

The problem of prospecting and development of inland groundwater resources in young tropical volcanic islands

J. L. JOIN, M. COURTEAUD, B. ROBINEAU, E. NICOLINI & J. COUDRAY

Laboratoire des Sciences de la Terre, Université de la Réunion, Faculté des Sciences, BP 7151, F-97715 Saint Denis Messag Cedex 9, France

Abstract The tropical Reunion Island consists of two juxtaposed volcanoes: the extinct Piton des Neiges (3069 m) and the still active Piton de la Fournaise (2631 m). With the growing development of the island, a reasoned exploitation of the coastal basal aquifer will be insufficient to satisfy the demand for water supply in the next decade. In the mountainous interior of the island, the evaluation of the water resources reserve of the aquifer, the water table level of which is located at high elevations but lying a thousand metres below the ground surface, requires new deep prospecting tools. The AMT method, and chemical and flow rate monitoring are proposed to evaluate this groundwater resource more accurately.

El problema de la prospección y del desarrollo del agua subterránea en las islas volcánicas

Resumen La isla tropical de la Reunion est formada de dos volcanes yuxtapuestos: el macizo extinto del Piton des Neiges (3069 m) y el activo Piton de la Fournaise (2632 m). Con el crecimiento del desarrollo y de la urbanización de la isla, la mera explotación del acuífero basal costero se revela insuficiente para satisfacer, en el decenio que viene, la demanda en agua potable. En las regiones montañosas del interior de la isla, la evaluación de las reservas de la capa profunda, cuyo nivel se situa bajo unos 1000 m de recubrimiento basáltico, requiere nuevas técnicas de prospección. El método geofísico AMT, el registro de los parámetros químicos y del caudal de las fuentes son propuestos para evaluar con mas precisión el recurso en aguas subterráneas.

INTRODUCTION

Reunion Island (21°07'S, 55°32'E) is located about 800 km east of Madagascar in the Indian Ocean (Fig. 1). Along with Mauritius and Rodrigues Islands, it belongs to the Mascarene archipelago. It is the youngest island in this group and has the highest peak (3069 m) in the southwestern Indian Ocean. Entrenched valleys with amphitheatre morphology or erosional internal cirques cut the mountainous and very rough topography. Steep slopes extend down to very abrupt coasts.

Reunion Island has a tropical climate characterized by a hot, humid season (November–May) and a cool, dry season (June–October). During the austral summer (November–February), tropical cyclones can generate very heavy rains. The western coast is the hot and dry side of the island. The average annual rainfall varies from 1340 mm on this side to 3850 mm on the east coast (Stieltjes *et al.*, 1988). The difference is attributable to the major influence of east-southeast trade winds.

