

Hydrogeological setting of a Rome city sector: shallow groundwater in the right side of Tiber River inside the G.R.A highway

Assetto idrogeologico di un settore della città di Roma: acque sotterranee superficiali nel settore destro del Fiume Tevere all'interno del G.R.A.

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Riassunto: Questo lavoro presenta uno studio idrogeologico di dettaglio del settore urbanizzato della Città di Roma, relativo al settore in destra Tevere, indicativamente compreso all'interno del Grande Raccordo Anulare (G.R.A.). Attraverso l'analisi geologico-stratigrafica effettuata a partire da dati reperiti anche presso il Dipartimento Tutela Ambientale di Roma Capitale e per mezzo dell'analisi delle carte topografiche e tematiche storiche del settore, è stato possibile ottenere un modello idrogeologico del sottosuolo di questo settore di Roma, più dettagliato di quello ad oggi disponibile nella Carta Idrogeologica di Roma in scala 1:50.000 (pubblicata nel 2015), che ha permesso di individuare, per la prima volta, le circolazioni sotterranee più superficiali, fornendo uno strumento molto utile per le amministrazioni che devono occuparsi di protezione delle risorse idriche.

Abstract: *This paper presents a detailed hydrogeological study of a Rome city sector, in the right side of Tiber River, inside the G.R.A. highway. A hydrogeological model of this city sector has been developed through geologic-stratigraphical analysis also of data provided by the Environmental Protection Department of Roma Capitale (Municipality of Rome) and the observation of historical topographic and thematic maps. This model is more detailed than the most recent Hydrogeological Map of Rome (1:50.000 scale), published in 2015, and allowed identifying the shallowest groundwater flow systems for the first time. This detailed model can be a very useful tool for agencies and administrations managing the protection of groundwater resources.*

Keywords: *urban hydrogeology, conceptual groundwater model, hydrogeological map.*

Parole chiave: idrogeologia urbana, modello idrogeologico concettuale, carta idrogeologica.

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Introduction

Several specific factors must be considered when dealing with groundwater in urban areas. As a result, urban groundwater has emerged in recent years as a specialized area of study within hydrogeology (Vázquez-Suñe et al. 2016). The reason for the introduction of this recent discipline is to be found in the growth of the cities related to possible environmental impacts on groundwater. Urbanization significantly affects the natural water cycle both in terms of quantity and quality. The process of urbanization generally involves an increase in flooding hazard, leading to disturbance of the natural hydrogeological cycle because the natural recharge system is completely altered: the natural soil sealing and the streams' capture in artificial sewers drastically reduce plant evapotranspiration, the exchange between surface and groundwater and therefore the recharge due to infiltration, as well as decrease the time of surface runoff worsening the quality of water. Conversely, the recharge is increased by the loss of the water supply and sewage system (Gisotti 2007). Flow and transport processes affecting urban groundwater are not essentially different from those affecting natural contexts, but the time and space scales involved are significantly different. Quantification of groundwater flow and modelling become difficult tasks, mainly due to lack of data, lack of possibilities to directly observe the natural phenomena under the urban covering, and last but not least, lack of urban planning (Vázquez-Suñe et al. 2005).

As urban population grows, conjunctive use of ground- and surface waters is likely to become increasingly common,

and water management is assuming more and more importance (Gossell et al. 1999, Aldrick et al. 1999). An integrated management of urban water resources provides the opportunity to optimize the whole urban water system and to minimise water and energy consumption, and recognises that different types of water can be used for different purposes (Freitas et al. 2015). Cities and urban populations are growing at a high pace and, as a consequence, so are the local scale anthropic impacts on the hydrologic cycle. The shallow urban underground is an intricate network of tunnels, conduits, utilities, and other buried structures comparable to a natural karst system, except that the “urban karst” is generated much more rapidly (Garcia-Fresca 2017).

During time, several research groups (e.g. Burian and Pomeroy 2010, La Vigna et al. 2015a, Lerner 1997, Lerner and Yang 2000, Marsalek 2008, Stevenazzi 2017,) have developed comprehensive methodologies for evaluating groundwater resources in urban areas. Two stages are necessary:

1. Identifying the most significant factors in the urban hydrogeological cycle;
2. Developing and applying methodologies to quantify and control these factors.

Moreover, it is crucial, inside the implementation of adaptation strategies, trying to get the maximum benefit from underground water resources with a view to environmental sustainability and urban resilience (La Vigna et al. 2015b).

The City of Rome became part of a project promoted by Rockefeller Foundation: the “100 Resilient Cities” program, since the end of 2014. “Rome Resilience Strategy” (Roma Capitale 2018) included two specific sub-actions dealing with groundwater: i) the development of a new Hydrogeological Map of the city (La Vigna and Mazza eds. 2015) and ii) the first development of a groundwater monitoring network of the city (La Vigna et al. 2015b).

In recent years the concentrated presence of various industrial and commercial activities in the city of Rome, have induced accidental or sometimes malicious spills of pollutants into the ground over time (Bonfà et al. 2017, La Vigna et al. 2019). Therefore, there are several potential contaminated sites (Fig. 1a) in the city which can threaten soil and aquifers quality. The aim of this paper is to present the processing of a very detailed hydrogeological conceptual model of a Rome city sector in order to identify the shallowest aquifers, which are also the most vulnerable to pollution, and to define the relationship between these aquifers and the deep regional one.

