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Hydrogeology of the Sabatini Volcanic District (Central Italy)

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ABSTRACT

This paper supports the 'Hydrogeological map of the Sabatini Volcanic District'. The map provides an overview of the hydrogeological setting of the Sabatini Volcanic District, using experimental water level data integrated with former volcanological and hydrogeological studies. The 1:50,000 scale map was produced in order to provide support to local authorities and professionals working on groundwater management. Fifteen hydrogeological complexes were defined based on volcanological properties and hydrogeological conditions.

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Hydrogeology; groundwater; volcanic aquifer; hydrogeological map; catchment hydrogeology

1. Introduction

Volcanic districts, widely spread out across the Tyrrhenian belt of Central Italy, are important sources of groundwater. Knowledge of the available groundwater resources represents a strategic tool for the development of these areas. The characterization and evaluation of groundwater resources is needed for decision-making in land use planning (Gragnanini, Mastroiello, Vignaroli, Mazza, & Rossetti, 2015). Mapping groundwater and surface water resources represents a fundamental step for optimizing water consumption and sustaining water supply (La Vigna et al., 2016).

Volcanic aquifers are often affected by natural geogenic contamination induced by host rock leaching such as Arsenic and Fluorine (Baiocchi, Lotti, & Piscopo, 2011; Preziosi, Giuliano, & Vivona, 2010; Sappa, Ergul, & Ferranti, 2014) or by the leaching of weathered volcanic deposits (Viaroli, Cuoco, Mazza, & Tedesco, 2016). For these reasons, the quantitative and qualitative study of groundwater resources is fundamental to assess the potential health risk induced by natural and anthropic processes.

The Sabatini Volcanic District (SVD) is located near the largest Italian City, Rome. Since Roman times it has been used as a source of water supply for the City, through the collection of water from springs around Bracciano Lake and from the lake itself. Currently the SVD is being researched for high enthalpy geothermal exploitation (Procesi et al., 2013), and also for the possible direct or indirect extraction of heat from the volcanic groundwater using heat pump systems (low enthalpy geothermal exploitation) according to the regional law (L.R. 21/04/16 n°32).

The objective of this study was to produce a hydrogeological map of the SVD at a scale of 1:50,000, with more detail than previous regional work (Boni, Bono, & Capelli, 1986; Capelli, Mazza, & Gazzetti, 2005), using experimental data collected during a seven-month hydrogeological survey. The map displays water table elevation contours of the regional volcanic aquifer, with a 10-meter contour interval, superimposed on new hydrogeological complexes. The locations of wells used for contouring are also shown. Five hydrogeological cross sections were produced to highlight the geometric relationship between the hydrogeological complexes and their role in regional groundwater circulation. A minor map at 1:150,000 scale of the morphology of the low-permeability pre-volcanic basement is also presented.

The map does not show direct information on the groundwater budget calculation because recharge and withdrawals were not calculated. These budget parameters were discussed in detail in specific research papers (Capelli et al., 2005). The hydrogeological map of the SVD provides fundamental information such as the delineation of the groundwater divides, the quantification of the natural discharge of the volcanic aquifer, such as linear springs, and the definition of the groundwater level for future comparison on the resource maintenance.

2. Study area

2.1. Geological setting

The SVD is one of the Quaternary volcanic districts of the Roman province. (Peccerillo, 2005; Sottili,

Palladino, & Zanon, 2004). It is located in the Lazio Region (Central Italy), about 30 km northwest of Rome (Figure 1). The volcanic deposits cover an area of about 1800 km² from the Tiber valley (eastward) to the Tolfa Mounts (westward) (Funicello & Parotto, 1978).

The origin of the K-rich magmatic activity is related to the development of the eastern extensional structures of the Tyrrhenian basin, between the orogenic belt of the Apennines and the slow spreading center of the Tyrrhenian Sea. The SVD activity started about 800 ka (Karner, Marra, & Renne, 2001) from fissure eruptions of both acidic and basic formations (Mattias & Ventriglia, 1970), aligned on NW–SE and NE–SW directions (Acocella & Funicello, 2002, 2006). The volcanic rocks derive from magmas originally hosted both in deep and shallow reservoirs (Conticelli, Francalanci, Manetti, Cioni, & Sbrana, 1997). The volcanic formations overly continental and marine Pliocene and Pleistocene deposits and allochthonous units (Mazza, La Vigna, & Alimonti, 2014).

