

The synthesis of decades of groundwater knowledge: the new Hydrogeological Map of Rome

La sintesi della conoscenza maturata negli anni sulle acque sotterranee: la nuova Carta Idrogeologica di Roma

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Riassunto: Questo articolo descrive i contenuti e il percorso seguito per arrivare alla nuova Carta idrogeologica di Roma. La carta, che è il risultato di una combinazione di elaborazioni manuali ed elaborazioni GIS, eseguite utilizzando i dati disponibili più aggiornati, si estende su tutto il territorio di Roma Capitale (1.285 km²) e si basa, sia sui più recenti studi scientifici nel settore, sia su nuove indagini svolte al fine di colmare le lacune di dati in diverse aree del territorio in esame. L'opera rappresenta anche un esempio di collaborazione inter-istituzionale tra agenzie governative, istituti di ricerca e università.

Abstract: *This paper describes the contents and the path taken to get to the new Hydrogeological map of the City of Rome. The map, which is the result of a combination of "expert elaborations" and GIS processing performed using the most recent available data, extends to the entire municipality (1285 km²) and is based on both the most recent scientific studies on groundwater field and new survey activities carried out in order to fill the data gaps in several areas of the examined territory. The work represents also an example of inter-institutional collaboration between government agencies, research institutes and universities.*

Parole chiave: gestione delle acque sotterranee nel contesto urbano, idrogeologia urbana.

Keywords: *groundwater city management, urban hydrogeology.*

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Ricevuto: 31 dicembre 2015 / Accettato: 2 febbraio 2016
Pubblicato online: 29 febbraio 2016

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Introduction

In recent decades, urban groundwater has generated worldwide concern, due to several problems: limited availability, groundwater table rise, contamination by either saline water or a broad spectrum of urban and industrial pollutants. In some urban areas, the outlook may appear bleak. However, in the past thirty years, it has been learnt so much about the influence of urban and industrial activity on groundwater quality and quantity, and the science of urban groundwater has immensely developed. The base knowledge is strong and technologies for resource conservation, management and protection are well advancing too (Howard and Israfilow 2002).

Urbanization is a worldwide trend, with more than 50% of the world's population currently living in cities, reaching the 70% in Europe (UN-HABITAT 2012). The urban water cycle is highly connected to human activities, and needs for 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 waters discharge, may exert a strong influence on hydrogeology, sometimes stronger than climate change (Taylor et al. 2013), causing changes in chemical-physical and quantitative status of surface and groundwater. Therefore, urban groundwater management poses not only scientific but also technical, socio-economic, cultural and ethical challenges (Freitas et al. 2015).

The covering and replacement of natural rocks, soils and vegetation by pavements, foundations, buildings, metallic structures, dams, tunnels, and other structures have a deep impact on the hydrology of an area. The urban underground is an intricate and rapidly changing network of tunnels, buried utilities, garages, and other buried structures that disturb the natural structure of the ground and alter its porosity and hydraulic conductivity (Garcia-Fresca 2007).

In addition, a not-environmentally-friendly tendency, perpetrated in recent decades (especially in Rome) is to obliterate the natural streams, often by piping them (Capelli this volume), without considering the obvious hydraulic relations with aquifers, the natural landscape value for the city and their function of blue infrastructure in a sustainability vision.

The largely invisible world of groundwater 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 the cities (Tan-

ner et al. 2009). Under this perspective, mapping groundwater and surface water resources represents a fundamental step for optimizing the urban water system and minimizing water consumption and deterioration.

Urban areas are worldwide experiencing different techniques for groundwater mapping. Hydrogeological maps are needed for a wide range of applications as: resource shortening and quality deteriorating (Ravikumar et al. 2011); defining groundwater protection zones in hardly urbanized contexts (Thomsen et al. 2004); assessing groundwater potential (Oh et al. 2011); evaluating the groundwater vulnerability (Wolf et al. 2006); quantifying the recharge due to sewer and pipes leakage (Yang et al. 1999), furnishing the basic information for underground infrastructure design and to perform city-scale groundwater modeling (Di Salvo et al. 2014; La Vigna et al. 2013).

