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Groundwater Resources on Active Basaltic Volcanoes: Conceptual Models from La Réunion Island and Grande Comore

Jean-Lambert Join, Jean-Luc Folio, Anli Bourhane and Jean-Christophe Comte

Abstract

La Réunion Island and Grande Comore are oceanic islands entirely formed by young and still active volcanoes, namely Piton de la Fournaise and Karthala. These geological features are responsible for a particular type of hydrosystem and present a unique challenge regarding the prospection and management of water resources. Young volcanic terrains are composed of lava flows with exceptional hydraulic conductivities. On both islands, despite high levels of precipitation, surface water resources are scarce due to high infiltration rates. Water infiltrates deep into the ground and reaches the water table at an elevation close to sea level. Access to water resources is particularly challenging on these islands due to: (i) the relative absence of perennial surface water resources, (ii) the widespread marine contamination in littoral areas, (iii) the excessive depth of the groundwater table due to high elevations. We present the main results obtained from twenty years of multidisciplinary investigation programs dedicated to groundwater resources development in La Réunion Island. This approach includes geological and hydrogeological investigations, geophysical prospections and geochemical analysis. Results have led us to propose an improved conceptual model describing groundwater resources and to implement a numerical model of groundwater flow applied to Piton de la Fournaise volcano. In the interior of the island, the presence of a piezometric dome reaching a height of over 1200 m above sea level has been revealed and is of major interest for groundwater development plans.

5.1 Introduction

Despite high precipitation rates, young or still active volcanic islands, which are mainly composed of stacks of lava flows, present difficulties

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for the access of water resources. High hydraulic conductivities promote deep infiltration and the depth of the water table increases dramatically with the island's elevation. As a consequence, inland prospection of groundwater is expensive and uncertain. Near the coast, wells are drilled until they reach the water table, which is close to sea level and at permanent risk of saltwater contamination. In addition, hydrogeologists commonly have to deal with the lack of direct observations or monitoring points. The major challenge today is to define conceptual groundwater models for inland aquifers (Izquierdo 2014).

A number of key hydrogeological studies have described aquifers in active volcanic islands, such as the Teide volcano (Ecker 1976; Custodio 1978), Karthala in the Comoros archipelago (Savin et al. 2001), the island of Mauritius (Join et al. 2000), Pico Island in the Azores archipelago (Cruz and Silva 2001) and the Hawaiian archipelago (Izuka and Gingerich 2003). Several conceptual models are used to describe volcanic island aquifers (Cruz and Silva 2001). They may be classified in two categories: (i) Hawaiian models (Peterson 1972; MacDonald et al. 1983), and (ii) Canary Islands models (Custodio 1974, 1978; Custodio and Saenz de Oiza 1973; Falkland and Custodio 1991).

Hawaiian models (Izuka et Gingerich 2003; Lau et Mink 2006), distinguish between the "basal groundwater" and the "high-elevation groundwater saturated zones". The basal groundwater is characterized by a lens-shaped water body floating on saltwater with a flat water table. This aquifer is composed of a thick accumulation of basaltic lava flows with high hydraulic conductivity. The high-level saturated zones are found at elevations much higher than the basal groundwater. These bodies are described as "perched" or "dyke impounded".

The Canary Islands models consider a progressive decrease of hydraulic conductivity with depth, which controls the general hydrogeological behaviour of active shield volcanoes. The basal groundwater is assumed to extend continuously from coastal areas to the caldera and rift zones. In the mountainous interior parts of the volcanoes, the water table has the shape of a high elevation dome (Custodio et al. 1988). This is because hydraulic conductivities are assumed to be smaller as the average depth of the basal groundwater below the land surface increases. In addition, the recharge is usually higher in these areas. In this model, perched or dike-impounded water bodies can be found locally but it is assumed that the main streams or springs in the high elevation zones are connected to the basal groundwater.