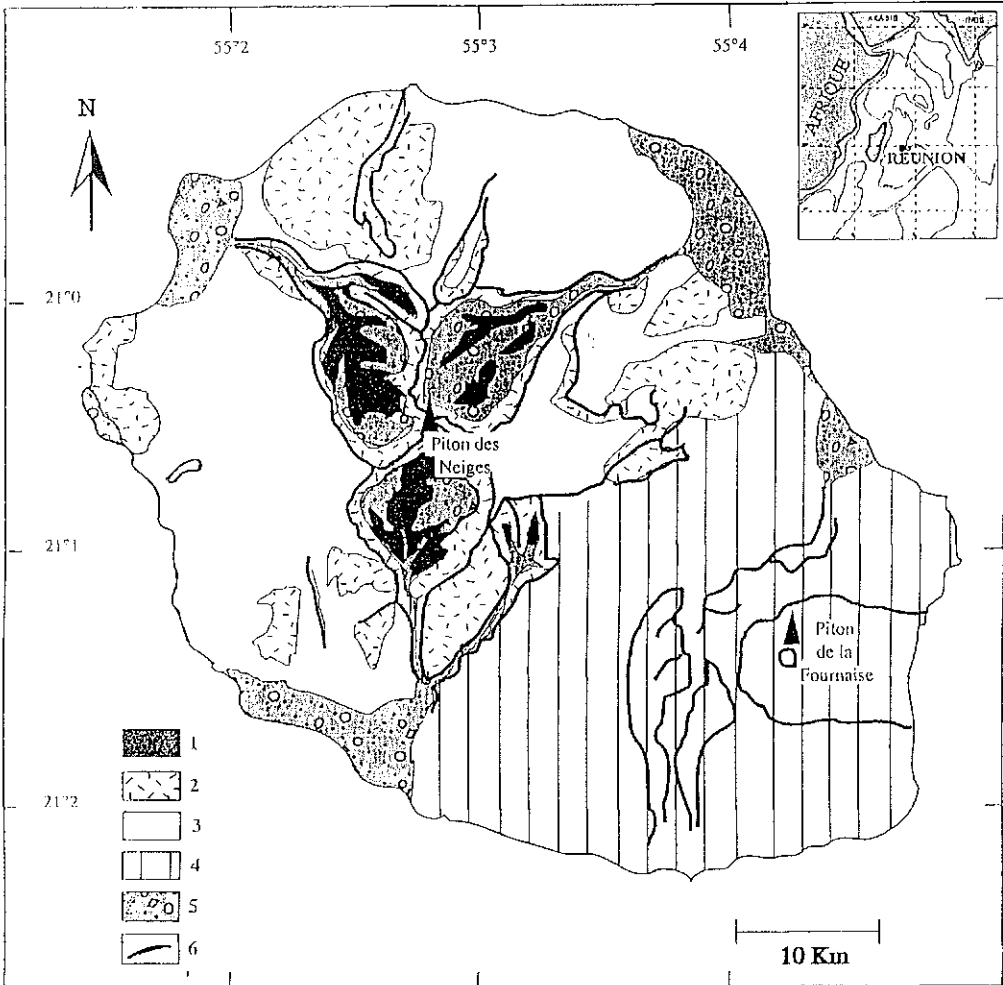


Fig. 1 Geological map of Reunion Island. 1: phase I, 2: phases II and III, 3: phase IV (lithostratigraphic units of Piton des Neiges volcano), 4: Piton de la Fournaise basaltic unit, 5: volcano-detritals and alluvial deposits, 6: cirque rampart.

Bargeas (1984) estimated the feeding potential (infiltration + runoff) in the range 1000–9000 mm. Surface runoff occurs mainly after exceptional rain storm events and most of the precipitation goes into deep infiltration.

GEOLOGY

Reunion Island, entirely of volcanic origin, developed from the activity of the now dormant Piton des Neiges volcano or the active Piton de la Fournaise volcano. The volcanic formations have been locally weathered by tropical processes.

Four main periods of activity have been distinguished in the lithostratigraphy of Piton des Neiges, dating from 2.1 million to 20 000 years ago (Billard & Vincent, 1975). The two oldest periods (stages I and II) consist of lava flows and pyroclastics

of picritic basalt while the subsequent stages (III and IV) display more differentiated volcanics (Upton & Wadworth, 1972). The lava flows associated with Piton de la Fournaise are mainly composed of picritic basalt (Fig. 1). Horizons of pyroclastic and volcanodetrital materials are interbedded with flows.

GROUNDWATER RESOURCES

Until now, groundwater exploitation has mainly developed on the "basal coastal aquifer" (Fig.2). Hydrogeological data from wells, drilled in volcanic and mixed volcanic/alluvial formations, have been gathered in order to study the main hydraulic characters of this aquifer. Most of the wells (82%) are located at between 0 and 110 m elevation. Their average depth is about 110 m. In the last ten years, borehole