In the city of Rome, even if at the beginning of its lifetime the local historical springs provided the water supply (Corazza and Lombardi this volume), nowadays most of drinking water supply derives from springs located far from the city, and is delivered to population through the aqueduct network. Even if, currently, there are not specific issues related to water quantity, however, the Rome municipality is dealing with many groundwater related problems. Some examples are: pollution (La Vigna et al. this volume, Ellis 1999), relationships between poor quality streams and aquifers (La Vigna et al. 2010), natural background levels of dissolved elements and compounds (La Vigna et al. 2014), differential settlements in streams valleys (Campolunghi et al. 2007), subsidence and salinization (Manca et al. 2014; Manca et al. 2015) as well as groundwater flooding in the coastal aquifer. The hydrogeological map of Rome constitutes a first important step for future development of surveys and research aimed at solving such problems.

Previous maps

Due to its millenary history indeed, the environmental aspects of Rome have been considered and studied by many authors since a long time. This provided many previous hydrogeological data, studies, and maps (Fig.1). The new hydrogeological map of Rome has been drawn up with the intention to encompass the outcomes of those studies and data paying special care to the reconstruction of the water table, based on experimental field data.

In the past, an enormous contribution to the geological and hydrogeological mapping has been provided by the works of Sciotti (1971) and Ventriglia (1988-1990, 2002) (Argentieri this volume). The cartographies and databases by Ventriglia (1988-1990, 2002) regarded for the first time all the City territory and they are considered as a milestone for all professionals approaching the geology of the city. Even if the general setting and assumptions of these cartographies are still considered very useful, the base geological data and the included hydrogeological measures are nowadays outdated.

Corazza and Lombardi (2005) realized a very detailed hydrogeological map highlighting different overlapping aquifers, but limiting to the downtown area.

More recently the hydrogeologists of Roma Tre University realized a general hydrogeological map of the main urban area (Capelli et al. 2008) and a more detailed map focusing on the lower Aniene River basin (La Vigna et al. 2008). Meanwhile Succhiarelli and D'Ottavio (2008) updated the hydrogeological cartography produced by Lombardi (2003) for the master plan of the city of Rome, using the new literature data available at that time.

Thus, previous hydrogeological maps of Rome did not provide, nowadays, an updated and complete description of the hydrogeological setting of the city.

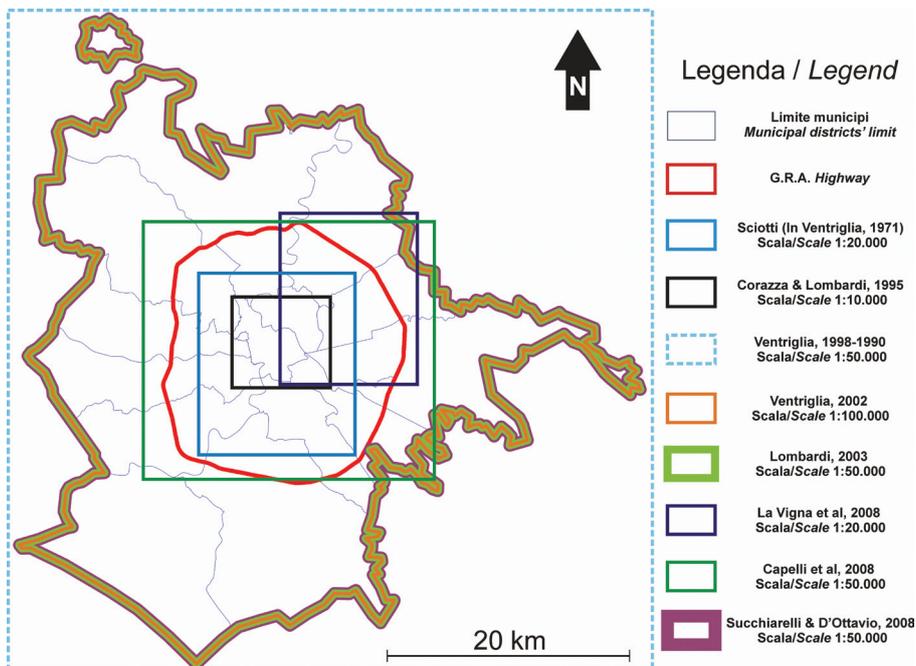


Fig. 1 - Previous hydrogeological maps of Rome and their coverage.