Those two categories of conceptual models were synthesized by Join et al. (2005) and are clearly different with regard to hydraulic conductivity distribution and the level of hydraulic continuity between coastal and mountainous areas (Fig. 5.1). Hawaiian models consider a binary distribution of hydraulic conductivities (very permeable/impervious) and a hydraulic discontinuity between basal groundwater and high-level saturated zones. In contrast, Canary Islands models assume a smoother hydraulic conductivity distribution that enables better hydraulic continuity. Custodio (1989) noted that the widely-used classification for Hawaiian models is not suitable for the case of the Canarian archipelago, especially the relationship between the high-level saturated zones and the basal aquifer that consists in a huge and relatively sudden head loss. More recently, Izuka and Gingerich (in 1998 then 2003) suggested that a new conceptual model of groundwater occurrence in shield-volcano islands is needed to explain the conditions observed in Kauai Island (Hawaii). They described a hydrogeological feature called "fully saturated vertically extensive fresh water body" which is similar to the continuous basal groundwater proposed in the Canary Islands models. In fact, the Canary Islands and Hawaiian models are not antagonistic but complementary and influenced by the age of the geological materials of volcanic islands, their degree of erosion, the relative position of young basaltic lava flows and the type of volcanism (Join et al. 2005).

Taking into account the hydrological similarities between the islands of Grande Comore and La Réunion, we propose here to use La Réunion and the two massifs of Piton des Neiges and

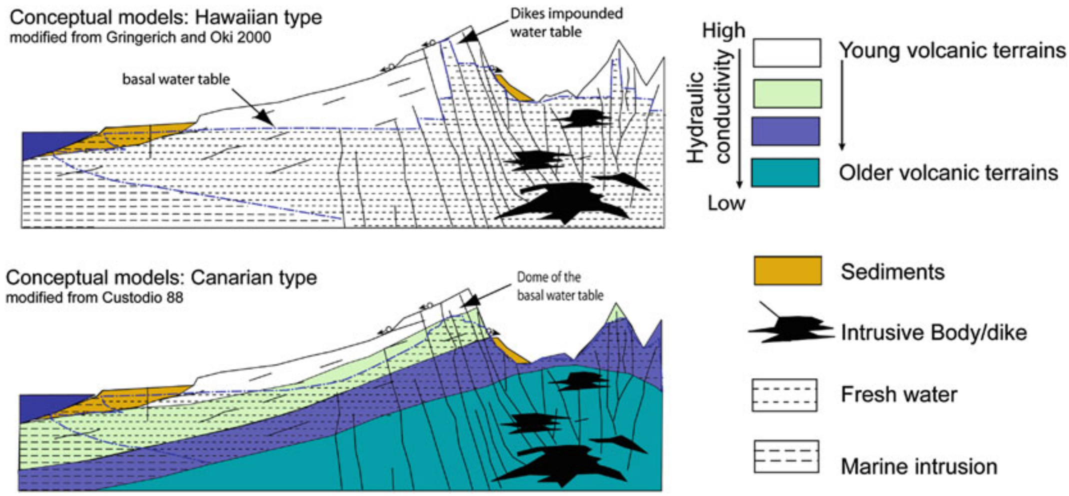

Fig. 5.1 Hydrogeological conceptual models of young oceanic volcanoes (modified from Join et al. 2005)

Piton de la Fournaise as a pilot site for the understanding of the groundwater settings of these two young volcanic islands. The main hydrogeological analysis results obtained in La Réunion will be set out below. These results have enabled a conceptual model to be defined and a simulation of flows path to be generated. Finally, the potential applications of this simulation are expounded in terms of prospection of groundwater resources on this type of volcano.

5.2 Climatology of La Réunion: The Case of Piton de la Fournaise

Precipitations fluctuate from a massif to another due mainly to its situation to tradewinds. However in both La Réunion and Grande Comore islands, the climate is inter-tropical with two seasons: a hot rainy season from December to April and a temperate dry season from May to November. In La Réunion the windward eastern slopes are subjected to high precipitations, with between 2 and 12 m of rainfall per year. Conversely, the western leeward side receives only between 0.5 and 2 m of rainfall per year. In La Grande Comore, annual rainfall varies from less than 1.5 m in the north-east to more than 4 m in the south-west of the island. Despite the abundance of the precipitations, there are no permanent rivers on the flanks of these volcanoes. In La Réunion Island, permanent streams only exist within the deep erosion cirques that are absent in Grande Comore. However, in both islands the increase of precipitations with elevation promotes the existence of small springs in higher-altitude areas.