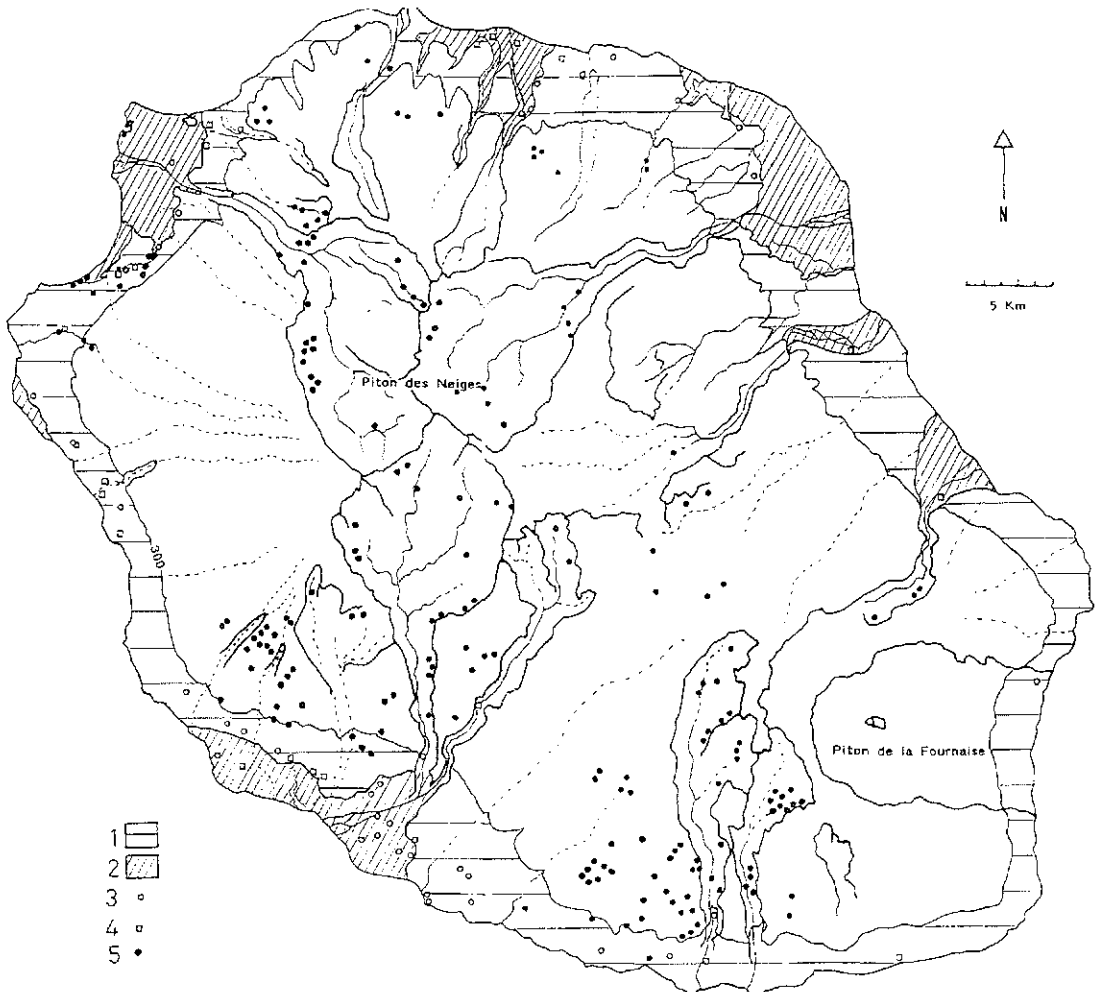


Fig. 2 Groundwater resources. 1: basal coastal aquifer (up to 300 m a.s.l.), 2: basal coastal aquifer in alluvial formation, 3: borehole, 4: well, 5: spring.

investigations have been extended further inland up to 200 m a.s.l. Above this altitude, investigations become more hazardous and wells are exceptional (less than 3%). As a consequence of the steep slopes of the volcano, 88% of the wells are located from the coast line to 4 km inland.

The water level is encountered very close to the mean sea level. A majority of wells (77%) present a piezometric level under 6 m a.s.l.; only 12 % are above 15 m a.s.l., and those are generally located in a specific hydrogeological context in relation to alluvial aquifers.