Fig. 1 - Areali coperti dalle precedenti cartografie idrogeologiche rispetto al territorio di Roma Capitale.

Data and methods

One of the most important replicable experience coming out from this work is related to team work and inter-institutional data sharing and cooperation. In order to allow a successful coordination, monthly plenary meeting was planned at the beginning, the different roles of partners were specifically defined and all necessary and available data were shared on a cloud database. All uploaded GIS files by every partner had to be in the same coordinate system and projection. Even if it should be obvious, exchanging datasets among different institutions, often gives unexpected surprises. Being a crucial point this was fixed during the first plenary meeting, in order to prevent possible mismatching of information. The working period started on July 2014 and finished on July 2015.

Concerning both plain view cartography and cross sections, the Geological Map of Rome Municipality, 1:50.000 scale (Funicello et al. 2008) has been hydrogeologically revisited. This choice was driven by the fact that such map represents the most recent and complete geological existing product, based on CARG (Italian Official 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 the active quarry areas. This incongruence caused the mismatch of the elevations and/or the information sketched in some parts of the topographic map (streets, buildings, etc.) and it was highlighted by the making up and verification of the hydrogeological cross sections. Nevertheless, this map is the only suitable for the scale of the present work and was used, with some minor corrections and updates.

New piezometric data were collected during a survey campaign, which took place between July 2014 and May 2015. The investigation was performed relying on the recently established Groundwater Monitoring Network of Rome (La Vigna et al. 2015) which is currently made up of 101 measuring points comprising 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 Castel Porziano Presidential Estate (Banzato et al. 2013) (Fig.2). In order to reconstruct the potentiometric surface and piezometric lines, the Numerical and Quantitative Hydrogeology Laboratory of RomaTRE University (LinQ) database was used too. This database consists of more than 5000 records concerning wells and springs in the roman area. This repository has been populated since the early '90 with the data coming from different hydrogeological studies conducted in Rome and surrounding areas (Fig.2).

Groundwater physical-chemical characterization (i.e. temperature, electric conductivity, pH, measurements) as well as alkalinity tests were performed onsite by means of portable meters and hydrochloric acid titration, respectively. A pump powered by a battery or a bailer, where needed, was used to collect water samples. Moreover, T, pH and alkalinity were used to compute partial pressure of dissolved CO₂ (pCO₂).

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.

Linear springs' data (streambed springs) were plotted querying the LinQ database.

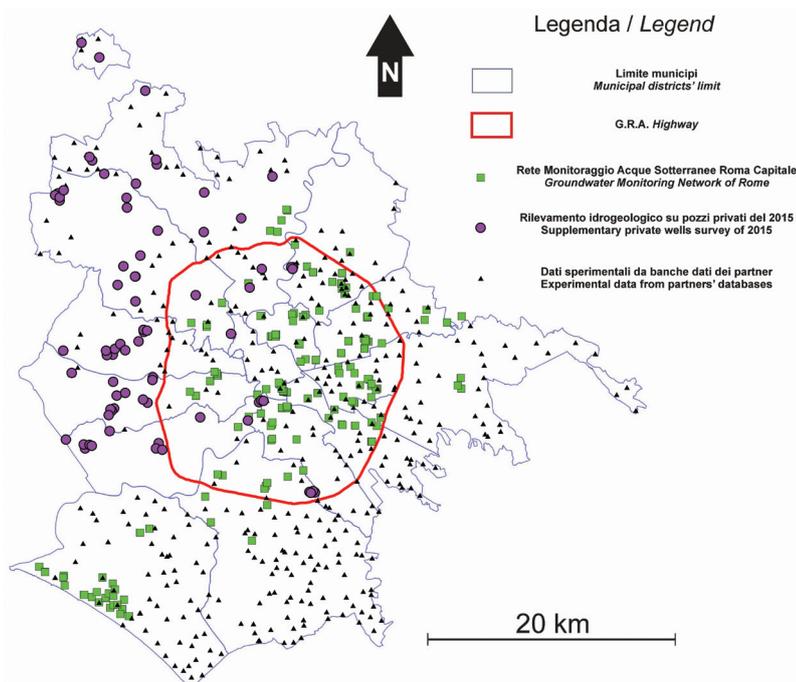


Fig. 2 - Available piezometric data inside the whole territory of Rome. It is evident the important contribution given by the partnership with other institutions and their data.