Study area

This right side of the City of Rome is characterized by several densely urbanized sectors alternating with areas that have maintained their natural appearance. Several streams drain the area with an articulated hydrographic pattern. The most important streams are the Rio Galeria and the Rio Magliana, tributaries of the Tiber River on its orographic

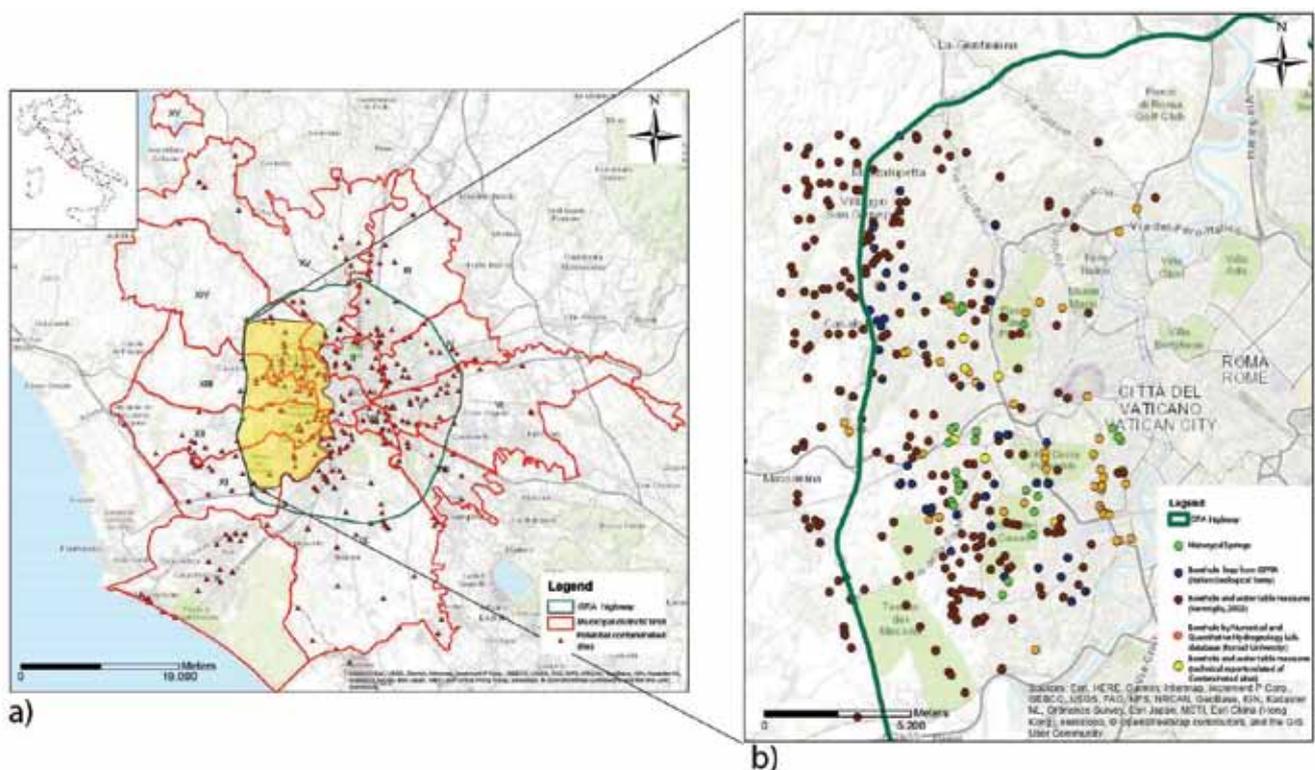


Fig. 1 - a) Localizzazione dell'area di studio con la distribuzione degli oltre 400 siti notificati come potenzialmente contaminati sul territorio di Roma Capitale b) Dettaglio in cui è mostrata la distribuzione dei dati utilizzati in questo lavoro.

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right. Elevations of this sector of the city are variable from of about 100 m a.s.l. of the north-east side to the 10-15 m a.s.l. of the valleys' bottom.

The geological bedrock of the whole roman area is the Monte Vaticano Formation composed by clayey-sandy sediments of marine environment overlaid by quaternary deltaic and volcanic lithotypes (Parotto 2008).

On a regional scale, the hydrogeological setting is characterized by two large hydrogeological structures: the Vulsini-Cimini-Sabatini Mounts and the system of the Alban Hills (Capelli et al. 2012). The hydrogeological conceptual model and groundwater circulation in the area of Rome municipality are driven by the structural setting, by the relationship of groundwater exchange between the five hydrogeological Units and by the two main rivers flowing in the study area, Tiber River and Aniene River (Capelli et al. 2008). Groundwater circulation is limited at the base by a very low-permeability bedrock formed by a basal clayey-sandy complex (Monte Vaticano, Monte delle Piche and lower levels of Monte Mario formations) acting as an aquiclude. The stratigraphic sequence of quaternary volcanic and sedimentary deposits, on this bedrock, is characterized by several vertical and lateral permeability variations. Above these Formations there are anthropogenic deposits (Corazza and Lombardi 1995).

In the study area four regional Hydrogeological Units can be recognized (Fig. 2) (La Vigna et al. 2015c , La Vigna et al. 2016):

- **Pre-volcanic and continental sedimentary deposits Hydrogeological Unit** - This unit is composed by deposits which are over the basal aquiclude and below the volcanic products. Important aquifers are hosted in the gravelly and sandy facies of this unit.
- **Sabatini Mts Hydrogeological Unit** - All volcanic products originated by the Sabatini Mts are regionally considered as a single hydrogeological unit and its main groundwater flow is inside the coarse levels, sustained by more ashly horizons.
- **Alban Hills Hydrogeological Unit** - All volcanic products originated by the Alban Hills, which are generally fairly limited in this part of the City, are regionally considered as a single hydrogeological unit.
- **Recent and actual alluvial deposits Hydrogeological Unit** - In the alluvial deposits the groundwater circulations are both in the shallow levels which are hydraulically connected with the water courses, and in the coarse gravel mattress generally located at the base of the deposits of main rivers and streams.

