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Guardians of the aquifers: ehancing Rome's groundwater monitoring network

Guardiani degli acquiferi: potenziamento della rete di monitoraggio delle acque sotterranee di Roma

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Riassunto

Questo articolo propone una metodologia di gestione del monitoraggio delle acque sotterranee in area urbana mediante un apposito sistema di data entry installata su dispositivi mobili direttamente sul campo e un database geografico relazionale che consente la visualizzazione e l'interrogazione dei dati tramite apposita interfaccia web.
L'area di studio è la città di Roma, dotata di un sistema di monitoraggio capillare che prevede una rete costituita da circa 150 fra piezometri e pozzi, al momento monitorati in discreto. Il metodo proposto si avvale della piattaforma Entreprise cloud (ESRI, 2024) gestita da ISPRA-SNPA, che garantisce lo stoccaggio dei dati raccolti in un sistema cloud online e l'utilizzo di applicazioni Web. I dati delle serie temporali di livelli piezometrici e parametri chimico fisici quali temperatura, pH, conducibilità, sono consultabili liberamente mediante tabelle degli attributi, grafici ed elementi dell'interfaccia web. I risultati evidenziano ampie possibilità di ampliare la rete dei pozzi attivi che consentano di attingere alle risorse idriche sotterranee per azioni di adattamento ai cambiamenti climatici in atto.

Abstract

This paper proposes a methodology for managing groundwater monitoring directly in the field through a specific data entry system installed on mobile devices and a relational geographic database that allows the visualization and querying of data via a specific web interface. The study area is the city of Rome, where a monitoring system of approximately 150 piezometers and wells, currently manually monitored twice a year. The proposed method uses the Enterprise cloud platform (ESRI, 2024) managed by ISPRA-SNPA, which guarantees the repository of the data collected in an online cloud system and the use of Web applications. The data of the time series of levels and chemical-physical parameters such as temperature, pH, conductivity are freely accessible through attribute tables, graphs, and viewer elements. The results highlight numerous possibilities for expanding the network of active wells, enabling the use of groundwater resources for adaptation measures to address ongoing climate change.

Introduction

Urbanization is the leading global trend of our time, and groundwater from springs and wells has been essential for urban water supply since the earliest human settlements. Nowadays, the extraction of groundwater through deep wells equipped with submersible electric pumps has significantly supported urban expansion worldwide. Factors driving groundwater usage include its reliability for municipal supply, its accessibility for private use, the declining security of river intakes due to pollution, and the relatively low cost for the construction of water wells. The substantial natural storage capacity of most aquifer systems is vital for ensuring water supply security during droughts and will be crucial for future climate change adaptation. Considering the ongoing changes in groundwater usage in 'urban aquifers' and the hydrogeologic uncertainty in accurately predicting their behavior, it is advisable to implement an 'adaptive management approach' for urban groundwater resources (Howard et al., 2015). This approach should rely on continuous monitoring of groundwater levels and quality and should be directed by a numerical aquifer model that is periodically updated (Howard et al., 2015). Furthermore, accurate and comprehensive data collection is essential for resource planning and the sustainable management of groundwater resources. This planning must account for the variability of urban groundwater systems, which are subject to changes in hydrogeological conditions. These changes are directly influenced by the combined effects of anthropogenic activities and the specific characteristics of the geological, hydrogeological, and hydrological conditions (Lo Russo & Taddia, 2009).

As highlighted in the review work made by La Vigna (2022), only a few cities have a dedicated groundwater monitoring network, even if the number of drillings and water wells is typically high and widely distributed. However, city-scale groundwater monitoring is a reality in some places. For instance, Miami (Florida, USA) has a real-time monitoring network managed by the US Geological Survey (Prinos et al., 2002). In Beijing (China), a monitoring network has been operating since the 1960s, providing comprehensive data on water table behavior despite some operational interruptions (Zhou et al., 2013). The metropolitan government of Seoul (South Korea) has maintained a local groundwater monitoring network of 119 wells to track changes in groundwater quantity and quality since 1997 (Lee et al., 2005). Cardiff (UK) monitors groundwater levels and temperature, partly to control thermal variations from shallow open-loop ground-source heat pumps (Patton et al. 2020). Bucharest (Romania) and Glasgow (UK) also have established monitoring networks (Bonsor et al., 2017; Gaitanaru et al., 2017). Additionally, Dutch and German cities have significant monitoring networks, with Amsterdam (The Netherlands) having over 2,500 bimonthly measured stations (Bonsor et al., 2017) and Munich (Germany) having nearly 500 monitoring wells (Menberg et al., 2013).

The monitoring activity carried out within the framework of the agreement between ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale – Italian Institute for Environmental Protection and Research) and Roma Capitale (Municipality of Rome) provides the periodic and systematic measurement of the approximately 150 water wells owned by the City administration. Moreover, the development of an open access online data visualization and consultation system guarantees an important monitoring and control activity with respect to the quantity of groundwater resources.