The morphology of the pre-volcanic basement is strictly connected to the tectonic evolution of this area, which created a *horst* and *graben* framework (Pre-volcanic elevation map reported on the map). The basement shows an E-W depression, related to the migration of volcanic activity from the east to west (De Rita, Funicello, Rossi, & Sposato, 1983). The deepest sections of the pre-volcanic basement correspond to the main emission centers and calderas, localized in the area of Bracciano Lake, and in the volcanic districts of Martignano, Baccano and Sacrofano (Buonasorte, Carboni, & Conti, 1991)

Volcanological and geochronological data, reported in former studies, show that the SVD volcanism encompassed a variety of eruption styles such as lava flows, pyroclastic flows and pyroclastic falls deposits (Cioni, Laurenzi, Sbrana, & Villa, 1993), characterized by different intensities and magnitudes (Sottili, Palladino, Gaeta, & Masotta, 2012).

De Rita, Funicello, Corda, Sposato, and Rossi (1993) divided the SVD evolution in four steps, as summarized in Figure 2.

- (a) The first SVD activity started in the eastern sector with the development of the Morlupo-Castelnuovo di Porto volcano (Figure 2(A)). During this phase, acid trachytic deposits were erupted.
- (b) The volcanic activity migrated westward, to the Sacrofano area. Lava flows and fall units are typical of this activity, which represents the most widespread and enduring phase of the SVD (500–360 ky BP). The Sacrofano activity started simultaneously with some cinder cones aligned along extensional faults located north of Bracciano Lake (Figure 2(B)).

- (c) Around 400–300 ky BP a paroxysmal stage developed all over the district (Figure 2(C)). The strong emission rate determined a sector collapse within the district and the development of a volcano-tectonic depression, which hosts Bracciano Lake (De Rita, Rodani, Rosa, & Puzzilli, 1997).
- (d) The last stage of volcanism was characterized by violent hydromagmatic eruptions from Martignano, Baccano and other smaller emission centers in the eastern sector of the SVD, (Figure 2(D)). The activity in the SVD ceased around 80 ky BP with the emission of the Baccano units and the caldera collapse (De Rita & Zanetti, 1986a, 1986b).

2.2. Hydrogeological and hydrological settings

Two main aquifers can be distinguished in the SVD area:

- (1) the regional volcanic aquifer within the SVD deposits, recharged by rainfall infiltration (Boni, Bono, & Capelli, 1986; Capelli et al., 2005).
- (2) The carbonate thermal aquifer, confined in deeper Meso-Cenozoic units and separated from the volcanic aquifer by the clayey and allochthonous low-permeability basement (Bono, 1981).

The regional volcanic aquifer is made up of both porous (pyroclastic units) and fractured (lava flows) layers. Porous layers may show marked lateral and vertical heterogeneities according to the depositional framework. Even though volcanic units are inhomogeneous in term of geometry and hydraulic properties, at regional scale all the volcanic aquifer layers can be considered a large continuous multi-layered aquifer (Maruffi, 1970; Mazza et al., 2014). Therefore, groundwater circulation is affected by the physical characteristics of volcanic units as well as the morphologies of volcanic structures and the pre-volcanic aquiclude. Thermal and mineral springs such as the Stigliano, Claudia, Manziana and Nepi, are clear examples of localized rising water from the deeper carbonate aquifer (Boni, Bono, & Capelli, 1986; Boni, Bono, & Capelli, 1988; Camponeschi & Lombardi, 1969; Lombardi & Giannotti, 1969). The main groundwater discharge in the SVD occurs as base-flow of the drainage network like linear springs rather than punctual springs (Mazza et al., 2014). Therefore, in spite of their limited length and the limited size of their catchment basin, watercourses have a constant flow because they are continuously supplied by groundwater recharge (Baldi, Ferrara, Masselli, & Pieretti, 1973). The Bracciano and Martignano Lakes represent the level of the regional aquifer, while the Monterosi Lake is related to a perched aquifer.

