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SCIENCE

# Groundwater of Rome

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**ABSTRACT**
This paper describes the contents of the new Hydrogeological Map of the City of Rome (1:50,000 scale). The map extends to the entire municipality (1285 km$^2$) and is based on both the most recent scientific studies on the groundwater field and new survey activities carried out in order to fill the data gaps in several areas of the examined territory. The map is the result of a combination of different urban groundwater expertise and Geographic Information System (GIS)-based mapping performed using the most recent available data and has been produced with the intention of furnishing the City of Rome with the most recent and updated information regarding groundwater.

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## 1. Introduction

Groundwater monitoring systems and related maps have become critical. Such maps and analysis provide a context for activities that affect what we cannot see – the water world beneath the ground. This largely invisible world is involved in many aspects of city life: water supply systems, sewage, surface water features, the health of plants and trees, flood potential and drought events. Recently, groundwater has been recognized as a cornerstone in the resilience of cities (Tanner, Mitchell, Polack, & Guenther, 2009).

Urbanization is a worldwide trend, with more than 50% of the world's population currently living in cities, reaching 70% in Europe (UN-HABITAT, 2012). The urban water cycle is the key to integrated sustainable management (Marsalek et al., 2008) for ensuring supply of safe (good quality) water, sanitation and correct drainage systems. Moreover, human activities such as land use change, extensive withdrawals and waste water discharge may exert a strong influence on hydrogeology, sometimes stronger than climate change (Taylor et al., 2013), causing changes in the chemical–physical and quantitative status of surface and groundwater. As a consequence, urban water management poses not only scientific but also technical, socio-economic, cultural and ethical challenges (Chaminé, Afonso, & Freitas, 2014; Freitas et al., 2014, 2015). In this context, mapping groundwater and surface water resources represents a fundamental step for optimizing the urban water system and minimizing water consumption and deterioration.

Urban areas worldwide are employing different techniques for groundwater mapping. Hydrogeological maps are needed for a wide range of applications such as (see details in Chaminé, Carvalho, Teixeira, & Freitas, 2015; Margat & van der Gun, 2013): protecting groundwater resources from deterioration (Ravikumar, Venkatesharaju, Prakash, & Somashekar, 2011); defining groundwater protection zones in newly urbanized contexts (Thomsen, Sondergssrd, & Sorensen, 2004); assessing groundwater potential (Oh, Kim, Choi, Park, & Lee, 2011); identifying groundwater vulnerability (Wolf, Eiswirth, & Hotzl, 2006); quantifying the recharge due to sewer and pipe leakage (Yang, Lerner, Barrett, & Tellam,1999), furnishing the basic information for underground infrastructure design and to perform city-scale groundwater modeling (Di Salvo, Moscatelli, Mazza, Capelli, & Cavinato, 2014; La Vigna, Demiray, & Mazza, 2013; La Vigna, Hill, Rossetto, & Mazza, 2016) and the historical evolution of urban groundwater systems (Chaminé et al., 2014; Freitas et al., 2014).

In the city of Rome, most drinking water supplies derive from springs located far from the city, and is delivered to the population through the aqueduct network (Bono & Boni, 1996). Even if, currently, there are not specific issues related to water quantity, the Rome municipality is dealing with many groundwater-related problems. Some example are: pollution (Ellis, 1999),

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relationships between poor quality streams and aquifers (La Vigna, Ciadamidaro, Mazza, & Mancini, 2010), natural background levels of dissolved elements and compounds (La Vigna, Bonfà, & Martelli, 2014), differential settlements in stream valleys (Raspa et al., 2008), subsidence and salinization (Manca, Capelli, La Vigna, Mazza, & Pascarella, 2014; Manca, Capelli, & Tuccimei, 2015) as well as groundwater flooding. The Hydrogeological Map of Rome (Main Map) constitutes a first important step for future development of surveys and research aimed at solving such problems.

The new Hydrogeological Map of Rome (Main Map) has been prepared with the intention of incorporating the findings of previous studies concerning the hydrogeological setting of the city, with special attention paid to the reconstruction of piezometric levels, based on field data (La Vigna et al., 2016).

Previous hydrogeological maps of the city do not cover the total extent of the municipality (Capelli, Mazza, & Taviani, 2008; Corazza & Lombardi, 2005; La Vigna, Capelli, & Mazza, 2008) or were drawn only using literature data (Succhiarelli & D'ottavio, 2008) or use now-outdated sources (Ventriglia, 1971, 1990, 2002). For these reasons, this map aims to become the new groundwater benchmark for Rome.