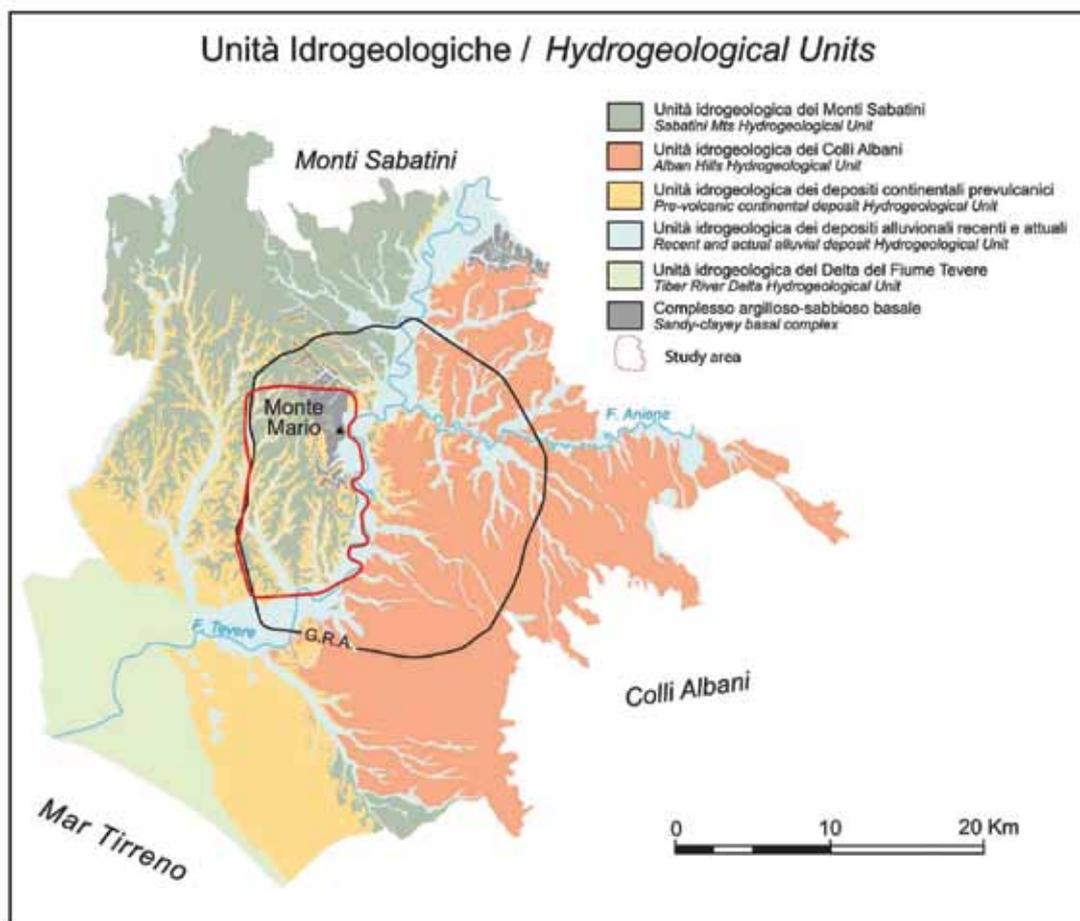


Fig. 2 - Hydrogeological Units of Rome (La Vigna et al. 2015c).

Fig. 2 - Unità idrogeologiche dell'area di Roma (La Vigna et al. 2015c).

Materials and methods

In order to reconstruct the geological, structural and hydrogeological setting of the area, an in-depth bibliographic search was carried out. Most of data (borehole logs, water table monitoring) have been provided by technical reports related to notified cases of the Contaminated sites remediation office of Rome Municipality. Further data (borehole logs, water table measures, springs' location) have been extracted by the work of Ventriglia (2002). The Roma Tre University Numerical and Quantitative Hydrogeology Lab. database (water table measures, borehole logs, springs' location) and the online national archive of Italian Geological Survey (borehole logs) related to Law 464/84 data (ISPRA 2010) have been used as well. All detailed hydrogeological assumptions started according to the Hydrogeological Map of Rome (1:50.000 scale) which has been considered the base dataset and the regional scale most recent conceptual model of groundwater circulation (La Vigna and Mazza eds. 2015; La Vigna et al. 2016). Historical springs locations have been identified by means of historical topographic and thematic maps of Rome. This cartography analysis has been also supported by targeted field surveys (Fig. 1b).

Data have been elaborated by means of detailed hydrogeological cross sections. The water table contours' elaboration of the different identified circulation was manually drawn by means of triangulation methodology using about 350 water table data. Some of the Hydrogeological Complexes proposed in the Hydrogeological Map of Rome (La Vigna and Mazza eds. 2015; La Vigna et al. 2016) have been redefined according the processed piezometric pattern and starting from the original geological data as well (Funicello and Giordano 2008), because of the extreme detail of the analysis.

Results

The most important result of this work is the definition of the hydrogeological conceptual model of the study area, identifying, for the first time the presence of two overlapping shallow aquifers bodies:

1. The first in the upper volcanic deposits, located in the northern and central sectors.
2. The second in the most superficial sandy sediments of the "Ponte Galeria" Formation ("Sabbie Salmonate" Complex), located in the central and in the southern sectors.

Hydrogeological complexes defined in this work are listed in Table 1. In some cases the hydrogeological complexes correspond to the Hydrogeological Map of Rome ones. In other cases, according to the detailed analysis performed, they have been redefined in some aspects, e.g. the permeability degree.

The hydrogeological complexes difference interpretation mainly concerns the Sedimentary Units (in detail: "Ponte Galeria" Formation and "Monte Mario" Formation) and the Volcanic deposits of the Geological Map of Rome Municipality (Funicello and Giordano 2008) as follow (Fig. 3):

Sedimentary Units:

- "Monte Mario" Formation (included in the "Coarse sands of Monte Mario Formation and Ponte Galeria Complex" in Hydrogeological Map of Rome) has been considered more permeable than the other sedimentary formations and has been redefined in:
 - » Coarse sand of "Monte Mario" Complex: Acting as an aquifer and hosting the regional aquifer.