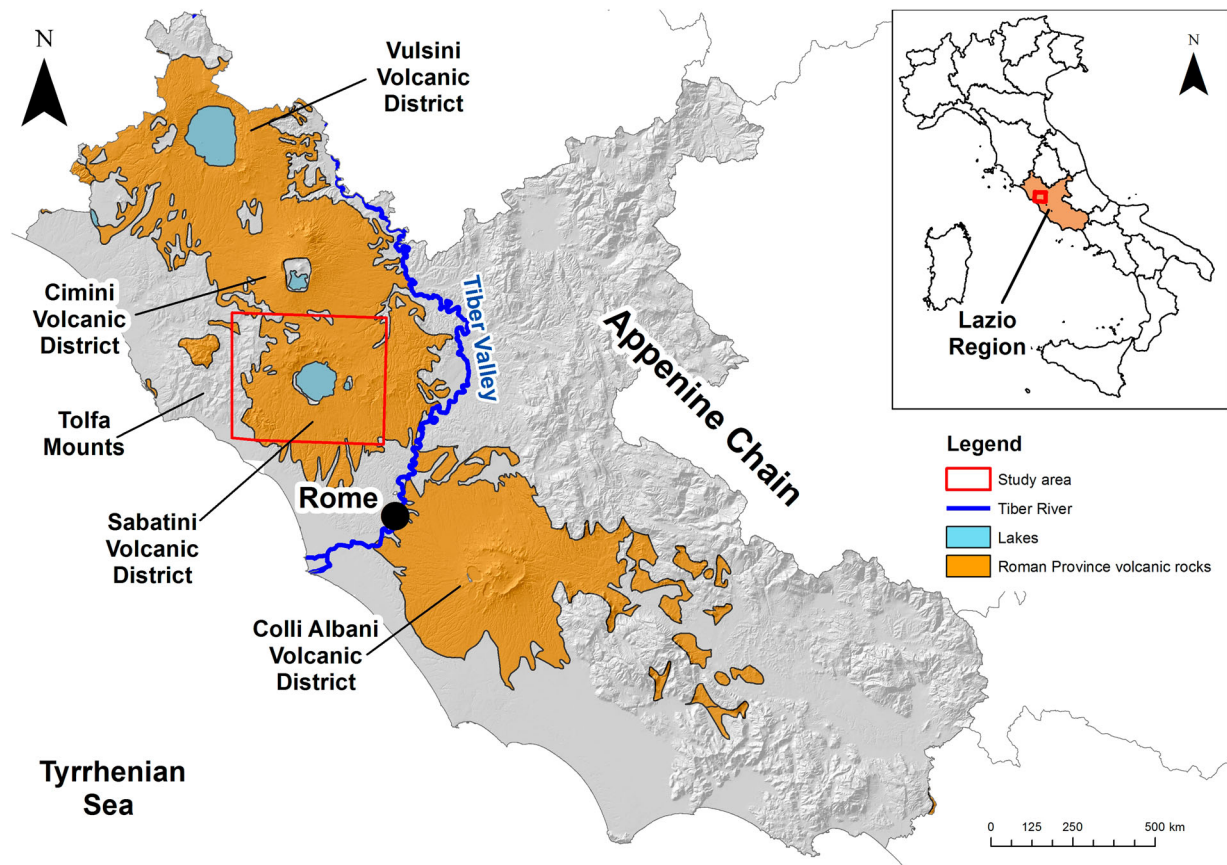


Figure 1. Location of the study area.