The piezometric slope ranges from 0.5 to 3‰; the highest values usually indicate a connection with alluvial aquifers. Transmissivities obtained from well test and model results are higher than $1E - 1 \text{ m}^2 \text{ s}^{-1}$ for 57% of the wells (Fig. 3). The modal specific discharge is equal to $50E - 2 \text{ m}^3 \text{ s}^{-1} \text{ m}^{-1}$ and reaches $0.7 \text{ m}^3 \text{ s}^{-1} \text{ m}^{-1}$ in some cases. Such results are very close to the hydrodynamic characteristics of Hawaiian volcanoes in a similar geological context (Peterson, 1972; Ingebritsen & Scholl, 1993).

Further inland, groundwater exploitation is restricted to the catchment of natural springs. Springs, mainly located in the particularly rough relief of the main valleys and cirques, range most frequently in altitude from 800 to 1200 m a.s.l.

According to the geological characteristics of water-bearing beds, the hydrogeological context of the springs has been divided into three categories (Join, 1991): (a) superficial water tables related to subsurface flows in aquifers of very limited extent; (b) perched water tables where flows are channelled through palaeo-valleys or stretched on extensive zones of ash; and (c) basal water tables observed in entrenched valleys of “amphitheatre” morphology (Fig. 4).

The first two categories are characterized by springs with a variable specific discharge (e.g. $DCE/DC6 = 0.3$; with $DCE =$ daily mean discharge not exceeded

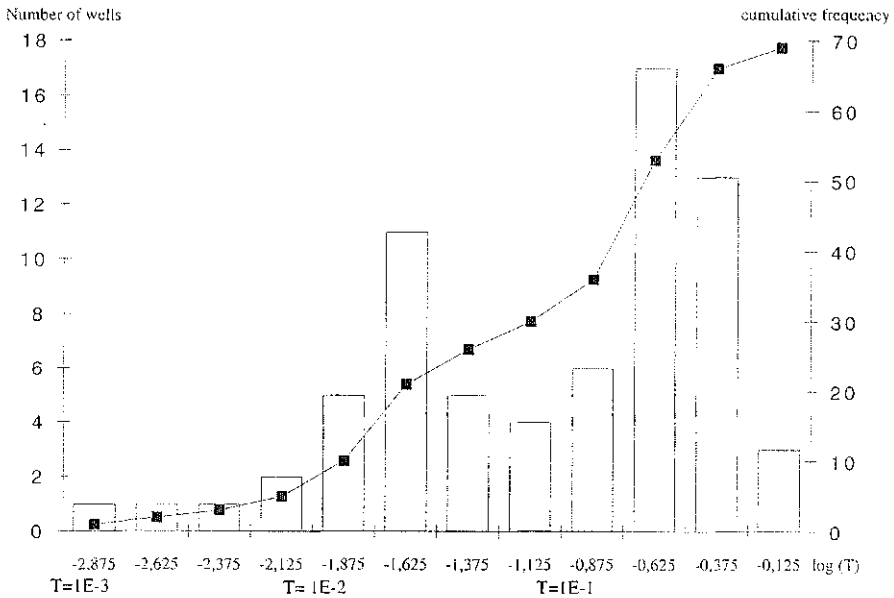


Fig. 3 Frequency distribution of transmissivities in the basal coastal aquifer.