The subsoil of Rome hosts a large quantity of water. Through sustainable use and in accordance with Goal 6 of the Sustainable Development Goals of the United Nations, groundwater can contribute to urban resilience:

- providing a fundamental resource for the maintenance of existing green areas and the design of further "green infrastructures" for better adaptation to the evolving climate.
- promoting a widespread use of geothermal heat pumps, which could be highly efficient exploiting the slightly anomalous aquifer temperatures due to the volcanic and tectonic context in which the city is located, thus contributing to reducing energy consumption and climate-altering emissions.
- knowing the geometry of the aquifers in greater detail to define areas where the natural infiltration of excess rainwater towards local aquifers could be promoted, lightening the artificial drainage networks and recharging the aquifers (Lentini et al., 2022).
- being able to use groundwater resources with greater awareness and sustainability thanks to the new synthesis of knowledge in those sectors of the Rome area where a strong agricultural vocation is maintained.

Data and Methods

Site description

The Rome water supply withdrawals within the city represents only a modest part of its drinking water needs: the distribution networks are mainly fed by sources located in the Apennines (Boni & Bono, 1996). However, significant water resources are stored underground in the vast urban center. These resources are contained in volcanic and alluvial aquifers, which create a rather complex groundwater circulation paths and in some cases even overlap (Mazza et al., 2016; La Vigna et al., 2016; La Vigna et al., this volume).

The hydrogeological structure and the groundwater circulation of Rome are conditioned by the presence of a complex low permeability aquiclude, the geological structure with the consequent water exchange relationships between five different hydrogeological units, and the presence of two perennial watercourses (Capelli et al., 2008, La Vigna et al., 2016). The Hydrogeological Units (HUs) characterizing the Roman area are: Sabatini Mountains and Alban Hills HU (both volcanic), pre-volcanic continental deposits HU, recent and current alluvial deposits HU, and the Tiber River Delta HU (La Vigna et al., 2016). These HUs are underlain by a hydrogeological complex with very low permeability values (marine orgin clays of Pliocene age).The depressions and structural elevations of the basal aquiclude, together with the different permeabilities that characterize the hydrogeological units, determine the complex groundwater circulation under the city.

In particular in the city area of Rome, 4 main groundwater circulations can be identified (Mazza et al., 2016): the main Regional aquifer, the Shallow and the deep aquifers of the Alban Hills area, and the Confined aquifer in the basal gravel of the Tiber River (Fig. 1). According to this brief hydrogeological description, Rome can be considered primarily as a Volcanic Groundwater City and secondarily as a Lagoon Delta Groundwater City (La Vigna, 2022).

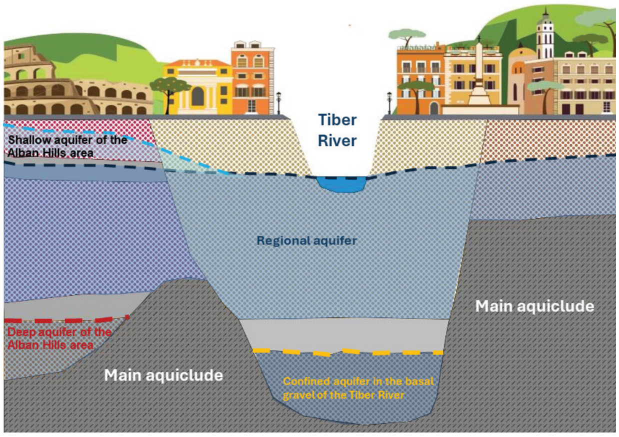

Fig. 1 - Schematic conceptual model of groundwater circulation under Rome urban area (proportions and distances not to scale).

Fig. 1 - Modello schematico di circolazione idrica sotterranea al di sotto dell'area urbana di Roma (proporzioni e distanze non in scala).

Description of the monitoring network and activities

The monitoring stations are mostly constituted of wells and subordinately piezometers, mainly owned by the Municipality of Rome. Most of the wells are used for irrigation systems of green areas, while the piezometers are related to previous groundwater investigation projects for various purposes.

The stations are well distributed in the city area due to the many green spaces existing in Rome. The altitude of the water table varies based on the reference aquifer from about 95 m above sea level to about 10 m below sea level; due to the orographic conformation of Rome, the elevation of the stations varies from about 120 m above sea level to about 2 m above sea level moving towards the Tyrrhenian Sea. The distribution and the different depth and location of the monitoring stations allow to have monitor points located in three of the main aquifers (Fig. 1).

The monitoring activity takes place periodically (through manual measurements) twice a year, respectively between the months of April and May (wet period) and between October and November (dry period).

In particular, the groundwater levels in the wells and piezometers are measured. Where it is possible, the basic chemical-physical characteristics of the water (temperature, pH, specific electrical conductivity, dissolved oxygen and redox potential) are monitored through sampling by the existing pump or by bailers. The monitoring network is currently not used for systematic quality assessments because the monitoring network for such sampling is managed by another environmental agency. Moreover, most of these stations are not suitable for quality sampling according to Italian legislation because they are often long inactive and the existing pump out of order.

The monitoring network is the result of the census of the measurement stations that are summarized in Figure 2. To date, 216 stations have been registered, of which: a) 148 measurable/sampleable stations; b) 46 stations not accessible at the moment; c) 22 stations accessible but currently not measurable.