3. Material and methods

A hydrogeological survey was carried out from March to September 2009 over an area of about 800 Km². The location of every survey point was obtained using a global positioning system (GPS) receiver, while the elevation was determined from the most detailed topographic map resource (Technical Regional Chart (CTR) at 1:10,000 scale ED 50 UTM 33N Projected Coordinate Systems) (Regione Lazio, 1990). The 1:50,000 scale SVD hydrogeological map was produced using the IGM (Military geographic institute) topographic map types, modified by 'Studio G. Marinelli – Roma'. The 1:50,000 scale geological map produced by De Rita, Di Filippo, and Sposato (1993) was used to classify the outcropping volcanic units in to hydrogeological complexes, according to the method described in Capelli et al. (2005).

During the hydrogeological survey, 221 water table levels under static conditions were measured using a contact meter, in wells used for domestic, agricultural, livestock and drinking water purposes. The flow rate of 23 localized springs were measured using the volumetric method. Stream flow measurements, using a mini current meter, at 74 streams were made in the period from July to August to identify and quantify the discharge of the linear springs in the watercourses. Collected data were managed in a Microsoft Access Database and then, spatially analyzed in Esri ArcGIS

10.1. The potentiometric surface map was produced using the triangular interpolation method and then digitized in ArcGIS.

Geological and construction information (such as the bottom depth and screened interval) for each well were reviewed, in order to identify and separate the high productivity regional aquifer from the perched and low productivity ones. Wells producing water from perched aquifers were not used in the development of the hydrogeological map. The non-homogeneous data collection network and the lack of technical information about some measured wells present a level of uncertainty in development of the hydrogeological map. Nevertheless, at the regional scale these issues were considered negligible.

The sedimentary pre-volcanic basement was studied in detail using the stratigraphy of several boreholes and geophysical data, collected for geothermal research in the 1980s (Buonasorte et al., 1991), integrated with borehole stratigraphic data collected during the survey (reported in the cross sections on the Main Map).

The hydrogeological cross sections were produced using data from several borehole data coming from different databases, such as LINQ (2010), ISPRA (2010; retrieved from <http://sgi.isprambiente.it/GMV2/index.html>), ENEL geothermal exploitation database (Baldi et al., 1982; ENEL, 1987 retrieved