Fig. 2 - Dati piezometrici disponibili su tutto il territorio di Roma Capitale. E' chiaramente evidente l'importanza del contributo dato dalla collaborazione con altri enti e le relative banche dati.

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

The hydrogeological information was referred to an IGM topographic map specifically edited for the Geological Map of Rome (Funicello et al. 2008). The same topographic map supports the GIS processing of the present work. 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 in the map take up the recommendations reported in the Italian Official Guidelines for hydrogeological survey and representation (Mari et al. 1995) and in further experimental tests and proposals of implementation (Roma and Vitale 2008; Tarragoni et al. 2011), which aimed to 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. Hydrogeological complexes with high to intermediate relative permeability values are represented on the map with red to orange colors, 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 respectively, of the related outcropping areas. Patterns

overlaying the areal symbols have also been 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 heavily modified by anthropogenic causes, the presence of linear springs made the automatic interpolation not properly applicable. 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 pointing out some discrepancies and making more representative the water table reconstruction. Contours' intervals are denser where the water table gradient is lower, as in the coastal area. A rather innovative 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 go to join, or conversely, should go to separate. However, since this union/merge (or separation) of two flowpaths occurs in large undefined areas, it was adopted to symbolize the shallower flow contour from the splitting point using a dotted line pattern (Fig.3).

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 the stratigraphic asset.