Within La Réunion Island, the massif of Piton de la Fournaise is the rainiest area, whose water budget is given by Barcelo and Coudray (1996). Mean annual rainfall is 6200 mm. Evaporation and runoff are each close to 1000 mm, which is approximately the uncertainty regarding estimated rainfall. Recharge would therefore be around 4200 mm/year. However, a very contrasted distribution of rainfall over the volcano is observed, with more than 12,000 mm/year on the eastern side of the massif.

On the whole massif and despite abundant rainfalls, only three rivers feature perennial flow reaching the sea; they are located in the deepest incised valleys of the massif. On the volcano flanks, runoff occurs only during the most intense rainfall events. Barcelo (1996) has shown that these runoff events are associated with high infiltration in the river bed that contributes to recharging the aquifers.

5.3 Groundwater Bodies: Typology, Geological, Hydrodynamical and Geochemical Aspects

5.3.1 Hydrogeological Analogy Between the Islands of Grande Comore and La Réunion

The first deep geophysical surveys performed on the flanks of the Karthala volcano enabled the analogy of the hydrogeological conditions between the Karthala massif and the better-known context of La Réunion Island to be discussed for the first time (Savin et al. 2001). Later, Join et al. (2005) revised the conceptual hydrogeological model of La Réunion Island and proposed its application to other volcanic islands such as Grande Comore. According to these works, the hydrogeological context of La Réunion can be divided into two hydrogeological domains: the littoral domain and the altitude domain. These two categories are artificial and result from historic uncertainty relative to inland continuity of the well-known volcanic coastal aquifer.

5.3.2 The Coastal Area

The geographical zone corresponding to the coastal area is defined arbitrarily as the zone of prospection of the basal groundwater by drilling. In practice, this zone is limited to the area whose elevation is below 300 m. At higher elevations, survey soundings become scarce and access to hydrogeological information becomes more difficult. In the littoral domain, the analysis tools stem from geological and hydrodynamic data derived from interpolations of soundings and hydraulic tests.

Since the eighties, thanks to a large number of deep wells drilled within the framework of a development programme of the Water Research Department undertaken in La Réunion Island as well as the United Nations Development Programme in Grande Comore, the hydrogeological conditions in both islands' coastal areas have been better known than inland. In most cases, the piezometric level measured in the wells is close to the mean sea level (the mean hydraulic head is under 1 m). This confirms the very low hydraulic gradient of the coastal groundwater. Moreover, the water level in the wells and groundwater salinity are strongly influenced by tidal fluctuations. The marine impact is, however, greater in Grande Comore where the mean tidal range reaches 3 m (1.2 m in La Réunion Island). In both cases, it is tricky to determine both upgradient and downgradient hydraulic conditions. Upgradient, the estimation of fluxes is even more complicated because of the non-conformability between superficial and underground catchments. At the downgradient boundary, the interface with seawater corresponds to a head condition. Nevertheless, control of the outflows remains uncertain.

5.3.3 The Inland Domain

The inland domain can be defined from the point of view of the problem of groundwater accessibility by the classical hydrogeological investigation methods based on drilling. In la Réunion island, the rare drilling surveys performed at the centre of the island show that the water table depth of the base aquifer can reach several hundred meters (typically >300 m up more than 3 km from the shoreline). Therefore, beyond an elevation of 300 m, drilling investments are exceptional and groundwater exploration requires different investigation methods. The distinction between altitude and littoral domains is thus based on two types of methodological approaches of investigation.

In the high elevation zones of the two volcanic massifs of La Réunion island, the existence of aquifer systems is evidenced by more than 400 springs which appear mostly in the wettest part of the island or in the erosion morphology and mark the points of groundwater emergence. This abundance of springs in La Réunion contrasts with Grande Comore, which lacks such erosion. This difference is related to the much wetter climate of La Réunion.