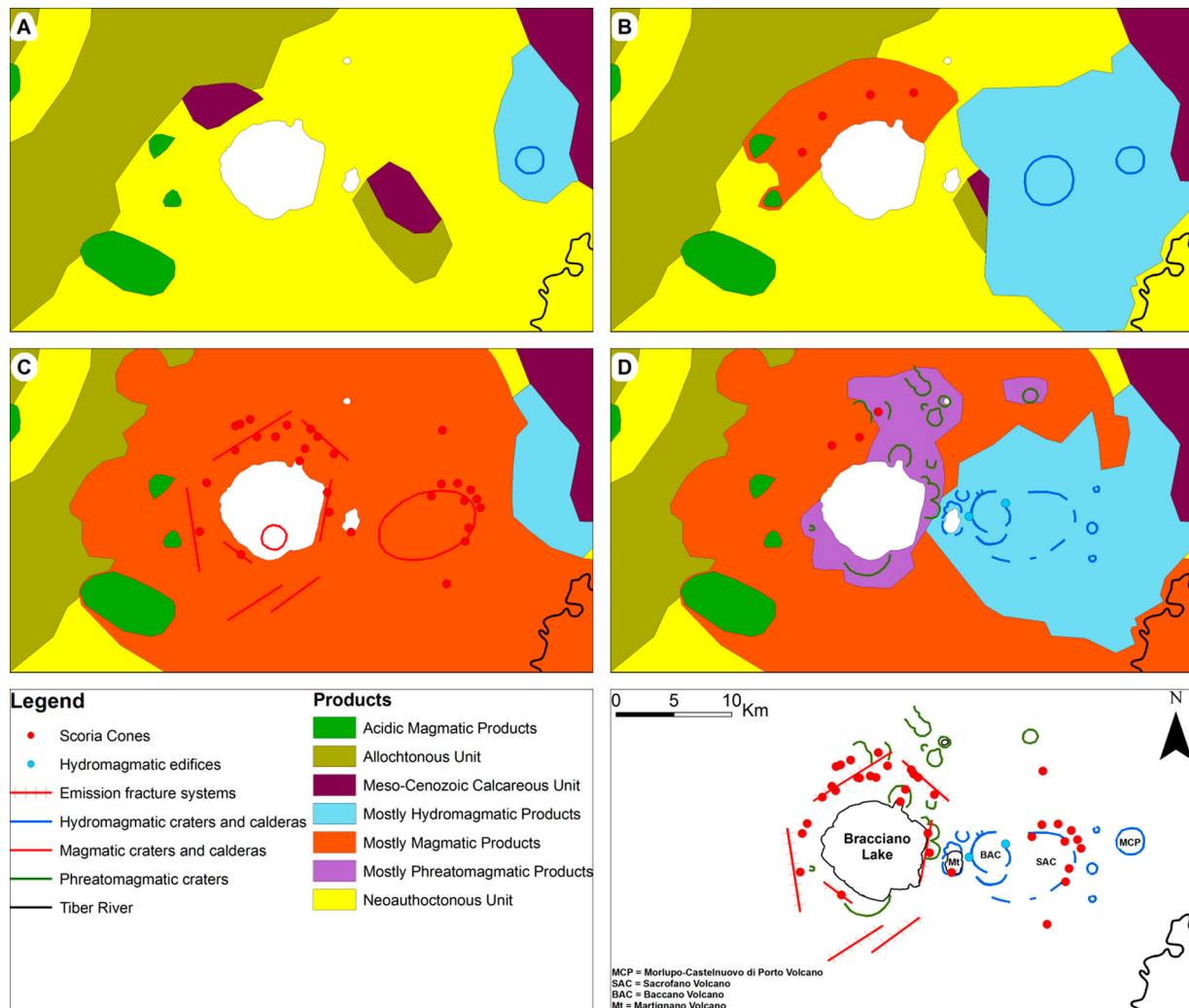


Figure 2. Evolution of the SVD (modified from De Rita, Funicello, et al., 1993). (A) Pre-volcanic structure and development of the first emissions centers; (B) The Sacrofano hydromagmatic activity and magmatic activity in the northern sector; (C) Paroxysmal stage of the magmatic activity in the SVD and (D) The final phase of the SVD activity.

from <http://unmig.sviluppoeconomico.gov.it/unmig/geotermia/inventario/rapporto.asp?id=16>; ENEL-VDAG-URM, 1994), municipal service bureau data and geological reports by freelance geologists.

4. Results and discussion

4.1. Hydrogeological complexes

The SVD formations show wide lateral and vertical lithologic variations deriving from bedding and textural features. The hydrogeological complexes were defined on the basis of the stratigraphy, structural characteristics and the permeability of each formation, in order to understand their role in groundwater circulation (Baiocchi, Dragoni, Lotti, Luzzi, & Piscopo, 2006; Baldi, Decandia, Lazzarotto, & Calamai, 1974; Boni, Bono, & Capelli, 1986; Boni, Bono, Capelli, Lombardi, & Zuppi, 1986; Capelli et al., 2005). Hydrogeological complexes have been used in former regional studies to classify the Quaternary volcanic domains of Lazio Region. Brunamonte, Cosentino, D'amico,

Prestininzi, and Romagnoli (1987) and Boni et al. (1988) distinguished two main hydrogeological complexes, indistinct pyroclastic deposits and lava flow deposits. Ventriglia (1990) and Capelli et al. (2005) further refined the hydrogeological complexes, distinguishing the phreatomagmatic complex from the pyroclastic one.