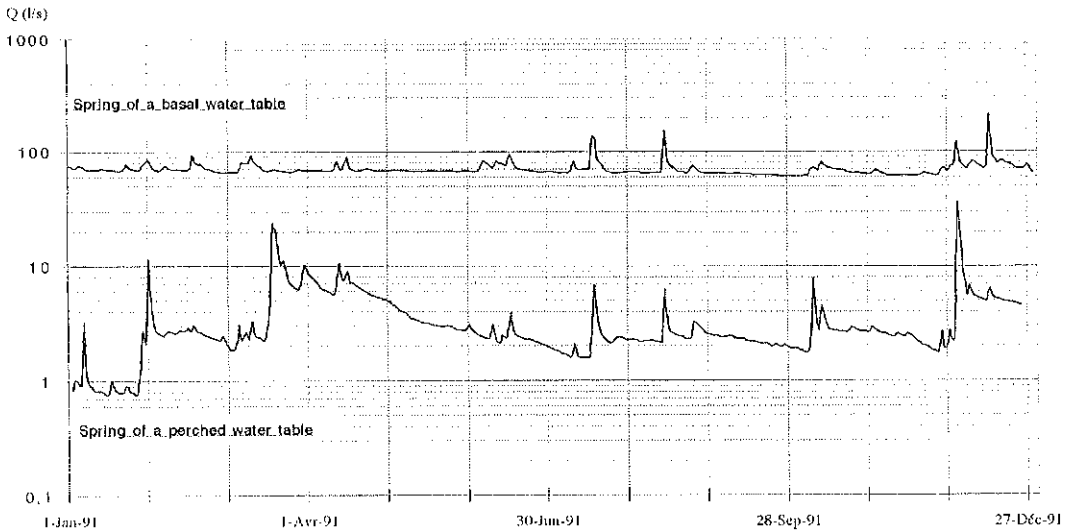


Fig. 4 Flow rate discharge of springs.

during ten days per year, and $DC6$ = daily mean discharge not exceeded during 6 months per year) and high decreasing rate of groundwater discharge (e.g. $\alpha = 48E^{-9} s^{-1}$ with a depletion coefficient). Springs of the basal water table are characterized by a constant specific discharge (e.g. $DCE/DC6 = 0.9$) and a smaller depletion coefficient (e.g. $\alpha = 3.4 E^{-9} s^{-1}$) (Fig. 4).

More recently, this classification of Reunion Island springs has been supported by a statistical analysis of hydrochemical data performed on 243 springs sampled in the massif (Join *et al.*, 1997). The definition of a high level basal water table in the interior involves a drastic decrease of permeability in the core of the island. Geological observations made in the deep erosional morphology of the massif provide some evidence of lithological changes in the oldest stages of the two volcanoes (Rançon, 1982). The occurrence of dikes may contribute to the diminution of horizontal permeability, but their role in impounding groundwater as defined in Hawaiian volcanoes, has never been clearly observed in Reunion.

A global hydrological pattern at the regional scale of the massif is proposed, showing a supposed continuous relation between the inland basal water table and the coastal basal water table. The main particularity of this model is to be consistent with hydrological patterns proposed for the different and older volcanoes of the Canarian archipelago (Custodio *et al.*, 1988) (Fig. 5).

IMPLICATIONS FOR GROUNDWATER PROSPECTING AND EXPLOITATION

In Reunion Island, groundwater resources are today almost totally provided by volcanic aquifers in the coastal area. There, withdrawal is possible by means of wells to the maximum depth of about 200 m a.s.l., resulting from technical and economic constraints of borehole investigations. As this area is restricted to a small stretch of