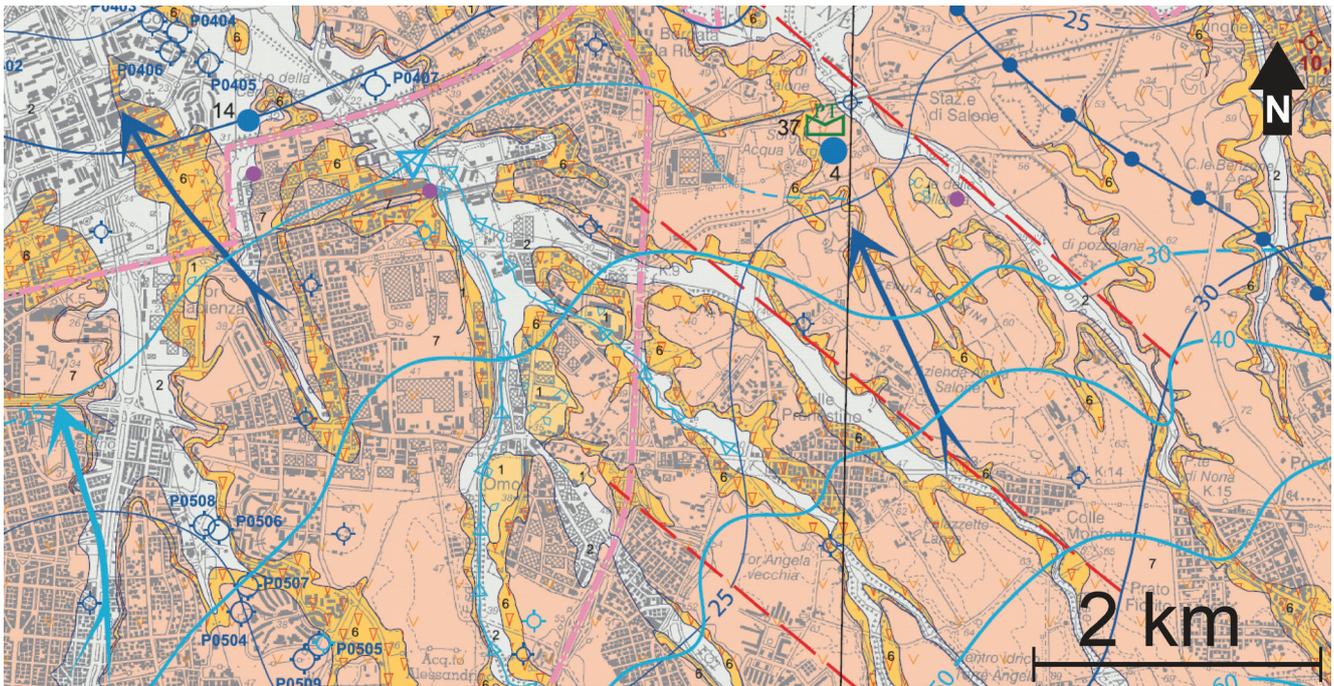


Fig. 3 - Hydrogeological map excerpt (zoom 1.8x). Piezometry of elevation 25 m. a.s.l. and 30 m. a.s.l. splitting (or joining) between the "Regional aquifer" and the "Alban Hills upper aquifer".

Fig. 3 - Stralcio della Carta Idrogeologica (ingrandimento 1,8x). Sdoppiamento (o unione) delle piezometrie rispettivamente di quota 25 m. s.l.m. e 30 m. s.l.m. tra "Falda regionale" e "Falda superiore del settore albano"..

A peculiar symbol has been adopted for natural and anthropogenic objects related to the same identified aquifer: both point and linear elements have been associated, according to their features, to one of the four identified aquifers by using different colors. The excerpt of the map in figure 1 shows how springs, water table and wells have been attributed to the different aquifers.

Linear springs (streambed springs) are reported along water courses adopting the same criterion. Therefore, a water course section interested by a linear spring due to different stretches fed by different superposed aquifers is represented using a different color which highlight their different correspondence. Thus, the same line feature can be characterized by different colors from the starting point where the spring begins to contribute to the stream discharge by a different aquifer.

Four hydrogeological cross-sections have been elaborated in correspondence with the geological sections showed in the Geological Map of Rome Municipality (Funicello 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 crosscut 16 out of the 17 total identified hydrogeological complexes and also the gravel layers (only visible in cross-sections) located at the bottom of the alluvial and the lacustrine deposit complex and within the S. Cecilia formation complex.

The geo-database built up to realize the map encompasses different shapefiles. It will be integrated in a specifically built GIS, whose architecture is being tested (Martarelli et al. 2015).

All data processing and spatial analysis regarding the map were performed by GIS software (ArcGIS 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)

Results

The groundwater flow in the Roman area is 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 to 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); 4) the proximity to the Tyrrhenian Sea coast. The groundwater flow is in fact directed mainly from the volcanic reliefs toward the base level of Tiber and Aniene rivers and the Tyrrhenian Sea. The hydrogeological boundaries and the groundwater directions in 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.

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 lowermost levels of Monte Mario formations) acting as an aquiclude which has been defined "Top surface of the basal aquiclude". 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 this surface, two main incisions are shown: the first is the Middle Pleistocene NW-SE trending depression of the Paleotevere Graben (Auct.), located in the northern and eastern sectors of the city; the second corresponds to the Tiber River valley incision, etched during the last lowstand of sea level (Wurmian age) (Funicello et al. 2008).

The groundwater flow (for more details see Mazza et al this volume) is concentrated in four aquifers. In the Tiber River right bank sector just one aquifer has been identified, while in the left bank sector three different groundwater flows partially overlap. The first one (Alban Hills upper aquifer) is hosted in the shallower volcanoclastic deposits of the Alban Hills Hydrogeological Unit; it is characterized by radial flow-paths within the volcano edifice, with piezometric head values ranging between 100 m a.s.l. and 25 m a.s.l. A dense stream system network along the volcano edifice drains this groundwater flow. The second groundwater flow (Regional aquifer) is widespread all over the left bank sector of the Tiber River, showing piezometric heads ranging between 60 m a.s.l. and the lower values corresponding to the main rivers base flow levels and to the sea water level. This flow merges with the first shallower groundwater flow at about the 25 m a.s.l. isopotentiometric line. The third groundwater flow (Alban Hills deep aquifer) occurs at higher depth below the volcanic deposits of the Alban Hills. It is characterized by a lower hydraulic gradient with respect to the uppermost circulation, with piezometric heads values around 20 m a.s.l.. Due to the lack of many head data, it was not possible to contour the third piezometric surface all over the left bank sector; only few isolines were plotted in the western area, while in the eastern area of the sector only groundwater measured points were plotted.