Field work carried out on the Piton des Neiges massif contributed to defining the main conditions

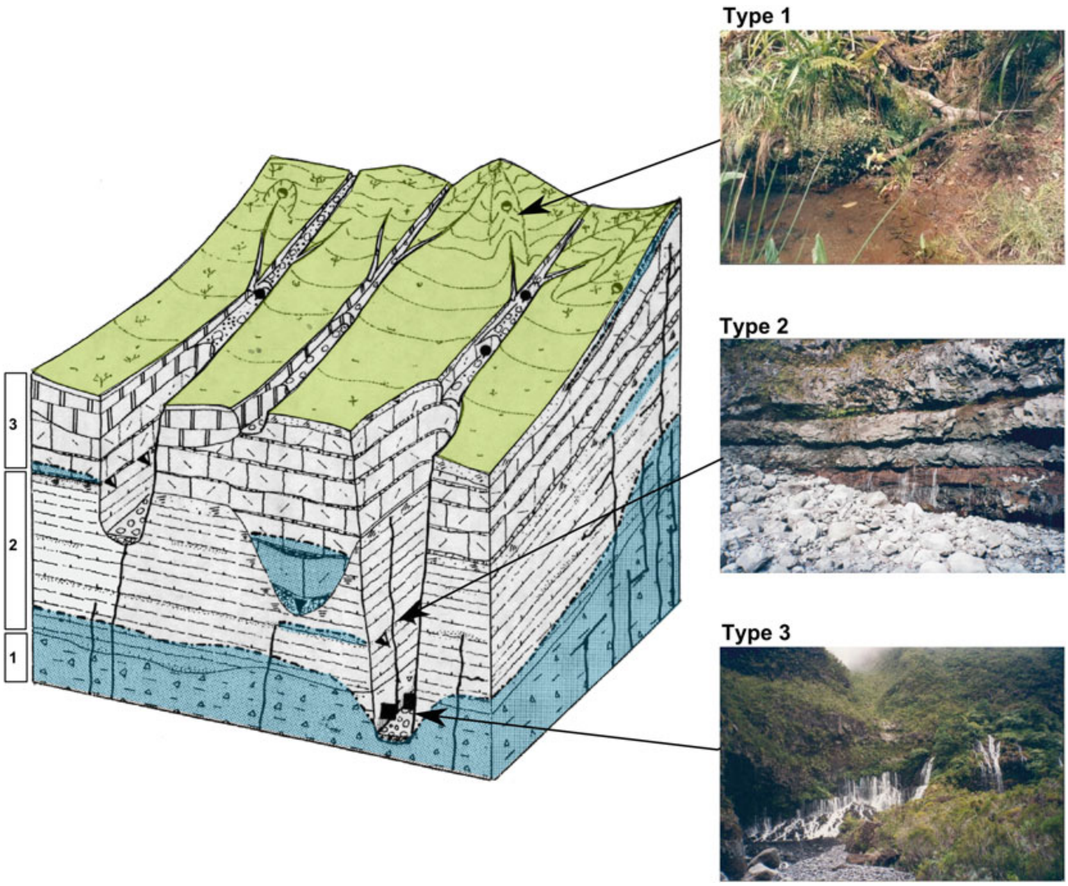

Fig. 5.2 Hydrogeological conceptual model of inland aquifers. Groundwater: *type 1* springs from superficial aquifer, *type 2* springs from intermediate aquifer, *type 3* springs from deep aquifer. Geology: from older unit (*1*) to younger unit (*3*) volcanic terrains

of aquifer deposits in altitude zones (Join and Coudray 1993). A hydrogeological conceptual model of the springs and their reservoirs was proposed with a view to describing the different aquifer systems occurring in the inland zone (Fig. 5.2). Three types of aquifer systems were differentiated: this classification was later adapted to the Piton de la Fournaise.

- Type 1 represents the superficial aquifers developed in weathered horizons facilitated by the presence of pyroclastic accumulations at the surface. In the wettest zones, a weakly incised hydrological network participates in the groundwater drainage of these small aquifers. The variability of the instantaneous outflows confirms the absence of reserve.
- Type 2 represents the perched aquifers observed in the cliff walls of erosion canyons and cirques. They are supported by thin impervious horizons associated with paleo-valleys or paleo-soils. Like type 1, these aquifers are characterized by high depletion rates.
- Type 3 represents the deep saturated zone (the basal aquifer) within the oldest volcanic units of the massif. In La Réunion, this deepest saturated zone yields most of the emergences observed as well as the biggest rivers in the two volcanic massifs. Springs appear preferentially at the bottom of the erosional amphitheatre of the largest rivers such as the Rivière des Remparts, the Rivière de l’Est and the Rivière Langevin (Coudray et al. 1990). They are also

observed in the massif of Piton des Neiges (Atlas Hydrogéologique de la Réunion, coll. 1986). The outflow values are remarkably sustained during the driest periods.