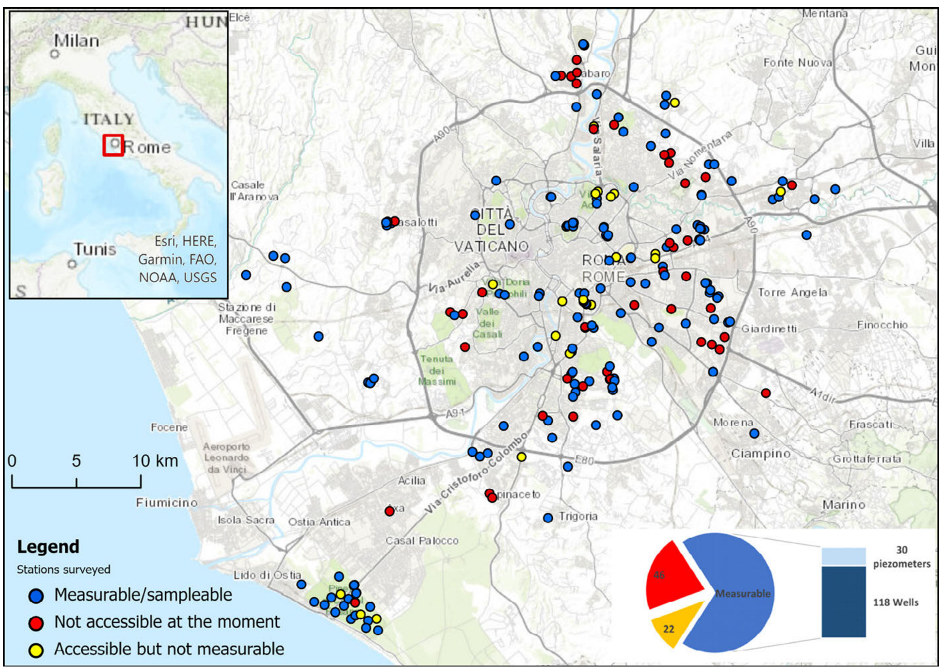

Fig. 2 - Measuring stations recorded during the census.

Fig. 2 - Stazioni di misura rilevate nel censimento.

Of the 148 stations available todate: a) 30 are piezometers; b) 118 are water wells.

Of the water wells, 25 are clearly active, 23 are clearly not used due to the lack of pump or connection to the electricity network, while for the others it was not possible to define their relative state of activity. Although these wells are equipped with a pump and apparently connected to an electricity network and with pipes installed, it is not clear whether they were ever put into operation or how long they have been out of service.

Workflow and data structure

The information from the monitoring network and the historical data measured at these stations in Rome formed the initial database. The information associated with the network points is therefore collected in a relational geographic database and resides in the respective alphanumeric tables. Specifically, the administrative and technicalinformation of the network points is collected in the attribute table associated with the point layer (Fig. 3). The general information about the points includes the typological description of the artifact structure and all data related to the aquifer.

The measurements of hydrogeological parameters, both historical and recently acquired during periodic measurement campaigns, are stored in a dedicated table (Fig. 4) and linked to the points through a unique and global key (GUID) with a "one-to-many" cardinality (1:n; one point:many measurements). The data collected periodically at each station in the network consists of measuring the depth of the piezometric surface, which is automatically converted to absolute height above sea level, as well as the main chemical-physical parameters of the aquifer: temperature, pH, electrical conductivity, dissolved oxygen, and redox potential. Similarly, it is also possible to collect photographic material associated with the monitoring network point in a dedicated system table.

The geodatabase actually resides on the ESRI Enterprise cloud platform managed by ISPRA-SNPA (Istituto Superiore per la Protezione e la Ricerca Ambientale - Sistema Nazionale per la Protezione dell'Ambiente – Italian Institute for Environmental Protection and Research – National System for Environmental Protection). The geospatial platform is a browser-based GIS system that allows for the creation of maps, data analysis, and sharing of results (ESRI, 2024). It is a set of online tools that enable the management and analysis of geographic and alphanumeric data, along with the publication of map services.

Starting from the Enterprise Geodatabase (DataStore), a point-based information layer dedicated to the monitoring network (Feature Layer) was created, which contains both the network points and the related table for data collection (Fig. 5). The Feature Layer, once configured and prepared in dedicated WebMaps useful to visualize the three different hydrogeological field survey groups, is fully managed by field apps installed on mobile devices. This setup allows for the updating of information related to the monitoring network points and the data periodically collected directly in the field. Using the same Feature Layer and a dedicated WebMap, a webGIS tool is simultaneously created for free consultation of the data related to the network points through specific widgets, including graphical representations.

In the future, the same working group could apply the same methodology for the census of springs in the territory of Rome and the relative monitoring of some of them.