Tab. 1 - Hydrogeological complexes defined in the study area; green cells indicate complexes object of the redefinition performed in this study (see details in Fig.3), white cells indicate complexes correspondent to same complexes of the Hydrogeological Map of Rome.

Tab. 1 - Complessi idrogeologici definiti nell'area di studio; le celle verdi indicano i complessi oggetto della ridefinizione effettuata in questo lavoro (vedere i dettagli in Fig.3), le celle bianche indicano i complessi che risultano corrispondenti a quelli della Carta Idrogeologica di Roma.

Number	Hydrogeological complex	Hydrogeological Unit	Groundwater behaviour
I	Anthropogenic deposits complex	Recent deposit	aquitard
II	Alluvial and lacustrine deposit complex	Recent and actual alluvial deposit	aquitard
III	Heterogeneous clastic deposits complex	Sabatini Mts + Alban Hill	aquifer
IV	"Tufo Lionato" complex	Alban Hill	aquifer
V	High permeability Albani Volcanic Complex	Alban Hill	aquifer
VI	Sabatini Volcanic deposits Complex	Sabatini Mts	aquifer
VII	"Tor de' Cenci" Complex	Alban Hill	aquiclude
VIII	"Valle Giulia" Formation Complex	Pre-volcanic and continental deposit	aquifer
IX	"Santa Cecilia" Formation Complex	Pre-volcanic and continental deposit	aquiclude
X	"Sabbie Salmonate" Complex	Pre-volcanic and continental deposit	aquifer
XI	Clayey sandy "Ponte Galeria" Complex	Pre-volcanic and continental deposit	aquiclude
XII	Gravelly Sandy "Ponte Galeria" Complex	Pre-volcanic and continental deposit	aquifer
XIII	Coarse Sand of "Monte Mario" Complex	Pre-volcanic and continental deposit	aquifer
XIV	Sandy clayey Basal Complex	Sandy-clayey basal Complex	aquiclude

- “*Ponte Galeria*” Formation Complex (regionally part of the Pre-volcanic and continental sedimentary deposits Hydrogeological Unit, Figure 2) of the Hydrogeological Map of Rome has been divided into three different complexes according to the performed detailed piezometric pattern:
 - » “Gravelly-Sandy *Ponte Galeria* Complex”: including *Conglomerate lithofacies* (PGLa) and *Conglomerate-sandy lithofacies* (PGL3a). Acting as an aquifer and hosting the regional aquifer.
 - » “Clayey-sandy *Ponte Galeria* Complex” including: *Argille ad Helicella Aucct.* (PGL2), *Sandy-clay lithofacies* (PGL3b), *clayey-sand lithofacies* (PGLb). Acting as a local aquiclude.
 - » “*Sabbie Salmonate* Complex” including: sandy lithofacies (PGL3c). Acting as an aquifer and hosting the second shallow aquifer.

Volcanic Deposits:

- The “Low Permeability *Albani Volcanic* deposits Complex” and “*Sabatini Volcanic* Complex” (regionally part of the Alban Hills and the Sabatini Volcanic Hydrogeological Units, Figure 2) of the Hydrogeological Map of Rome, has been redefined according to the performed detailed

piezometric pattern:

- » “*Sabatini Volcanic* Complex” including only: “Tufi stratificati varicolori di “*La Storta*” Formation (LTT) and “Tufi stratificati varicolori di *Sacrofano*” Formation (SKF), acting as a local aquifer and hosting the first shallow aquifer.
- » “*Tor de’ Cenci* Unit Complex” including only “*Tor de’ Cenci*” Unit (TDC), acting as a local aquiclude.

In the northern sector, the first shallow aquifer (marked with purple lines in Figure 4) is hosted in the shallower volcanoclastic deposits of the Sabatini Volcanic Complex terms sustained by “*Tor de’ Cenci* Unit Complex”. This aquifer is characterized by a discontinuous shape because of the land morphology consisting of ignimbrite plateaus engraved by deep stream valleys that create small ridges. Water table elevation ranges between 90 and 65 m a.s.l. (Fig. 4), the general groundwater flow direction is towards South-West, but locally it could considerably vary. The regional aquifer in this sector (marked with blue line in Figure 4) has water table elevation values ranging between 80 and 50 m a.s.l..

In the southern sector, the second shallow aquifer (marked with the green lines in Figure 4) is hosted in the “*Sabbie Salmonate* Complex”, sustained by “Clayey-sandy *Ponte Galeria* Complex”. It is characterized by a continuous trend showing