5.3.4 Hydrochemical Aspects

Among the 243 springs analysed across the island, only 5 springs (≈2 %) are clearly identified as being hydrothermal in type. They are essentially located in the three cirques of Piton des Neiges. They can be characterized by temperatures higher than 25 °C and electrical conductivities higher than 200 µS cm^{-1}, with a predominance of the SO_4–Na chemical feature (Daesslé et al. 1988). The remaining springs are mainly located in high areas. The highest occurrence is situated between 900 and 1300 m. These waters are poorly mineralized and water mineralization does not appear to be a sufficient criterion to differentiate the three types of inland aquifers. Join et al. (1997) have shown that the electric conductivity of the inland springs ranges from 17 to 143 µS cm^{-1}, while that of the basal aquifer springs varies only between 52 and 64 µS cm^{-1} and is below the mean value of the springs from superficial and perched aquifers (71 µS cm^{-1}). The waters are characterized by HCO_3–Mg or HCO_3–Ca chemical facies, but sodium can constitute the secondary facies and become preponderant in some springs within the cirques. By classifying samples on a Piper diagram (Fig. 5.3), one can identify the differences between superficial springs (related to presence of ando soils) which are characterised by chloride (and also nitrates), and the basal aquifer springs (issuing from the oldest volcanic rocks) which are characterised in part by sodium.

Silica is always present in high quantities [the mean value is 27 mg/L (Daesslé et al. 1988)]. Because of the high solubility of silica in the soils, high concentrations can be reached after a short time in the subsurface (Nicolini et al. 1988).

In the basal aquifer, Grünberger (1989) showed the preponderant influence of the marine environment on the groundwater chemistry of the

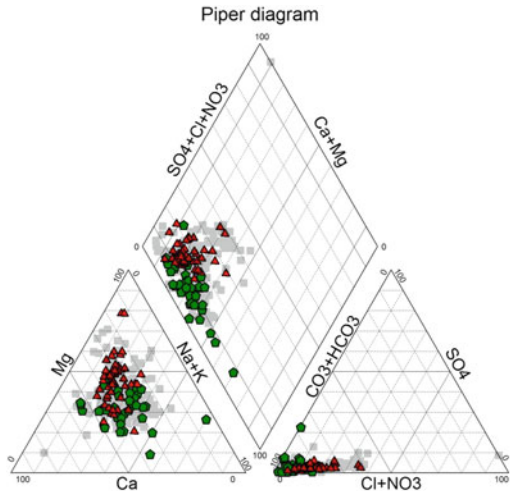

Fig. 5.3 Piper diagram from the 243 spring data set. *Green dots* basal aquifer characteristics, *red dots* superficial aquifer characteristics, *grey dots* intermediate or unknown characteristics

littoral aquifer. This has been confirmed by Daesslé and Duchamps (1989) who have studied the hydrochemical variability of 73 boreholes drilled mainly in the coastal area. A modal analysis is given as representative of the mean groundwater mineralization in the basal aquifer (Table 5.1). As an example, we present the analysis provided from the drill hole of a saltwater-contaminated site (Well "La Saline").

The preponderant role of marine contamination is well highlighted; the less mineralized waters define an initial chemical feature that is HCO_3–Mg or HCO_3–Ca in type, that changes to Cl–Na type. The mean electrical conductivity is 120 µS cm^{-1}, corresponding to a mineralization of 100–120 mg/L (BRGM, Atlas hydrogéologique de La Réunion, *coll.* 1986).

5.3.5 Continuity Between Littoral Basal Groundwater and Deep Groundwater of High Elevation Zones

The chloride and sodium contents of 240 springs from Join et al. (1997) are plotted on a graph of Cl (mg/L) as a function of Na (mg/L). Springs plotted on this graph have first been differentiated

Table 5.1 Chemical analysis of the basal groundwater

	Cond. (µS)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	HCO_3^- (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)
Modal analysis (73 samples)	275	13	9	11	2.1	115	7	1.5	0.5
Forage La Saline	635	18.5	19	91	4.9	107	145	24	10.3