Results

The main result of the presented monitoring activity is the developed web application. The data are displayed and can be analyzed via a special open access viewer designed for consulting information regarding both the basic

Pozzi e piezometri | Piezometria (m s.l.m.) | Complessi idrogeologici | misure

Opzioni ▾ Filtro per estensione mappa Zoom a Cancella selezione Aggiorna

Sigla/label	Località	Municipio	Tipo prospezione	Profondità raggiunta	Quota misura GPS	Ente gestore	Stato di attività	Utilizzo	Codice DB Roma Capitale	Data ultimo rilevamento	Falda misurata	Profondità media livello piezometrico	Allegati
P0101	San Sisto 1	Municipio I	Pozzo per acqua	22,00	25,94	ROMA CAPITALE	Attivo	Pubblico	PZ0035	20/11/2023, 2:21:23 PM	Falda Regionale	Mostra	3 file
P0102	San Sisto 2	Municipio I	Pozzo per acqua	42,30	22,63	ROMA CAPITALE			PZ0036	20/11/2023, 2:19:57 PM	Falda Regionale	Mostra	3 file
P0103	San Sisto 3	Municipio I	Pozzo per acqua	12,00	24,94	ROMA CAPITALE	Attivo	Pubblico	PZ0037	20/11/2023, 2:32:59 PM	Falda Regionale	Mostra	3 file
P0105	Parco S.Sebastiano 1	Municipio I	Pozzo per acqua	69,00	33,90	ROMA CAPITALE	Non in uso	Pubblico	PZ0022	20/11/2023, 2:55:10 PM	Falda Regionale	Mostra	2 file
P0106	Parco S.Sebastiano 2	Municipio I	Pozzo per acqua	65,00	29,54	ROMA CAPITALE			PZ0023	20/11/2023, 3:03:38 PM	Falda Regionale	Mostra	2 file

Fig. 3 - Table of general attributes for each individual monitoring station. Main attributes in the table: code, type of artifact, depth of the work, elevation measured with Global Position System (GPS), activity status, type of use, investigated aquifer.

Fig. 3 - Tabella degli attributi generali per ogni singola stazione di monitoraggio. Principali attributi nella tabella: codice, tipo di manufatto, profondità dell'opera, quota misurata con GPS, stato di attività, tipologia di utilizzo, falda investigata.

Pozzi e piezometri | Piezometria (m s.l.m.) | Complessi idrogeologici | misure

Opzioni ▾ Filtro per estensione mappa Zoom a Cancella selezione Aggiorna

Data/ora	Tipo misura	Profondità livello piezometrico	Quota falda (s.l.m.)	Temperatura	pH	Conducibilità	TDS Residuo fisso
8/5/2023	Rilevamento parametri	24,50	27,15	17,60	6,42	705,00	458,00
8/5/2023	Rilevamento parametri	29,07	17,39	17,70	6,53	1.033,00	688,00
8/5/2023	Rilevamento parametri	35,02	16,89	17,30	6,53	647,00	420,00
8/5/2023	Rilevamento parametri	11,55	19,14	18,00	6,58	904,00	592,00
8/5/2023	Rilevamento parametri	29,57	18,49	17,30	6,54	840,00	547,00
8/5/2023	Rilevamento parametri	8,83	15,60	17,80	6,51	461,00	299,00
10/5/2023	Rilevamento parametri	21,20	19,57	16,50	6,28	762,00	496,00
10/5/2023	Rilevamento parametri	20,50	19,33	17,23	6,53	830,00	540,00

Fig. 4 - Table of measurements for each individual monitoring station. Main attributes of this table: measurement date, depth of the piezometric surface and its height above sea level, temperature (°C), pH, electrical conductivity.

Fig. 4 - Tabella delle misure per ogni singola stazione di monitoraggio. Principali attributi di questa tabella: data di misura, profondità e quota della falda, temperatura (°C), pH, conducibilità elettrica.

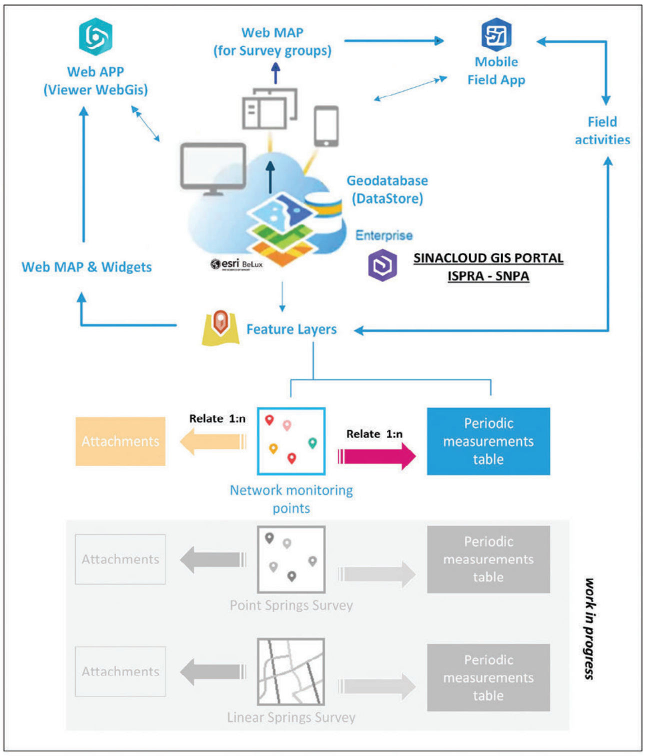

Fig. 5 - Workflow diagram and used GIS system (ESRI, 2024, modified).

Fig. 5 - Diagramma del flusso di lavoro e sistema GIS utilizzato (ESRI, 2024, modificato).

hydrogeological setting (hydrogeological complexes, water table) and the monitoring network; through the navigation of a dedicated map and the use of specific tools, the information and periodic measurements recorded can be reached (Fig. 6).