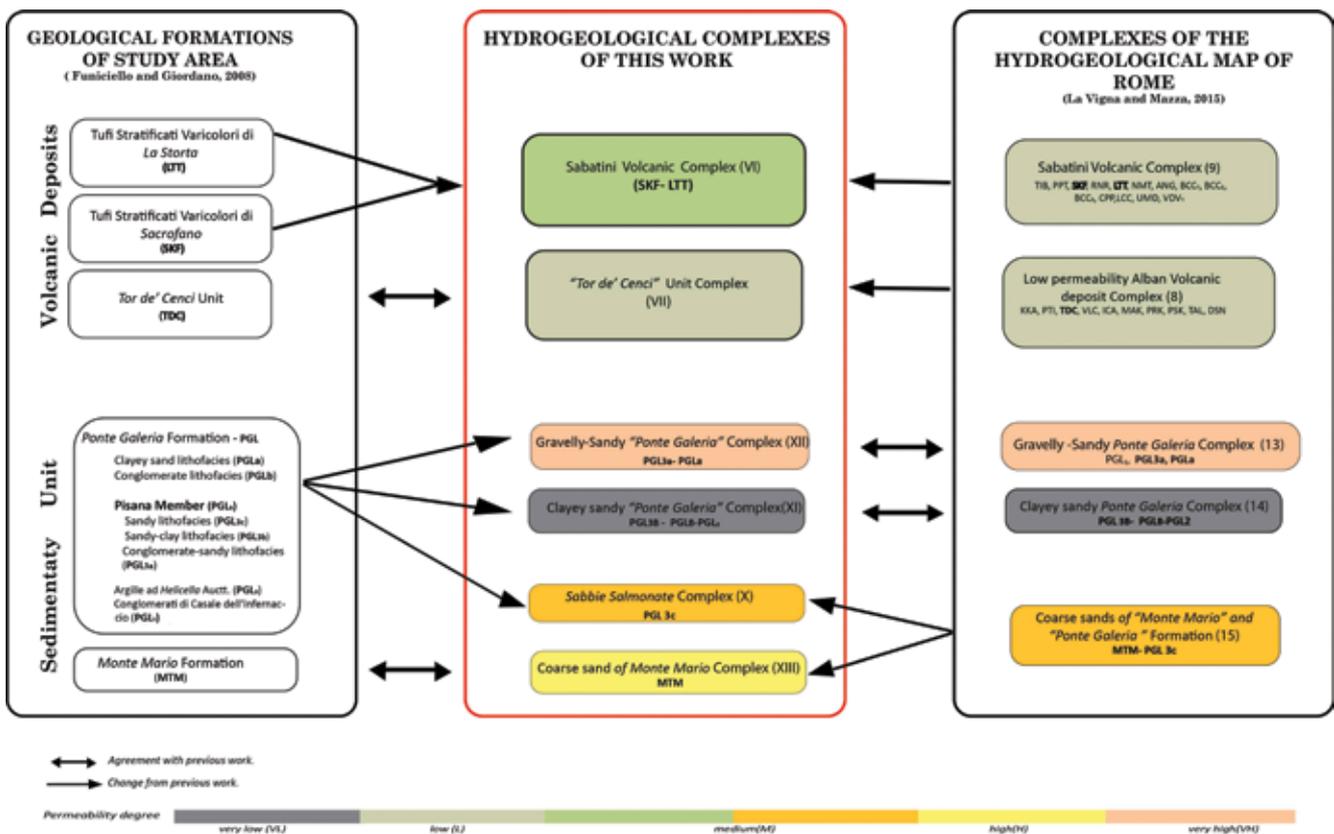


Fig. 3 - Main hydrogeological complexes of the study area (in the middle) compared with original geological formations on the left and the hydrogeological complexes of hydrogeological Map of Rome on the right.

Fig. 3 - Complessi idrogeologici principali dell'area di studio (al centro) confrontati con le formazioni geologiche originarie a sinistra e i complessi della carta idrogeologica di Roma a destra.



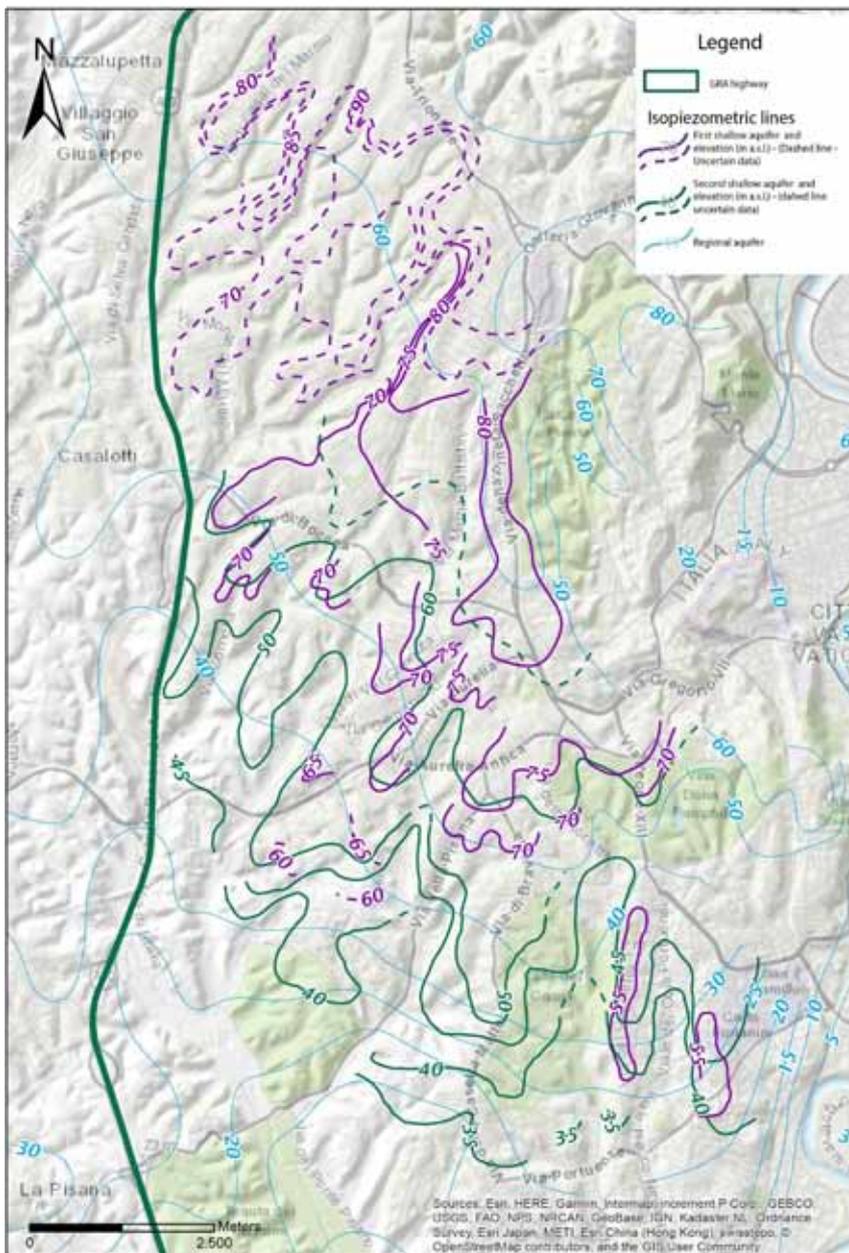


Fig. 4 - Piezometric pattern in the study area.