## 2. Hydrogeological conceptual model

The hydrogeological conceptual model and the groundwater circulation in the Rome municipality are driven by: (1) the local morpho-stratigraphic and structural setting, which is dominated by two main middle-late Quaternary volcanic complexes, the Sabatini Mts to the North West and the Albani Hills South East of the city, and by several NW–SE and N–S trending horsts and grabens that dissect Plio-Pleistocene marine and continental sedimentary sequences underneath the volcanic cover; (2) the relationship of groundwater exchange between the hydrogeological units; (3) the two main rivers flowing in the study area, the Tiber and Aniene River (Capelli et al., 2008) and (4) the proximity to the Tyrrhenian Sea coast. The groundwater circulation is in fact directed mainly from the volcanic relief toward the base level of the Tiber and Aniene rivers and the Tyrrhenian Sea. The hydrogeological boundaries and the groundwater directions of the main aquifers depend on the position of the horsts and grabens, as well as on the different permeabilities which characterize the main hydrogeological complexes.

Conceptually, the groundwater circulation is represented by four aquifers, three of which overlap. Isopotential lines in the map highlight that groundwater flowpaths are similar to those of surface water, so that the hydrological and hydrogeological basins are quite similar.

In areas of higher elevation (i.e. the flanks of Alban Hills – Southern and Southeastern sector), the overlapped aquifers can be well defined and distinguished, whereas at lower elevations, the aquifers tend to merge into one single aquifer. This is consistent with the depositional architecture of a typical stratovolcano, as the Alban Hills Volcano is, characterized by the thinning and wedging out of the formations at the periphery of the complex.

The identified aquifers are bounded at the base by a very low-permeability bedrock, formed by a basal clayey–sandy complex (Monte Vaticano, Monte delle Piche and the lowermost levels of Monte Mario formations) acting as an aquiclude (see 'Top surface of the basal aquiclude' on the Map). The top of the aquiclude is strongly irregular due to the complexity of the morpho-structural setting and to the network of river incisions predating the emplacement of volcanic units. On the Map, two main incisions are shown: the first is the Middle Pleistocene NW–SE trending depression called the Paleotiber Graben, located in the northern and eastern sectors of the city; the second corresponds to the Tiber River valley incision, etched during the last low stand of sea level (Wurmian age).

For more details on the hydrogeological setting of Rome, see also the works of La Vigna, Mazza, Pietrosante, Martarelli, and Di Salvo (2015) and Mazza et al. (2016).

## 3. Methodology

With regard to both the plain view cartography and cross sections, the Geological Map of Rome Municipality, 1:50,000 scale (Funiciello, Giordano, & Mattei, 2008), has been hydrogeologically revisited. This choice was driven by the fact that the 2008 geological map represents the most recent and complete geological product, based on CARG (Italian Geological Cartography Project) data. The choice of this geological basis implicitly required the adoption of the IGM (Military Geographic Institute) topographic map (1:50,000 scale). This topographic product can be considered outdated for the area of Rome. Indeed, it does not match in detail the relief and the actual urban fabric, especially in peripheral sectors and in active quarry areas. The resulting mismatches became evident in the preparation of the hydrogeological cross sections. All groundwater levels were instead referred to the most available detailed topographic map (scale 1:5000).

The piezometric data were collected during a survey which took place between July 2014 and May 2015. The investigation was performed relying on the Groundwater Monitoring Network of Rome which is currently made up of 101 measuring points (wells and piezometers). This widespread hydrogeological survey included also private wells and/or piezometers located on the right bank of the Tiber River and the monitoring network of the Castel Porziano Presidential Estate (Banzato et al., 2013). In order to reconstruct the potentiometric surface and piezometric lines, the Numerical and Quantitative Hydrogeology Laboratory of RomaTRE University (LinQ) database was also used. This database consists of more than 5000 records related to wells and springs in the area of Rome. This repository has been populated since the early 1990s with the data coming from different hydrogeological studies conducted in Rome and the surrounding area.

Groundwater physical–chemical characterization (i.e. temperature, electric conductivity, pH and $pCO_2$ measurements) as well as alkalinity were performed onsite by means of portable meters and titration with hydrochloric acid, respectively. A pump powered by a battery or a bailer, where needed, were used to collect water samples. Moreover, T, pH and alkalinity were used to compute partial pressure of dissolved $CO_2$ ($pCO_2$).

Thermometric, rainfall and hydrometric gauging data were provided by the Regional Civil Protection Agency of Latium Region for the period 1984–2014. Only data belonging to the period 1994–2014 were selected on the basis of their time continuity and working periods of the gauging stations.

Riparian spring data (linear springs on the map) have been plotted querying the LinQ database.

Information about locations of springs and related data (if available) comes from the LinQ database, from surveys conducted by INGV, and from the Geological Map of Rome (Funiciello et al., 2008).

The WGS84 datum is adopted, and the metric coordinates reported close to the vertices framing the study area refer to the UTM 33N projection zone.

