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Structure and hydrogeological functioning of an insular tropical humid andesitic volcanic watershed: A multi-disciplinary experimental approach

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SUMMARY

The aim of the study is to establish an hydrogeological scheme of the structure and the functioning of andesitic volcanic systems in the insular and humid tropical context. A watershed has been instrumented at Féfé in Guadeloupe (French West Indies) in the Lesser Antilles to measure rainfall, runoff and piezometric fluctuations between 2003 and 2006. Given the heterogeneity of the volcanic deposits, a multi-disciplinary approach has been used: a geological and an hydrogeological survey, an hydrodynamic approach (hydraulic tests and signal processing of hydrological time series), and finally, an hydrogeochemical approach (major elements and some trace elements). Two main superposed aquifer respectively in aerial deposits, and in recent nuées ardentes (glowing ash) and lava flows, as well as the underlying aquiclude (the highly weathered older substratum) were identified. At a local scale, some hydrogeological heterogeneities internal to the aquifers were highlighted and related to a polyphased building-up of the geological formations. Hydraulic relationships between the multi-layered aquifers, such as the confinement of the deep aquifer upstream of the basin, were identified. Groundwater/stream exchanges were characterised, detailing various contributions of the shallow and the deep aquifers to stream and spring waters; significant river losses were also observed. At a global scale, within such relatively permeable volcanic formations, the aquifer recharge is about 85% of the annual effective rainfall for an average rainfall year. The hydrogeological scheme appears to be coherent with a geological structure of cut-and-fill paleovalleys frequently observed in andesitic areas. Consequently, groundwater drainage axis are mainly localised in recent nuées ardentes deposits, whereas the inversion of relief characteristic of volcanic areas explains the non-superposition of surface water and groundwater divides and both surface water losses and springs. Finally, this work shows the highly heterogeneous hydrogeological processes occurring in volcanic formations of andesitic-type. It also shows the relationships between the geological structure and the hydrogeological functioning of such basins, and proposes an affordable methodological approach to investigate such a hydrogeological context in depth.

1. Introduction

The characterisation of the structure and functioning of hydrogeological systems is fundamental to the management and protection of water resources. These issues concerning groundwater are particularly crucial in the context of small islands where water resources are generally not very diversified. Surface waters are unavailable perennially for climatic reasons and because of the small size of the watersheds. Because several islands are of volcanic origin, improving our knowledge of hydrogeological functioning in a volcanic insular context is important (Ecker, 1976; Falkland and Brunel, 1989; Hahn et al., 1997; Herrera and Custodio, 2008).

Usually, two end-members of volcanism type are distinguished, depending on magma type: basaltic and andesitic. Currently, most of the available hydrogeological conceptual models for volcanic areas concerns basaltic oceanic islands, which are mainly constituted by shield volcanoes. Two different hydrogeological models describe large-scale systems at the volcano/island scale: (i) the Hawaiian model (Peterson, 1972; Macdonald et al., 1983) considers a low-lying basal aquifer linked to inland dike-impounded and perched aquifers – it has been applied also to the Azores archipelago (Cruz and Silva, 2001; Cruz, 2003) and in Madeira

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(Prada et al., 2005), (ii) the Canary Islands model (Custodio, 1989) considers a continuous basal aquifer – it has been recently presented as a suitable model for the Reunion Island (Join et al., 2005). In the case of volcanic formations of andesitic-type, even though prominently represented in the world mainly via subduction zones, there is a lack of knowledge about hydrogeological functioning. In fact, in contrast to basaltic volcanism, this predominantly explosive volcanism generally generates a more important lithological variety, giving rise to a very high spatial and vertical variability of the structure and the hydrodynamic properties of the aquifers. This contrast is particularly important for the emerged part of the volcanic island, that is also commonly the most active as an hydrogeological standpoint (the part of the island constructed below the sea level being mostly composed of hyaloclastites in both types of volcanism). For example, in andesite-type volcanism, thin metric sequences of interbedded pyroclastic formations, for instance pumice flow that weather very fastly and nuées ardentes that keep longer permeable, exhibit very contrasted hydraulic conductivities, ranging in that case between 10^{-6} and 10^{-2} m s^{-1}, respectively (Foster et al., 1985; Lachassagne, 2006). Thus, in the andesitic context, since an approach at the whole island scale may allow to compute the water balance, hydrogeological processes and flowpaths can hardly be characterised at such a large scale. Theses processes must be studied at the watershed scale.