Fig. 4 - Linee isopiezometriche nell'area di studio.

water table values ranging between 60 and 35 m a.s.l. (Fig.4) the general flow direction is towards South-West as for the regional aquifer (marked with blue line in Figure 4), which in this sector have water table values ranging between 60 and 15 m a.s.l.. The piezometric lines merge with the deeper regional aquifer toward north, at 60 m a.s.l. where the groundwater flow is splitted. Both circulations are separated (by local aquiclude) from the underlying deeper regional aquifer, except for the sectors where the stratigraphic setting does not allow hydraulic separation and therefore determines a single groundwater circulation. In this sector it is possible to observe the first shallow aquifer body where there are residual strips of volcanic deposits.

The identified piezometric setting is shown in Figure 5 according to an unpublished detailed Hydrogeological Map

(Adele Clausi, Roma Tre University, Master Thesis 2019). Fourteen hydrogeological cross-sections have been realized and plotted in order to figure out the hydrogeological setting of the area in the fence diagram of Figure 6.

Discussion

In the urbanized area of Rome studied here, the water resources have no much importance relative to its productivity and availability, because Rome is historically supplied with water from Apennine springs, but it acquires importance in terms of natural resources protection and for possible issues during the execution of public or private works affecting the underground.

Although the local aquifers do not receive the right consideration, they still are the main local groundwater resource and they are still used in the rural sectors of the city

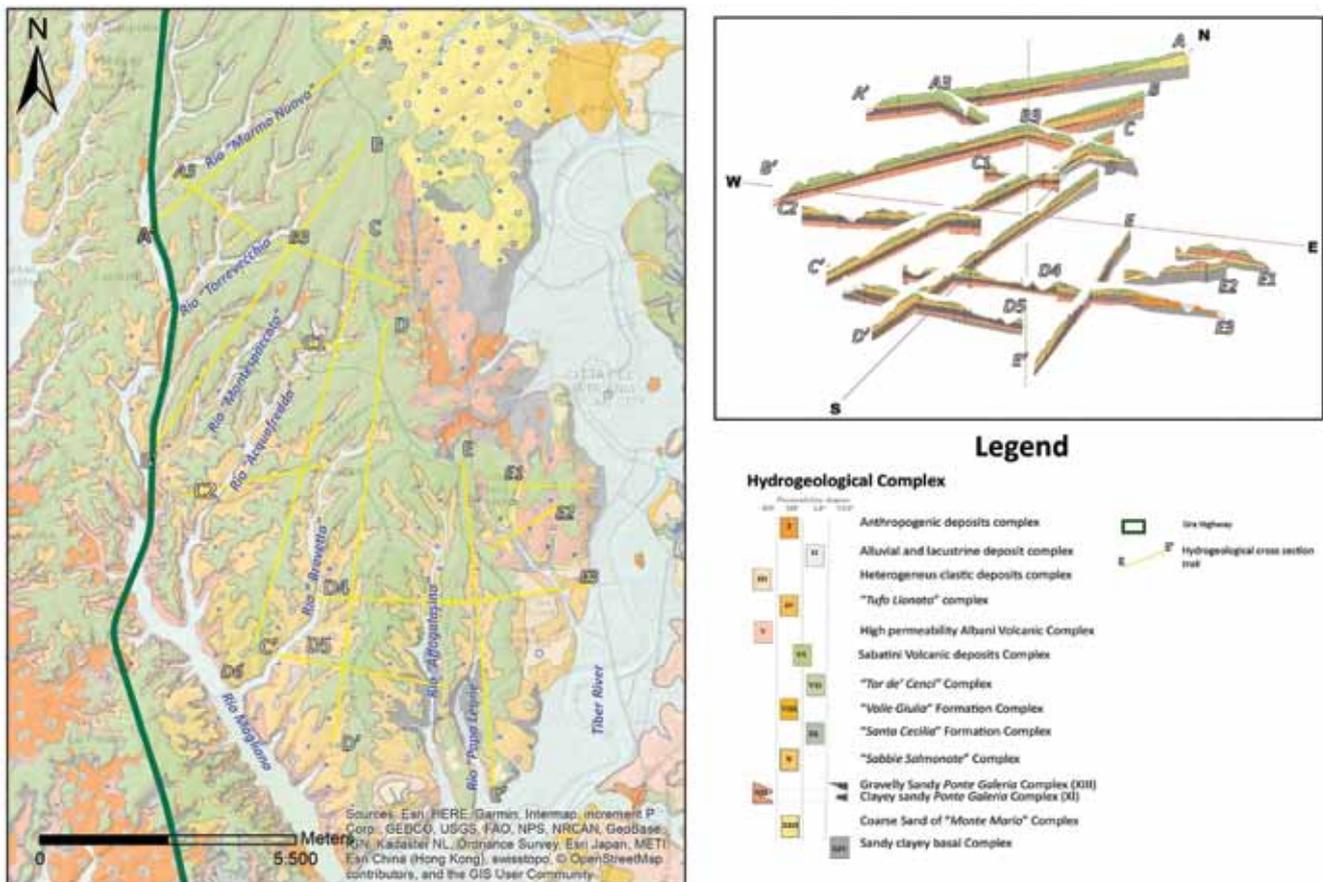


Fig. 5 - Hydrogeological cross section tracks shown in fence diagram and plotted on the hydrogeological complexes.

Fig. 5 - Andamento delle tracce delle sezioni idrogeologiche mostrate nel *fence diagram* rispetto ai complessi idrogeologici.