The hydrogeological symbols used on the map take up the recommendations reported in the Italian Official Guidelines for hydrogeological survey and representation (Mari, Motteran, Scalise, Terribili, & Zattini, 1995) and in later experimental tests and proposals of implementation (Roma & Vitale, 2008; Tarragoni, Martarelli, Pierdominici, Roma, & Boni, 2011), which aim to provide an immediate understanding and readability of the hydrogeological items.

The lithologies of the geological map were grouped in hydrogeological complexes by considering their relative permeability and their importance according to groundwater circulation. The area symbols for their representation adopts red to orange shades for complexes characterized by relative permeability ranging from high to intermediate values, while greenish to grayish shades correspond to scarce to very low relative permeability complexes. The lightest or darkest shades of color have been selected for each complex in order to highlight the minor or major extent, of the related outcropping areas, respectively. Patterns overlaying the areal symbols have been also used to show the lithological features of the high and intermediate relative permeability complexes.

The water table contours were obtained manually resorting to a triangulation method. The variability of elevations, the existence of areas with extensive anthropogenic modification and the presence of riparian springs made automatic interpolation inappropriate. In order to avoid the outcropping of the water table above the ground surface, the digital elevation model (DEM) of the equipotential surface of each aquifer has been compared with the most recent and detailed DEM of the topographic surface of the area. This comparison succeeds in highlighting some discrepancies and making the water table reconstruction more representative. Contour intervals are denser where the water table gradient is lower, as in the coastal area.

A particular symbology has been adopted for natural and anthropogenic features related to the same

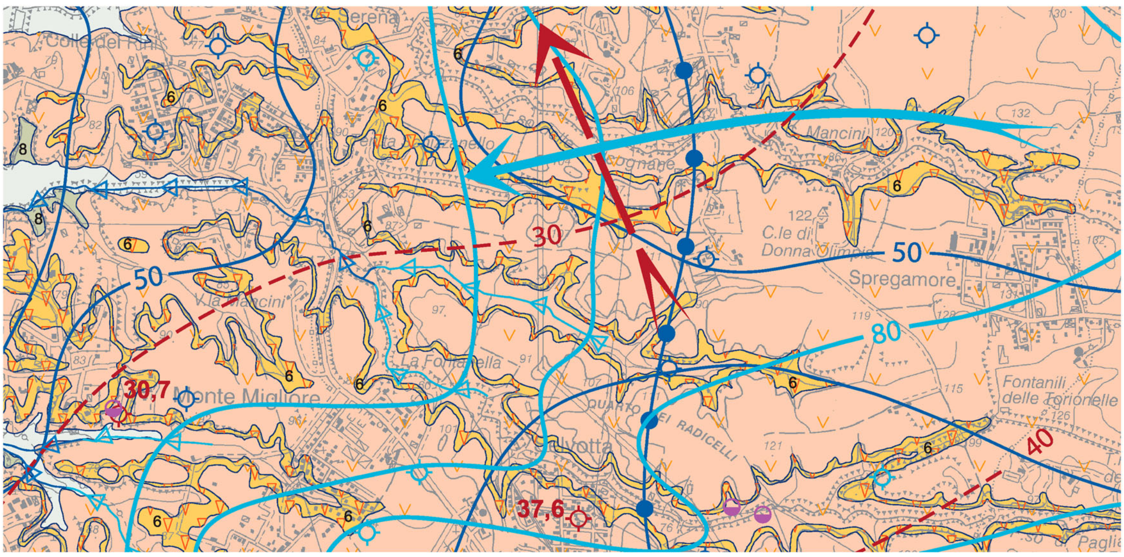


**Figure 1.** Hydrogeological map excerpt (zoom 1.5×). Riparian springs (linear springs on the (Main Map)), fed by different superposed aquifers, assume the color of the related source aquifers.

identified aquifer: both point and linear elements have been associated, according to their features, to one of the four identified aquifers using different colors. The excerpt of the map in Figure 1 shows how springs, water table and wells have been symbolized for different aquifers.

Riparian springs are reported along water courses adopting the same criterion. Therefore, a water course section intersecting riparian springs which are fed by different aquifers is represented with the different colors corresponding to the aquifers. Thus, the same line feature is characterized by a different color from the starting point where the spring begins to contribute to the stream discharge by a different aquifer.

Four hydrogeological cross sections have been produced along the lines of the corresponding geological sections shown on the Geological Map of Rome Municipality (Funiciello et al., 2008). The previous C–C′ cross section has been extended toward the Tyrrhenian coastline by a further stretch oriented from north to south.

The hydrogeological sections contain 16 out of the 17 hydrogeological complexes identified in this study, as well as a separate gravel layer located at the bottom of the alluvial and the lacustrine deposit complex and within the S. Cecilia formation complex.

The geo-database built to produce the map encompasses different shape files. It will be integrated into a specifically built GIS, whose architecture is being tested (Martarelli et al., 2015).