Isopotential lines in the map highlight that groundwater flowpaths are similar to those of surface water, so that hydrological and hydrogeological basins are quite similar.

In areas of higher elevations, (i.e. the flanks of Alban Hills – Southern and South-Eastern 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 temperature distribution of the regional aquifer (Fig.4) has been mapped considering only those well data which have been identified as related to that regional flow (see Pizzino et al this volume for more details on groundwater geochemistry). The values range from 15°C to more than 20°C. The

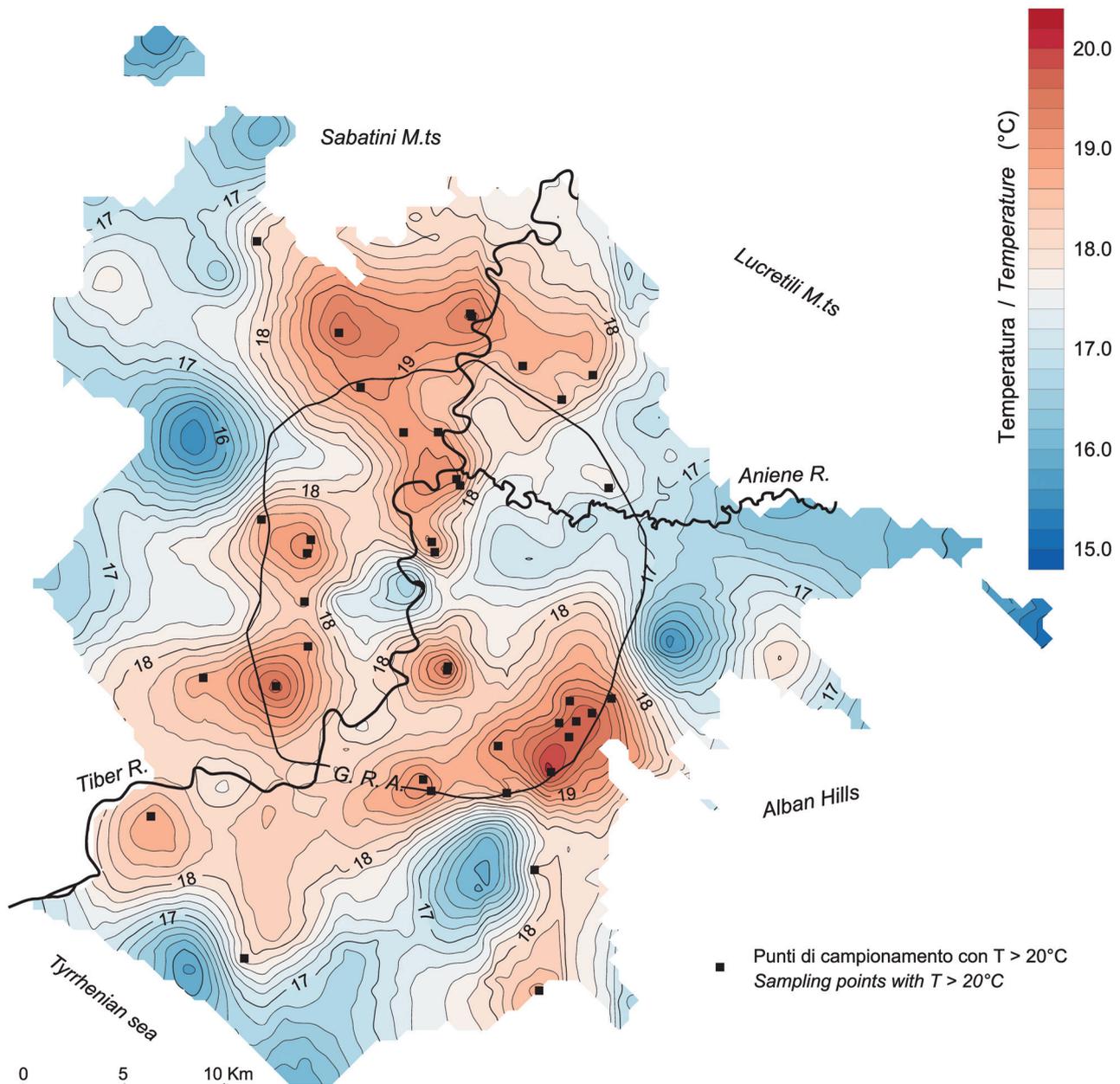


Fig. 4 - Temperature distribution in the regional Aquifer .

Fig. 4 - Andamento delle temperature nell'acquifero regionale.

positive anomalies are located most in the western sector of the urbanized area of the city (inside the G.R.A. highway), along the Tiber River Valley and the Rio Magliana Valley. Other positive anomalies have been recorded in the Northern and Southwestern sector of the area. The relatively mostly cold water characterizes indeed the Aniene River basin and the Rio Galeria sector together with the Ardeatina sector Southward.

The analysis of climatic data, which are treated more in detail by Conte et al. (this volume), identified the mostly rainy months which are October, November and December, and the mostly dry months as June, July and August. Meanwhile

hottest months are July and August, and coldest ones are January, February and December.

Discussion and conclusion

According to Vazqu ez-Su n e et al. (2005) the impacts of groundwater within a specific urban area depend both on its geographical location and the economic status of the city or even the country. While for cities of developing countries the main interests are therefore water quantity and quality, in developed countries, urban groundwater is posed in economical and environmental terms. Use of groundwater may reduce pressure upon conventional freshwater supply sources. On the

other hand, not using this groundwater may lead to flooding and structural damage to underground structures (underground railway systems, basements, underground parking areas, etc.). Quantification and modelling of groundwater fluxes become difficult tasks, mainly due to lack of data, lack of planning (actions usually respond to emergencies rather than planning), and difficulties in communication between the scientific community and city managers/policy makers. In recent years several research groups have developed comprehensive methodologies for evaluating groundwater resources in urban areas, for which the following stages are necessary:

- identifying the most significant factors in the urban hydrogeological cycle, and
- developing and applying methodologies to quantify and control these factors.

The Hydrogeological Map of Rome (figure 5, see previous page) together with the recently established Groundwater Monitoring Network of the city, have been realized following the above mentioned stages.

With this map the City of Rome has the possibility to manage groundwater in a larger context. Private demands for water wells, contaminant plumes, groundwater flooding, natural background levels of dissolved elements and compounds, issues such as how the urban development may affect saltwater intrusion or damage other infrastructures and resources, can be now considered in an objective approach that can bring arguing parties to the negotiating table. This in turn will facilitate appropriate planning and infrastructure development in order to prevent climate-related problems from occurring as well.

The hydrogeological map of Rome has been conceived to be easily consulted by experts, public administrations and stakeholders. In some parts of the map is necessary to pay attention because of several overlapping information layers, difficult to understand at a first glance. For example, in the Alban Hills sector (Southern and South-Eastern part of Rome Municipal Territory), the three superposed piezometric surfaces, are mapped together with the related flowpath arrows, the monitoring points and other themes.

One possible future development about groundwater mapping in Rome, would be to collect and mapping information about the groundwater flow into the anthropogenic deposits, likely hosting small and space-limited aquifers (La Vigna et al. this volume). Such deposits are difficult to be mapped in detail at the chosen scale of the Hydrogeological Map of Rome, they cover in a not uniform way the municipality territory having irregular shape and thickness (from few meters to few decameters). In fact, despite the availability of specific maps of anthropogenic deposits in Rome (in particular downtown) at various scale and produced with different techniques (Ventriglia 1971; Corazza and Marra 1995; Ciotoli 2015), a comprehensive mapping (or survey) of the entire municipal territory is still lacking, which may be useful for groundwater characterization, especially for shallow contamination issues.

Due to the innovative approach, the updated data and surveys, the contribution of all the most expert scientists and professionals, this map claims to become the new groundwater benchmark for Rome.

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