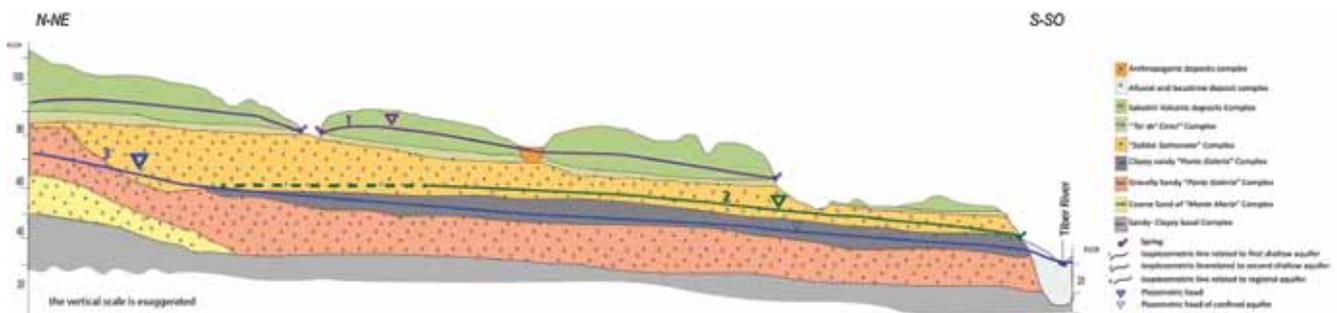


Fig. 6 - Hydrogeological conceptual model of the study area.

Fig. 6 - Modello idrogeologico concettuale dell'area di studio.

territory for agricultural activities and for irrigation needs of urban gardens and for this reason they must be protected.

The conceptual model of the groundwater flow in this right side of Tiber River is represented by three overlapping aquifers (Fig. 6), consistent with the extremely varied geological-stratigraphic structure, that have been recognized but that are not always coexistent; indeed locally, e.g. just the deeper regional aquifer is present and somewhere it can become itself the shallowest and therefore the first receptor of possible pollution phenomena. In the more frequent groundwater flow configuration, the shallowest aquifers are

located above the deeper aquifer so they are the first receptors of possible pollution phenomena and just in case of particular geological setting they can transfer, during time, eventual contamination to the deeper hydrogeological system. In the more urbanized sectors, the shallowest circulation is hosted in the "Anthropogenic Deposit Complex". Groundwater recharge in this case should derive exclusively from rainfall, but the recharge is difficult in those sectors where the urbanization has sealed the ground. In some cases which could not be evaluated at this stage, the recharge may derive from the losses of the water and sewerage network as well.

The regional aquifer shown in the Hydrogeological Map of Rome (La Vigna and Mazza eds. 2015) related to the study area of this work, has been revised and expanded according to new data collected, and together with the mapping of the two previously unknown shallower aquifers, they play important contribution to the basic knowledge for the study and management of local water resources. It is very important indeed to update and deepen thematic maps that can be the base knowledge for detailed issues; e.g. in this case, the hydraulic relationship between the three superimposed aquifers highlights the possibility, in some places, about leakage of localized shallow contaminations to the deeper groundwater system.

Hydraulic communications between these three aquifers are possible:

- in case of the sealing discontinuity caused by the depositional nature of the geological formations;
- where many boreholes have been drilled (very frequent in urban areas) which have crossed these geological bodies over time with the interruption of their original geological continuity.

In conclusion, the hydrogeological conceptual model developed in this work has highlighted the presence of shallow aquifers above the regional one in the area of Rome located in the right side of Tiber River inside the G.R.A. highway.

Two shallow aquifers were identified for the first time in this urbanized sector and represent very vulnerable resources to anthropic pressure and so their knowledge and mapping is a crucial tool for local administrations along with groundwater monitoring.

The development of such detailed thematic studies represents a useful tool for more specific investigation and the groundwater resources management. This work, giving more detailed information about the shallow groundwater circulations, also contributes to one of the goals of the resilience strategy proposed by Rome Municipality (Roma Capitale 2018), regarding the preserving of the ecological network and the recovering of the local water resources value.

A desirable future development of this work would be the extension of the research activity to the remaining part of the City sector in the right side of Tiber River, also outside the G.R.A. highway, in order to obtain complete information throughout the territory of the Municipality of Rome.