To optimize the acquisition operations by survey teams, a data entry system was developed for collecting and storing data directly in the field (ESRI, 2023). Through the use of an application installed on mobile devices (Fig. 7) and three different maps for the three survey groups (ISPRA & Roma Capitale teams), it is possible to send the data of the measured hydrogeological parameters in real time to the

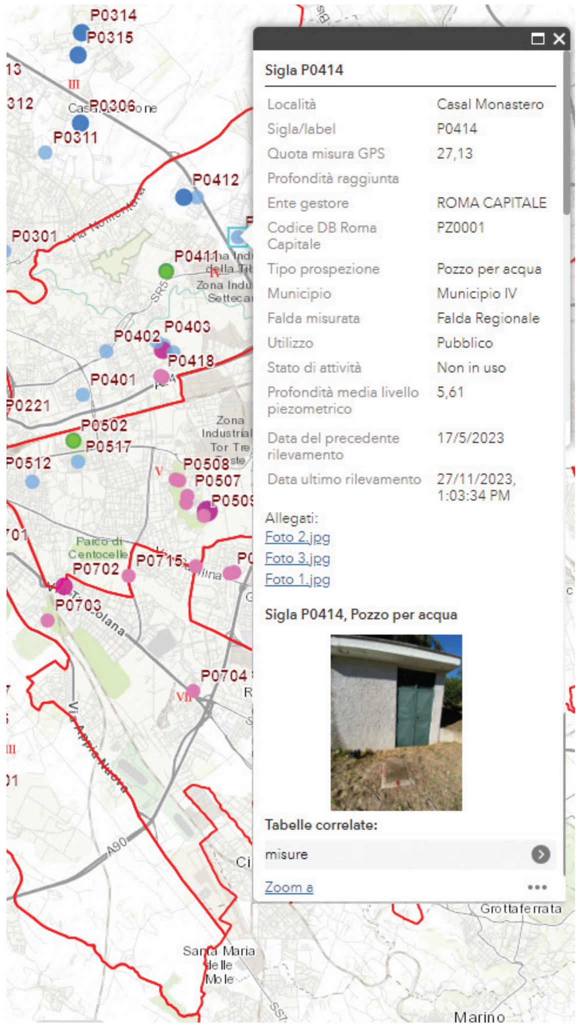

Fig. 6 - Map viewer for consultation with response system via pop-up window.

Fig. 6 - Map viewer di consultazione con sistema di risposta mediante finestra pop-up.

reference geodatabase and insert other general information, such as update of technical details of the artifacts, photos, and annotations.

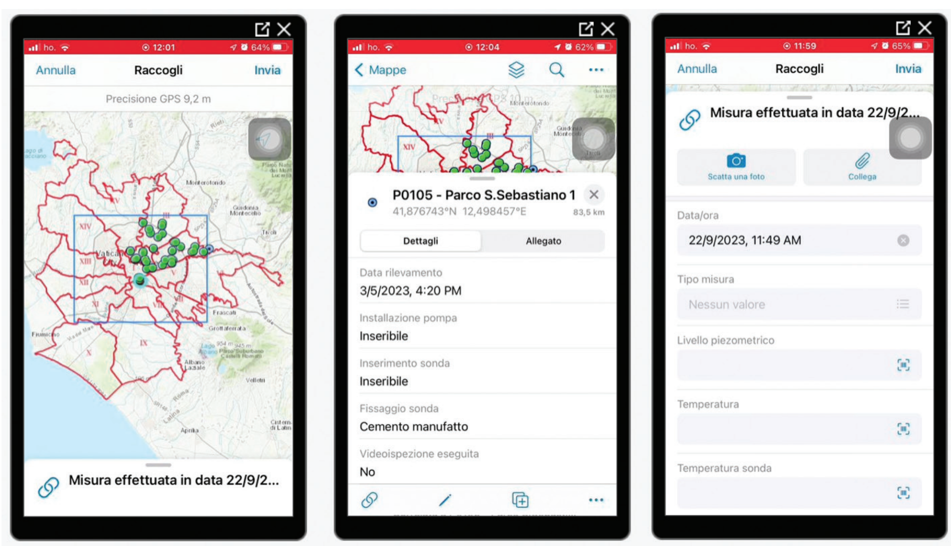

Fig. 7 - Field Map application (ESRI, 2023) interface used for the collection of hydrogeological data on the field.

Fig. 7 - Interfaccia dell'applicazione Field Map (ESRI, 2023) utilizzata per il rilevamento dei dati idrogeologici in campo.

Discussion

The irregular frequency of the monitoring in the years does not yet allow to make assessments on the quantitative and qualitative state of the groundwater resources in Rome. However, the web-gis visualization and consultation system has been set to highlight the deviations of the measured groundwater levels from the average of the historical time series, giving a rough indication of possible general trends. Specifically, in Figure 8 the blue points indicate values with a measured level above the average, the green ones indicate a stable groundwater level, and the violet ones represent levels below the average. In this way, the user can immediately see the scenario related to the groundwater level trend relating to an initial survey and first data collected (Fig. 8 – Working group ISPRA & Roma Capitale); further processing and elaborations based on periodic surveys can be compared. The rising water table visible in the Figure 8 is a phenomenon sometimes interfering also with heritage and historical sites in the city (Mastrorillo et al., 2016) and the possibility to monitor and quickly visualize this trend is surely helpful for the important roman heritage protection.