This study refined the classification of hydrogeological complexes in more detail given the availability of more recent hydrogeological data and the higher work-scale. Volcanic units of the SVD were classified as listed below, according to the eruption style (De Rita, 1993), given that similar emplacement dynamics produce similar textural properties of the deposits:

- (1) Pyroclastic fall deposits represent an accumulation of products ejected from a crater or fracture, characterized by a variable grain size, spanning from scoria to ash. The geometry depends on the eruptive column height and wind pattern. They exhibit mantle-bedding stratification and maintain

- a uniform thickness over relatively short distances. They show substantial primary porosity.
- (2) Pyroclastic flow deposits originating from subaerial eruptions of fluidized masses of rock fragments and gases. They are massive, chaotic and mostly lithoid deposits and their geometry depends on the pre-existing morphology. They are characterized by variable primary and secondary porosity.
 - (3) Phreatomagmatic products derived from a water-magma interaction. The mantle-bedding geometry shows a thickening in topographic depressions. These deposits show a thin stratification between different grain size deposits, so they are characterized by a low vertical primary porosity.
 - (4) Lava flows are the result of the solidification of outpouring moving lava. Their geometry depends on the pre-existing morphology and they are characterized by secondary porosity due to either cooling fractures or fragile deformation.

These volcanic units were included in the 15 hydrogeological complexes as described on the hydrogeological map and in the electronic supplementary material, in accordance with the geological classification of De Rita, Funicello, et al. (1993), the volcanic studies of the SVD (Bertini, D'Amico, Deriu, Tagliavini, & Vernia, 1971; Cavarretta, De Rita, Rosa, & Sposato, 1990; Masotta et al., 2010; Mattias & Ventriglia, 1970; Sottili et al., 2010) and the description of the hydrogeological properties in Baiocchi et al. (2006), Capelli et al. (2005) and Ventriglia (2002)

4.2. Regional aquifer geometry and groundwater pattern

The SVD is the result of various and widespread volcanic activity, with the development of several emission centers and the emplacement of units characterized by different permeability. The groundwater elevation map, produced from the experimental data, confirms the hydrogeological pattern described in previous studies (Camponeschi & Lombardi, 1969; Capelli et al., 2005; Lombardi & Giannotti, 1969). The pre-volcanic basement elevation was determined using geophysical and stratigraphic data reported in previous studies, integrated with information collected during this study. The basement morphology is shown on the map as contours (50 m interval) at 1:150,000 scale.

The SVD was divided in to five sections in order to describe hydrogeological features supported by the five hydrogeological cross sections shown on the map.

4.2.1. Northern sector

The northern sector is characterized by the outcrop of the northern pyroclastic fall deposits (**Np**) complex and the interbedded Lava (**la**) complex. These deposits were erupted by several scoria cones, which compose

the upper part of the regional aquifer. The lower part of the regional aquifer is composed of the Coarse grained Bracciano pyroclastic flow (**CgB**), by the Sabatinian Red Tuff with Black Scoria (**RTBS**) complexes, as identified in drill hole data (Cioni, 1993), and by undifferentiated volcanic units (D–D' cross section). The groundwater pattern shows a close relation with the Pre-volcanic (**Pre**) complex morphology, especially where it crops out (at a mean elevation of around 400 m a.s.l.). Moving southward the **Pre** elevation rapidly drops due to volcano-tectonic collapse, then the groundwater morphology is related to Bracciano Lake (164 m a.s.l.), which represents the level of the regional water table and the basal level of most the northern groundwater circulation. Part of the northern aquifer also drains toward the Mignone River basin (westward) and the Treia River basin (northward and eastward) with an overall measured discharge of linear springs of around 500 L/s. The presence of fine grained hydromagmatic units (**h**), erupted by local centers and characterized by a low hydraulic productivity, can support perched aquifers, as detected at the Monterosi Lake.

4.2.2. Eastern sector

The eastern sector is characterized by the widespread outcrop of the Hydromagmatic (**h**) complex, composed of the units of the final emission centers of Baccano, Martignano, and other minor ones. The alternating deposition of ash and pumice layers allows the formation of several minor perched aquifers, not represented on the hydrogeological map, which recharge local springs often characterized by seasonal behavior. These aquifers crop out in morphologically depressed areas forming Monterosi, Baccano and Stracciapappe lakes, although some of them are drained by canals.

