j.jclepro. 2006.07.051.
- Wilson, S. R., M. Ingham, and J. A. McConchie (2006), The applicability of Earth resistivity methods for saline interface definition, J. Hydrol., 316(1-4), 301-312, doi:10.1016/j.jhydrol.2005.05.004.
- Woodroffe, C. D. (2008), Reef-island topography and the vulnerability of atolls to sea-level rise, *Global Planet. Change*, 62, 77–96, doi:10.1016/j. gloplacha.2007.11.001.
- Woodroffe, C. D., D. M. Kennedy, B. G. Jones, and C. V. G. Phipps (2004), Geomorphology and Late Quaternary development of Middleton and Elizabeth Reefs, *Coral Reefs*, 23, 249–262, doi:10.1007/s00338-004-0374-1.
- Woodroffe, C. D., B. Samosorn, Q. Hua, and D. E. Hart (2007), Incremental accretion of a sandy reef island over the past 3000 years indicated by component-specific radiocarbon dating, *Geophys. Res. Lett.*, 34, L03602, doi:10.1029/2006GL028875.

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