The groundwater monitoring network, as previously mentioned, is primarily designed for quantitative purposes, although temperature, pH, and electrical conductivity data are also recorded during surveys. For instance, in the coastal sector, monitoring has shown that electrical conductivity values are higher near the coast, indicating increased salinity, and gradually decrease further inland, reflecting freshwater influence (Capelli et al., 2007). In deeper piezometers, conductivity increases significantly, suggesting the saltwater wedge is approaching or has already reached these depths. Nevertheless, the observed average rise in piezometric levels in this vulnerable area (Fig. 8) is a positive signal, helping the mitigation of the effects of saltwater intrusion. Furthermore, both artificial and natural channels have been identified as key pathways for seawater intrusion, especially during dry periods, high tides, storm surges, and strong winds, which contribute to the inland movement of the saltwater interface (Manca et al., 2014).

The groundwater temperature monitoring data will become increasingly relevant as the use of ground heat pumps expands, particularly in interactions with Rome's urban local aquifers (ULAs), and in assessing potential heat island effects on the aquifers.

For every monitoring station, through a specific widget of the web-gis application, it is possible to graphically display the historical piezometric level measurements and the measurements of the basic chemical-physical parameters measured: temperature, pH and electrical conductivity. Figure 9 shows the monitoring network points selected based on the aquifer they refer to. With the figures 10, 11 and 12 the water table variations related to the monitoring period are shown respectively for the Regional Aquifer, for the Shallow Aquifer of the Alban Hills sector, and for the Confined aquifer within the basal gravels of the Tiber River. As previously stated, due to the not continuous monitoring period and to the too short time series, deep considerations cannot be made on the groundwater level variations. A possible seasonal variation in

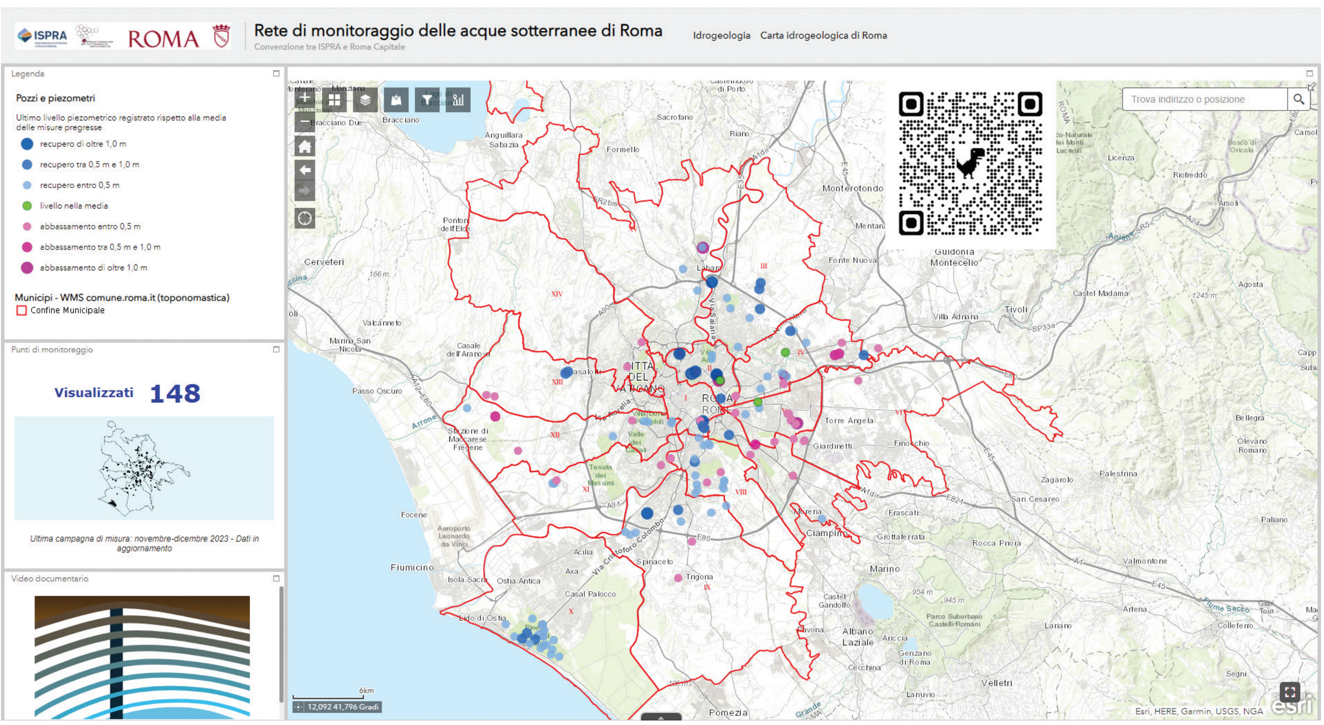

Fig. 8 - Data viewer from web-gis. The blue points indicate values with a level measured above the average, the green points indicate a stable groundwater level, and the violet ones represent levels below the average.

Fig. 8 - Visualizzatore dei dati da web-gis. I punti blu indicano che la falda ha una quota sopra la media, i punti verdi una quota della falda pressoché stabile mentre i punti viola indicano un livello di falda sotto la media.