The regional aquifer is hosted within the **RTBS**, Southeastern minor pyroclastic flows (**SE**), and Sacrofano fall pyroclastic (**Sfp**) complexes (E–E' cross section). They are underlain by the Sacrofano lower pyroclastic flow complex (**Slp**), acting as a regional aquiclude. A small portion of groundwater is drained toward the Bracciano Lake, whereas the main drainage pattern is toward the southeast to the Tiber River, out of the study area. In the southeastern peripheral area, the linear springs of the Valchetta Stream and Piazza d'Armi Trench drain the aquifer with a mean discharge of around 300 L/s.

4.2.3. Southern sector

The Southern sector is characterized by outcrops of the **SE**, **la** and **Sfp** complexes. The lava flows form a continuous plateau interbedded with the pyroclastic deposits. Where **la** appears unfractured, it might act as aquiclude for local perched aquifers (not represented on the hydrogeological map). The regional aquifer is mostly hosted within the **RTBS**, **Sfp** and in the

fractured **la** complexes (A–A' cross section), and it is laterally recharged by the Bracciano Lake. The aquifer discharges southward where the **Pre** complex crops out. The regional aquifer is drained by the Arrone Stream (around 200 L/s), starting from an elevation of around 140 m a.s.l. The Arrone Stream, the only natural surface discharge of the Bracciano Lake, is isolated from the lake by a dam system, so most of the river flow rate comes from the regional aquifer discharge and a minor part is related to sewage discharge. The **Pre** complex shows a NW–SE horst structure related to the Cesano *Horst*, which creates a piezometric mound separating groundwater flow to the Valchetta Stream basin (East) from flow toward the Arrone Stream basin (West).

4.2.4. Southwestern sector

The southwestern sector is mostly characterized by the outcropping of the **CgB** complex. The regional aquifer is here represented by the fractured **la** complex, emplaced on the **RTBS** (B–B' cross section), which directly overlies the undifferentiated SVD volcanic units and the **Pre** complex on the southern edge of the study area. The groundwater pattern is affected by the **Pre** morphology and the geometry of buried volcanic formations. In fact, southwest of Bracciano Lake, a NW–SE groundwater divide can be recognized, probably related to the presence of fracture systems, from which the **la** plateau was erupted, and later buried by the deposition of **CgB**, fine grained Bracciano pyroclastic flow (**FgB**) and **Sfp** complexes. The groundwater divide determines minor groundwater discharge directed northeastward to Bracciano Lake and the main groundwater discharge southward to the city of Rome. The regional aquifer is drained by some streams (about 70 L/s) in the peripheral area, where the **Pre** complex crops out. Perched aquifers, hosted within the **CgB** complex, recharge some minor springs, which flow out where the **FgB** aquiclude crops out.

4.2.5. Western sector

The Western sector is characterized mostly by the outcrop of **CgB**, **RTBS** and Peperini Listati (**PL**) complexes. The regional aquifer thickness, made up by **la** and **RTBS** complexes, decreases moving westward, in a strict relationship with the morphology of the **Pre** complex (C–C' cross section). The uplift of the **Pre** complex, due to the rapid emplacement of the Tolfa-Cerite-Manziate (**TCM**) complex (Cimarelli & De Rita, 2006), created a groundwater divide that splits flow paths eastward to Bracciano Lake and westward to the Mignone River basin. Linear springs, with an overall discharge rate of about 80 L/s, occur along western boundary of the SVD, where the **Pre** complex crops out. Some perched aquifers, hosted within the **CgB** complex and underlain by the **CfB** were also detected.

5. Conclusions

The hydrogeological map of the SVD provides the most detailed mapping to date of the groundwater resources of the study area. This work focused on the delineation of the regional productive volcanic aquifer. The volcanic and sedimentary formations were classified into 15 hydrogeological complexes. Around 1500 L/s of natural discharge were measured in linear and localized springs.

The hydrogeological map of the SVD provides a baseline for long time monitoring of water resource conditions. Repeated water level measurements in wells used in this study can help evaluate efforts to use the groundwater in a sustainable manner.

Software

All data processing and spatial analysis regarding the map were performed by GIS software (Arc Gis 10.1). Cross sections were realized by Corel Draw X4.

Final editing of the map was performed by Adobe Illustrator CS.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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