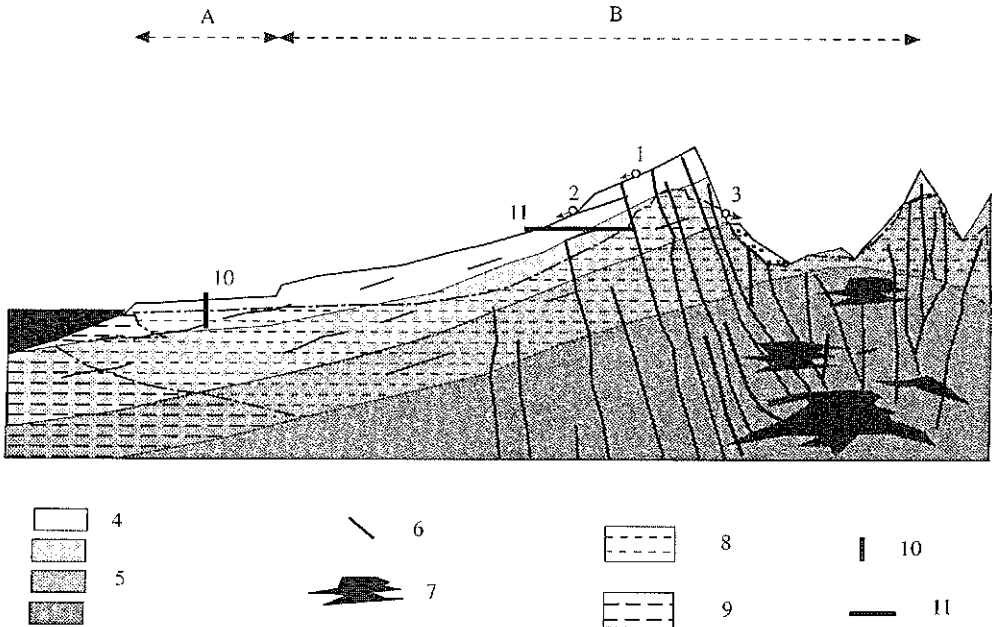


Fig. 5 Proposed hydrological patterns of a young volcano flank. 1: spring of superficial water table, 2: spring of perched water table, 3: spring of basal water table, 4: young volcanic flows, 5: old volcanic formations, 6: dike, 7: intrusive body, 8: fresh water, 9: marine intrusion, 10: borehole, 11: gallery, A: basal water table in coastal area, B: water table in highlands.

about 4 km inland, groundwater extraction is made with a risk of salt water intrusion due to the proximity of the ocean. Moreover, in the highly permeable terrains of the young volcanic flows, this risk is increased by the small elevation of the water table. In this context further investigations are focused on the prospecting of heterogeneities in the Ghyben Herzberg interface (Courteaud *et al.*, 1996). With this goal, new geophysical prospecting methods using time domain electromagnetics have been developed with success up to a hundred metres of depth investigation.

However, with the growing development of the island, a reasoned exploitation of the coastal basal aquifer will be insufficient to satisfy the demand for water supply in the next decade. New investigations look toward the available resources in the mountainous interior of the island. In these high lands, prospecting for perched aquifers by borehole investigation down to a hundred metres remains unsuccessful. When a water table was found, its extension and thickness were generally too small to allow sufficient withdrawal. In many case, the piezometric level was lost after deeper investigations. Such results can be correlated with the hydrodynamic characteristics of springs related with this type of aquifer (Join & Coudray, 1993).

Furthermore, numerous springs related to an extended basal water table were observed at the foot of the main ramparts and cliffs in the rugged topography of Reunion Island. Thus, this potential aquifer is not accessible for traditional investigations. On the basis of the Canarian experience (Ecker, 1976; Fernandopulle *et al.*, 1974), horizontal galleries, thousands of metres long, starting from the external flank of the volcano, have been proposed. However, such costly

investigations require a thorough understanding of the hydrogeological structure. In most cases the target groundwater resources lie hundreds of metres below the ground surface. Hydrogeologists have to look toward the use of deep prospecting tools. In this way, geophysical prospecting by means of AMT methods is able to provide details about the main characteristics of deep volcanic structures (Robineau *et al.*, in press). Chemical and flow rate monitoring of some of the remote springs of the island has been implemented in order to evaluate with more accuracy this groundwater resource.

CONCLUSION

Nowadays, for Reunion Island development, the challenge consists of evaluating the water resources reserve and the possibility of exploitation for an estimated deep groundwater body lying a thousand metres below the ground surface in the mountainous interior of the island. Geophysical prospecting by means of AMT coupled with springs monitoring has provided new information about this unknown groundwater resource. The first results obtained in both the volcanoes Piton des Neiges and Piton de la Fournaise attest the presence of hydrological potential at altitude. Nevertheless we have to keep in mind the uncertain accessibility of this resource.

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