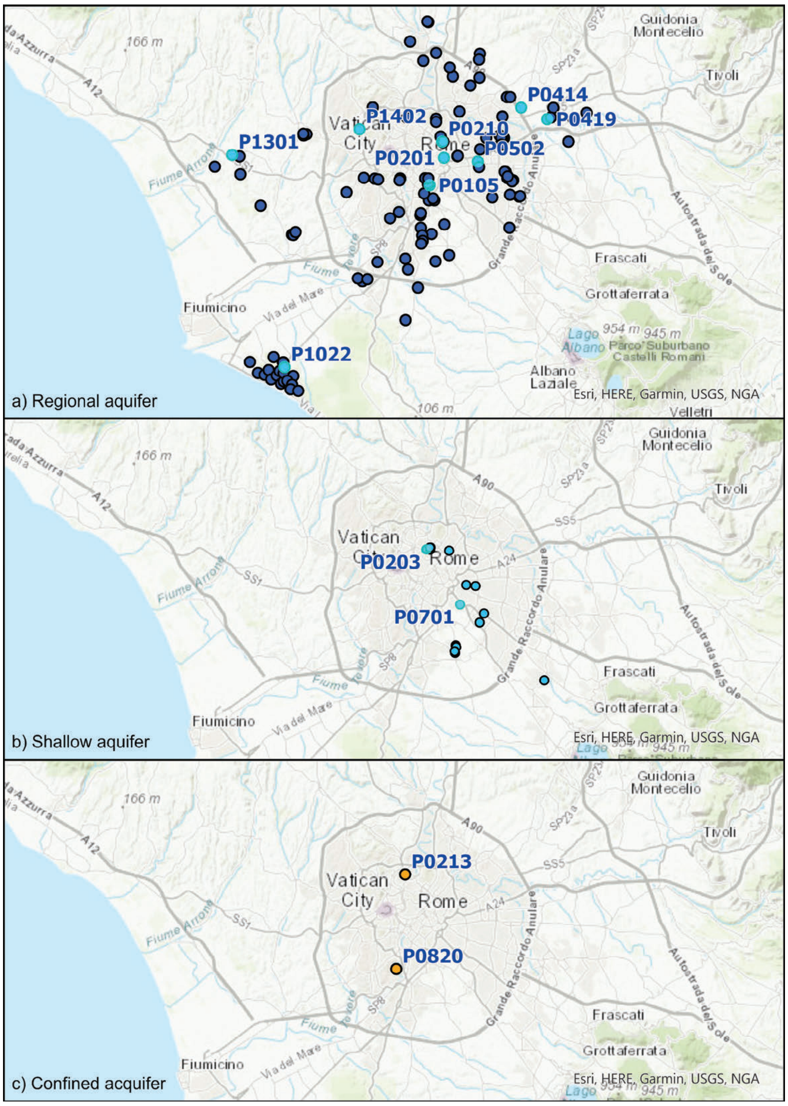

Fig. 9 - Monitoring points for: a) regional aquifer; b) Alban Hills shallow aquifer; c) confined aquifer within the basal gravels of the Tiber River. The highlighted and labeled points are represented with the water table level in the respective graphs of figures 10, 11 and 12.

Fig. 9 - Punti di monitoraggio per: a) falda regionale; b) falda superficiale del settore albano: c) falda confinata delle ghiaie di base del fiume Tevere. I punti evidenziati e con etichetta sono rappresentati con il livello di falda nel rispettivo grafico di figura 10, 11 e 12.

the last 4 years of the monitoring period is visible, as well as some outliers probably related to dynamic conditions of the water table at the time of the singular measurement.

This system, in addition to allowing the immediate acquisition of data, guarantees the homogeneity of the parameters acquired by the different survey teams through appropriate compilation constraints.

Conclusions

In conclusion, groundwater monitoring is particularly important for several reasons. The city is a place where several infrastructures but also the anthropic pressure in term of contamination and resources withdrawals interact with the subsoil. Therefore, it is important to learn as much up-to-date information as possible about groundwater levels, their fluctuations, and their quantitative and qualitative status. Although the water supply in Rome is managed via aqueducts that draw mainly from karst springs located in the Apennine chain far away from the city, ULAs (La Vigna et al., this volume) are still used and can be further used for industrial to irrigation purposes.

From this perspective, the knowledge and sustainable use of water resources stored in local aquifers can take on strategic significance for actions aimed at:

- mitigating urban heat islands in the summer period, using groundwater for the irrigation of green spaces and allowing them to remain alive and provide their heat mitigation effect;
- promoting the natural infiltration of excess rainwater towards local aquifers, lightening the artificial drainage networks and recharging the aquifers themselves (Lentini et al., 2022).

Monitoring these resources, therefore, is a valuable knowledge tool. The presented web-gis interface allows to reach both general information and measured data from the measuring stations. In an intuitive way it is possible to immediately shape, even in graphic form, the trend of the main hydrogeological parameters measured over time. These parameters provide important indications on the circulation of groundwater and therefore constitute an important useful tool for the decision-making processes of city administrators.