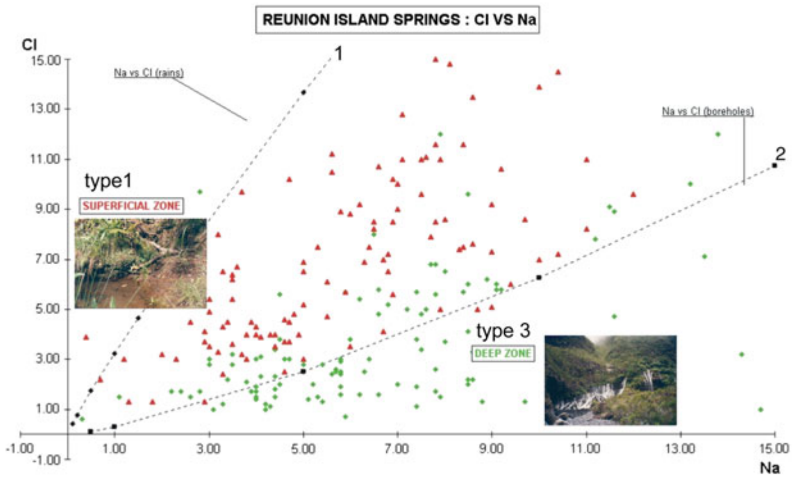

Fig. 5.4 La Réunion Island springs: chloride versus sodium (modified from Join et al. 1997). *Green dots* basal aquifer characteristics, *red dots* superficial aquifer characteristics; *1* curve of best fit defined in rainwater; *2* curve of best fit defined in boreholes

by their structural situation. Points represented by green filled symbols represent the basal springs and the remainder represent the superficial springs.

Data from poorly mineralized boreholes and rainwater are indicated in the same graph by two adjustment curves of chlorides (mg/L) as a function of sodium (mg/L). These relationships are indicated by dashed curves in Fig. 5.4.

The graph shows that the Na/CI ratio of the spring waters is well correlated with the structural distinctions between the superficial and basal aquifers. In fact, it increases from the superficial toward the basal aquifers. Variations range from low values such as the Na/Cl ratios typical of rainwater in the superficial aquifers, to the high ratios representative of basal aquifers (cf. rains and boreholes dashed curve Cl = f(Na) in Fig. 5.3). This process is independent of the total mineralization of the water. Join et al. (1997) suggest that in the superficial zone, aquifers are associated with an atmospheric source of chloride ions related to marine spray. During percolation, Na/Cl ratios increase progressively by the dissolving of sodium from volcanic rocks. The similarity Na/Cl of the deepest springs and coastal boreholes supports the hypothesis of inland continuity of the basal aquifer.

5.4 Hydrogeological Modelling of Piton de la Fournaise

Groundwater continuity between the coastal aquifer toward the inland deepest aquifers remains a debated question. In order to document this issue, a new hydrogeological model was proposed by using the 3D Femwater finite element code. This approach has been undertaken on the Piton de la Fournaise, considered as a perfect representative of young oceanic volcanoes

In order to describe the aquifer geometry, a 3D geological model of Piton de la Fournaise was built from geometrical hypotheses established from the former previous geophysical surveys (Courteaud et al. 1997; Descloitres et al. 1997; Lénat et al. 2000) as well as new geological investigations carried out on the lesser known sectors. More than a hundred EM soundings have provided reliable information about the geological structures, the existence of a substratum and the estimation of the water table's elevation (Folio et al. 2000; Join et al. 2005).

The model was built to represent the general structure of the volcano as defined by four main volcanic units from the oldest stage (Unit I) to historic and present activity (Unit IV) used as hydrogeological layers.

The boundary conditions compute the average annual groundwater recharge spatially distributed into homogeneous recharge zones, and constant head boundary conditions corresponding to both the sea level and the level of permanent rivers, which define the borders of the modelled area.

Hydraulic conductivities are distributed based on field survey results including the investigation of the oldest volcanic units of Piton de la Fournaise. They were carried out on outcrops in the deepest valleys of Piton de la Fournaise. The main results are provided in Table 5.2.

The results of numerical simulations of groundwater flow have provided hydraulic heads that reach 1800 m a.s.l in the vicinity of the volcano summit (Fig. 5.5). The simulated groundwater outflows are consistent with the discharge rates of springs and resurgences observed within the deepest valleys or along the shoreline.