REFERENCES

- Bonfà I, La Vigna F, Martelli S, Ticconi L (2017) Environmental issues due to organohalogenated compounds diffuse pollution in groundwater. Emerging issue in the Roman area?. *Acque Sotterranee - Italian Journal of Groundwater*, 6(2). <https://doi.org/10.7343/as-2017-280>
- Burian SJ, Pomeroy CA (2010) Urban Impacts on the Water Cycle and Potential Green Infrastructure Implications. In: *Urban Ecosystem Ecology, Agron. Monogr.* 55. ASA, CSSA, SSSA, Madison, WI. p. 277-296. doi:10.2134/agronmonogr55.c14
- Capelli G, Mastroiello L, Mazza R, Petitta M, Baldoni T, Banzato F, Cascone D, Di Salvo C, La Vigna F, Taviani S, Teoli P (2012) Carta Idrogeologica del territorio della Regione Lazio scala 1:100.000 "Hydrogeological Map of Latium Region – Scale 1:1000.000" Regione Lazio. SELCA. Firenze.
- Capelli G., Mazza R., Taviani S. (2008) Acque sotterranee nella città di Roma "Groundwater in the City of Rome". Memorie descrittive della Carta Geologica d'Italia, 80, p.221-245. ISSN: 0536-0242
- Corazza A, Lombardi L (1995) Idrogeologia dell'area del centro storico di Roma "Hydrogeology of the historical centre of Rome". La geologia di Roma. Il Centro Storico. Memorie Descrittive della Carta Geologica d'Italia, 50, 179-211.
- Funicello R, Giordano G (2008) Note illustrative della Carta Geologica d'Italia alla scala 1: 50.000, foglio 374 "Explanatory notes of Geological Map of Italy. 1:50.000 scale. Section 374" APAT Dipartimento Difesa Suolo. Servizio Geologico d'Italia. SELCA, Firenze.
- Freitas L, Pereira A, Afonso M, Chaminè H (2015) Urban groundwater mapping techniques: importance on urban water cycle. Congreso Internacional del Agua-Termalismo y Calidad de Vida. Campus de Auga, Ourense, Spain.
- Gisotti G (2007) Ambiente Urbano. Introduzione all'ecologia urbana. Palermo: Dario Flaccovio "Urban environment. Introduction to urban ecology".
- Gossell W, Herfert, J, Chowanietz U, Hermel U (1999) Sustainable groundwater management for the Berlin region. Chilton J(ed), Balkema, 139-143.
- La Vigna F, Sbarbati C, Bonfà I, Martelli S, Ticconi L, Aleotti L, Covarelli A, Petitta M (2019) First survey on the occurrence of chlorinated solvents in groundwater of eastern sector of Rome *Rend. Fis. Acc. Lincei* 30: 297. <https://doi.org/10.1007/s12210-019-00790-z>
- La Vigna F, Mazza R, Amanti M, Di Salvo C, Petitta M, Pizzino L, Pietrosante A, Martarelli L, Bonfà I, Capelli G, Cinti D, Ciotoli, F, Ciotoli G, Conte G, Del Bon A, Dimasi M, Falcetti S, Gafà RM, Lacchini A, Mancini M, Martelli S, Mastroiello L, Monti GM, Procesi M, Roma M, Sciarra A, Silvi A, Stigliano F, Succhiarelli C (2016) Groundwater of Rome. *Journal of Maps* DOI: 10.1080/17445647.2016.1158669
- La Vigna F, Mazza R (2015) Carta Idrogeologica di Roma-Scala 1: 50.000 "Hydrogeological Map of Rome-Scale 1: 50.000". Roma Capitale. Edizioni PO. LI. GRAF. Pomezia.
- La Vigna F, Mazza R, Amanti M, Di Salvo C, Petitta M, Pizzino, L (2015)b The synthesis of decades of groundwater knowledge: the new Hydrogeological Map of Rome. *Acque Sotterranee - Italian Journal of Groundwater*, 4(4). <https://doi.org/10.7343/as-128-15-0155>
- La Vigna F, Bonfà, I, Coppola A G, Corazza A, Di Filippo C, Ferri G, Succhiarelli C (2015)a La città di Roma e le sue falde acquifere: dalle criticità, alle opportunità di resilienza urbana "The City of Rome and its groundwater: from critical issues, to urban resilience opportunities". *Acque Sotterranee - Italian Journal of Groundwater* 4\2142, 59-69 DOI: 10.7343/AS-132-15-0159.
- La Vigna F, Mazza R, Pietrosante A, Martarelli L, Di Salvo C (2015) c Unità idrogeologiche del territorio romano e modello concettuale di circolazione "Hydrogeological Units of Roman area and groundwater conceptual model". Carta Idrogeologica di Roma – Hydrogeological Map of Rome. Note integrative, 12-16.

- Lerner DN (1997) Too much or too little: Recharge in urban areas. In: Chilton J et al. (ed) *Groundwater in the Urban Environment: Problems, Processes and Management*. A.A.Balkema/Rotterdam/Brookfield
- Lerner DN, Yang Y (2000) Quantifying recharge at the city scale using multiple environmental tracer. In: Dessargues A (ed) *Tracers and modelling in hydrogeology*. IAHS Publ. n°262, 355-361
- Marsalek J (2008) *Urban Water Cycle Processes and Interactions*. London: CRC Press, <https://doi.org/10.1201/9781482288544>
- Parotto M (2008) Evoluzione paleogeografica dell'area romana: una breve sintesi "*Paleogeographic evolution of the Roman area: a brief summary*". *La Geologia di Roma dal centro storico alla periferia*. Memorie Descrittive della Carta Geologica d'Italia 80, 25-39.
- Roma Capitale (2018) *Rome Resilience Strategy*. 100 Resilience Cities. Roma Capitale, Roma
- Stevenazzi S (2017) Time-dependent methods to evaluate the effects of urban sprawl on groundwater quality: a synthesis. *Acque Sotterranee - Italian Journal of Groundwater*, 6(4). <https://doi.org/10.7343/as-2017-295>
- Vázquez-Suñé E, Sánchez-Vila X, Carrera J (2005) Introductory review of specific factors influencing urban groundwater, an emerging branch of hydrogeology, with reference to Barcelona, Spain. *Hydrogeology Journal* 13.3: 522-533
- Vázquez-Suñé E, Marazuela Calvo MÁ, Velasco Mansilla DV, Diviu M, Perez Estaun A, Álvarez Marrón J (2016) A geological model for the management of subsurface data in the urban environment of Barcelona and surrounding area. *Solid Earth*, 7(5), 1317
- ISPRA (2010) Archivio Legge 4 Agosto 1984 n.464. Norme per agevolare l'acquisizione da parte del Servizio Geologico della Direzione generale delle miniere del Ministero dell'Industria, del Commercio e dell'Artigianato di elementi di conoscenza relativi alla struttura geologica e geofisica del sottosuolo nazionale "*Database of Law 4 August 1984 n.464. Rules to facilitate acquisition by the Geological Survey of the General-Directorate for Mines of the Ministry of the Industry, Commerce and Crafts of knowledge elements related to the geological structure and geophysics of the national subsoil*" *Gazzetta Ufficiale della Repubblica Italiana*, 226, 17/08/1984. IPZS, Roma, Italy. Available from <http://portalesgi.isprambiente.it/> - last accessed 15/11/2019