In the andesitic volcanic arc of the Lesser Antilles, to our knowledge, no hydrogeological scheme has ever been elaborated either at the island scale or at the watershed scale. Thus, to answer such an hydrological question and to study pesticide transport, an agricultural watershed (Féfé site) has been monitored since 2003 (to measure rainfall, runoff and piezometric fluctuations) in Guadeloupe (FWI), on the Eastern windward flank of the volcanic massif. The first phase of the project dealt mostly with the surface water monitoring of a small stream (Féfé Stream, surface watershed of 0.18 km^2) that was then modelled by a lumped approach (Charlier et al., 2008). It provided a water balance of this surface watershed, and also showed "deep losses" (deeper than the flow in the stream and in the soils) as well as groundwater contribution to streamflow. On this site cultivated with bananas, the mechanisms of pesticide transport in soils and surface waters were also studied (Charlier et al., 2009), leading to a better understanding of the runoff and re-infiltration processes in fields and ditches. The first research results dealing with surface waters and soils showed the need for a more integrated approach involving all the hydrological compartments, including groundwaters, at the scale of both surface and subsurface watersheds. Moreover, the lack of integrated research in such volcanic andesitic context as this, justified a deeper characterisation of the hydrological (s.l.) functioning of the Féfé area.

In this frame, the aim of this paper is to establish a conceptual scheme of the hydrogeological structure and functioning of an andesitic volcanic system located in an insular and humid tropical context. Considering the complexity of such a geological setting, a multi-disciplinary experimental approach was carried out. Geological, hydrodynamic and hydrogeochemical results allow the construction of a conceptual hydrological and hydrogeological model of the Féfé watershed.

2. Study site

2.1. Site location

The Féfé site (16°03′50″N, 61°37′12″W) belongs to the volcanic island of Basse-Terre, in Guadeloupe, on the Lesser Antilles insular arc (Fig. 1a and b). It is located on the Eastern windward flank of the Capesterre Mountain, between the altitudes of 300 and 450 m amsl, 6 km from the coast and approximately 5 km from the Soufrière massif (Fig. 1c). The Féfé site covers an area of around 45 ha (Fig. 2a). It is bordered on the south by the Pérou River and farther north by the Maillard River. The northern part of the site includes a steep-sloped relief (from 25% to 60%). The southern part consists of a short plateau with moderate slopes (9% on the average), drained by a small perennial stream, the Féfé Stream. With steep banks several tens of metres high, this plateau dominates the Pérou River upstream of the confluence with the Féfé Stream. The study site is a cultivated zone consisting of four farms whose main activities are banana and flower cultivation and pig and cattle farming. These farms border the eastern limit of the rainforest (Fig. 2a).

2.2. Climate

The Lesser Antilles are characterised by a humid tropical climate with marine influence with two distinct seasons, a dry season in February–March and a rainy season from July to November (Morell and Jérémie, 1994). From 52 years of rainfall data (between 1952 and 2004) at the Neufchâteau research station (16°04′38″N, 61°36′04″W, 250 m amsl), located 2 km to the north-east from the Féfé site, February and November are statistically the driest and the wettest months of the year, with mean values of 161 and 465 mm respectively (Météo-France, 2005). Therefore, the hydrological year was set to begin on 1 February and end on 31 January of the next year. Comparing annual rainfall data at Féfé and Neufchâteau during the survey period, it was possible to characterise the rainfall trend of the available data at Féfé (Charlier et al., 2008). Years 2005 (3689 mm), 2003 (4229 mm), and 2004 (7030 mm) were a dry year, an average year, and an exceptionally rainy year, respectively (the 2006 hydrological year was not complete). Concerning rainfall intensities on the eastern slopes of Basse-Terre, the rainfall depth return period of 2 years for 30 and 60 min are high with 30 and 42 mm, respectively (Chaperon et al., 1983).

Some complementary information on rainfall time series (representativeness of the survey period, and seasonal effect) are presented in Section 4.1.2.1.

2.3. Geology

2.3.1. Geological setting of the Basse-Terre Island

The Basse-Terre volcanic island belongs to the recent Lesser Antilles volcanic arc (Andreieff et al., 1989; Macdonald et al., 2000). This arc (Fig. 1b), located on the north-eastern edge of the oceanic Caribbean Plate, is the expression of Atlantic lithosphere subduction in a NE–SW direction. The northern part of this arc is well known for its active volcanoes of Soufrière Hills in Montserrat, Soufrière in Guadeloupe, Mount Pelée in Martinique, etc.

Basse-Terre Island (Fig. 1c), consisting exclusively of volcanic and volcano-sedimentary rocks, was progressively built from the northeast to the southwest over roughly the past 5 million years. According to Boudon et al. (1987), it comprises six main geological units:

(1) The 'basal complex', emplaced over 3.5 My ago, is exposed at the northern tip of the island. It consists mainly of submarine volcanic and volcano-sedimentary formations.
(2) The 'Northern massif' comprises submarine volcanic products and then sub-aerial formations that mark the emergence of the island.
(3) The volcanism of the 'Axial Chain', first submarine (hyaloclastites) and then mostly sub-aerial (massive superposed andesitic flows), continued that of the Northern massif southward. It formed the central volcanoes of the island that constitute the geological substratum of the Féfé area. Most of these rocks