These results have provided hydrodynamic evidence that supports the hypothesis of a hydraulic continuity from coastal areas to inland areas characterized by high water table. It improves the conceptual model previously proposed on the massif of Piton des Neiges. These results support the presence of a central groundwater dome, similar to those observed in the Canary or Azores islands, where volcanic terrains are older. The shape of the piezometric surface suggests that drilling infiltration galleries may be a relevant technique to access inland groundwater (Pennober et al. 2004). This have been recently validated by deep underground works within the Piton des Neiges volcano where a 18 km long tunnel was drilled for surface water transfer and have been interrupted by groundwater discharge up to 1 m^3/s (Bret et al. 2000).

5.5 Synthesis

Twenty years of hydrogeological investigations in La Réunion Island including both Piton des Neiges and Piton de la Fournaise massif have provided a refined conceptual model of groundwater resources in active oceanic volcanoes. Results are supported by various approaches from field geological survey of springs to hydrochemical characterisation of groundwater and flow path modelling. This model reflects the main issues of groundwater resources management in La Réunion. We assume that it could be applicable to the island of Grande Comore as another typical young and active oceanic volcano. In both islands, the low groundwater hydraulic gradients in the littoral zone are accessible by drilling, but the proximity of the sea makes this resource highly vulnerable to saline contamination. In the higher-altitude areas,

Table 5.2 Evaluation of hydraulic conductivity anisotropic (Kx, Ky, Kz) and isotropic equivalent (k) in the oldest units of Piton de la Fournaise (from Folio 2001)

Parameters	Unit I	Unit II	Unit III and IV
Kx, Ky (m/s)	$5 \times 10^{-5} - 8 \times 10^{-5}$	$10^{-4} - 3.10^{-4}$	10^{-2} (average value from pumping test)
Kz (m/s)	$4 \times 10^{-7} - 4 \times 10^{-5}$	2.10^{-4}	
Isotropic K model values	10^{-6}	10^{-4}	10^{-2}

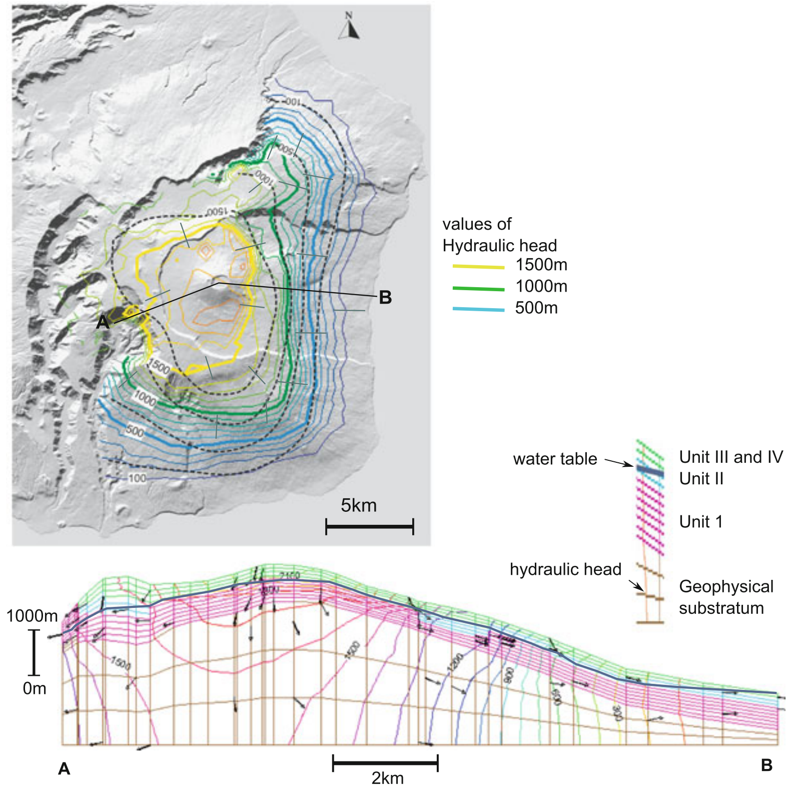

Fig. 5.5 Groundwater table in the Piton de la Fournaise volcano (modified from Folio 2000)

despite greater hydraulic gradients, the excessive depth of the water table leads to unacceptable operating costs. The implementation of horizontal infiltration galleries within elevations comprised between around 600 and 900 m constitutes an interesting technical alternative for exploiting the inland aquifer.

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