## 4. Discussion and concluding remarks

The Hydrogeological Map of Rome (Main Map) has been designed to lend itself easy to use by experts, public administrations and stakeholders.

In some parts of the map there are overlapping information layers. For example, in the Alban Hills sector (Southern and Southeastern part of Rome Municipal Territory) three superposed piezometric surfaces are mapped together with the related flowpath arrows, the monitoring points and other themes.

A special method of piezometric representation has been developed in the areas where piezometric contours of superposed aquifers merge into one. It is evident that, although differently represented by colors, in the above-mentioned areas, the isolines of equal elevation should join, or conversely, should separate, due to vertical and lateral heterogeneity. However, since the merge (or separation) of two flow paths occurs in large undefined areas, a dotted line was adopted to symbolize the shallower water table contour where it separates from the deeper ones (Figure 2). This technique makes it possible to represent the typical groundwater flow of stratovolcanoes, where superimposed aquifers, flowing radially towards lower elevations, merge into a single one, due to stratigraphic forcing. With this map, the City of Rome has in place the ability to manage groundwater at a larger strategic context. Demands for water wells, contaminant distribution and transport, the effect of groundwater development on saltwater intrusion or the integrity of infrastructure can be now considered in an objective manner that can bring parties in dispute to a common scientific understanding. This in turn will facilitate appropriate planning and infrastructure development in order to confront climate-related problems from occurring as well.

One possible future development concerning groundwater mapping in Rome could be to collect and map information about groundwater circulation in anthropogenic deposits (such as urban fill), likely hosting small and discontinuous aquifers. Such deposits are difficult to map in detail at the chosen scale of the Hydrogeological Map because of their irregular shape and thickness (from several meters to several decameters). In fact, despite the availability of specific maps of anthropogenic

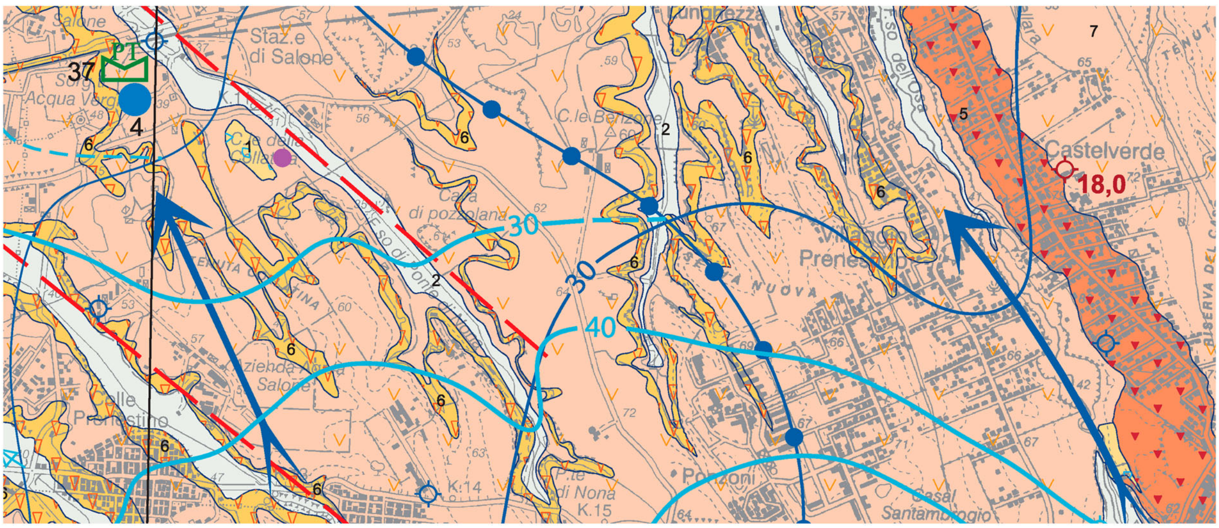


Figure 2. Hydrogeological map excerpt (zoom 1.5×). Piezometry splitting (30 m a.s.l.).

deposits in Rome (in particular in the downtown area) at various scales and produced with different techniques (Ciotoli et al. 2015; Corazza & Marra, 1995; Ventriglia, 1971), a comprehensive map (or survey) of the entire municipal territory is still lacking, which may be useful for groundwater characterization, especially for shallow contamination issues.

Another possible objective for the future could be to map all area affected by groundwater flooding to understand the flow dynamics in detail, especially in the lowland and underground heritage sites.

## Software

All data processing and spatial analysis regarding the map were performed by GIS software (Arc Gis 10). The, final editing aimed to obtain high-quality files for cartographic press and graphics has been achieved by using a vector graphics software (Adobe Illustrator CS6) coupled with a specific cartography plugin for the shape file geographic information management (Map Publisher 9.2)

## Disclosure statement

No potential conflict of interest was reported by the authors.

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