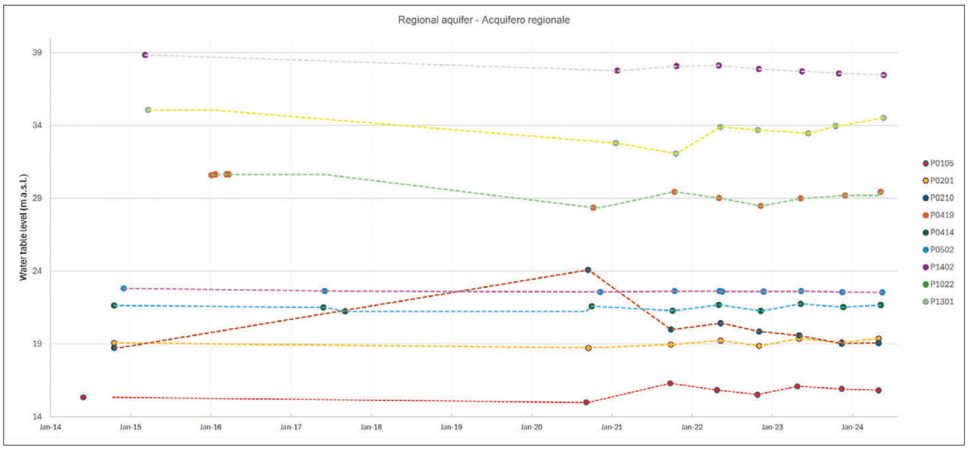

Fig. 10 - Graph of the measured water table of the regional aquifer. The monitoring points are highlighted in figure 9a.

Fig. 10 - Grafico del livello di falda dell'acquifero regionale. I punti di monitoraggio sono evidenziati nella figura 9a.

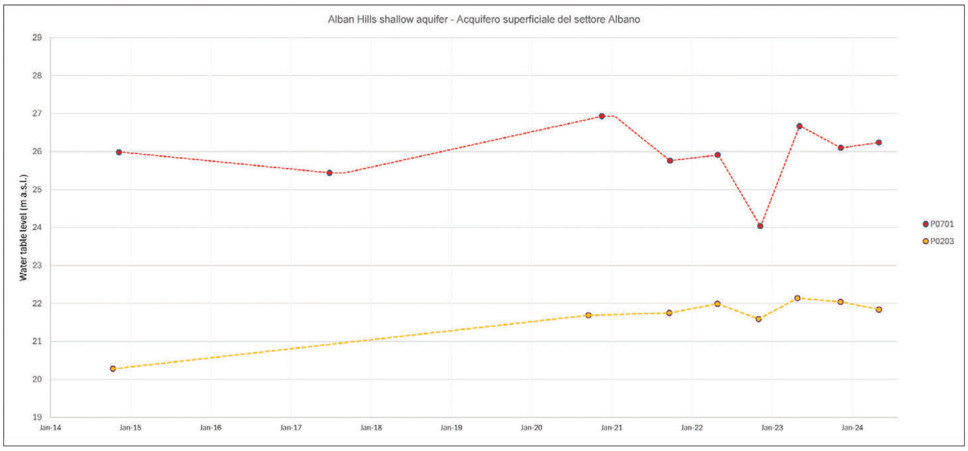

Fig. 11 - Graphs of the measured water table of the Alban Hills shallow aquifer. The monitoring points are highlighted in figure 9b.

Fig. 11 - Grafico del livello di falda dell'acquifero superficiale del settore Albano. I punti di monitoraggio sono evidenziati nella figura 9b.

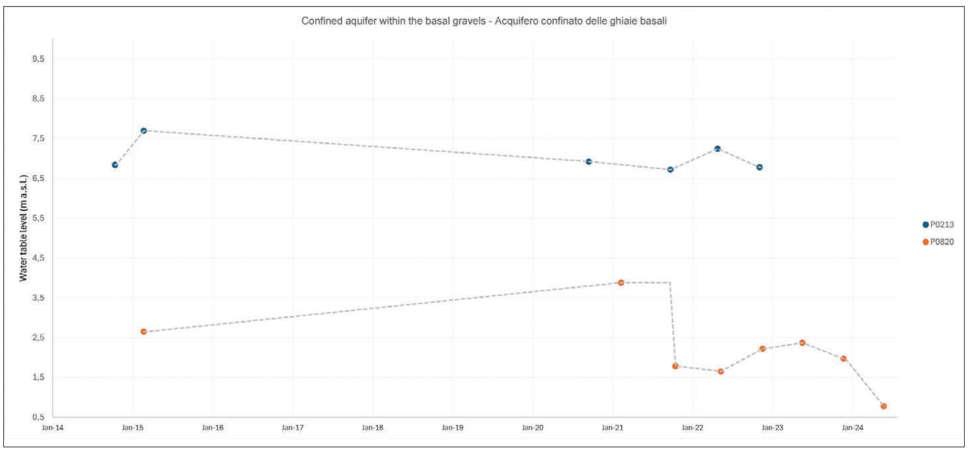

Fig. 12 - Graph of the measured water table of confined aquifer within the basal gravels of recent alluvial deposits. The monitoring points are highlighted in figure 9c.

Fig. 12 - Grafico del livello di falda dell'acquifero in pressione delle ghiaie di base delle alluvioni recenti. I punti di monitoraggio sono evidenziati nella figura 9c.

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Competing interest

The authors declare no competing interests.

Author contributions

Mauro Roma, database development, main writing, co-authors coordination. Valerio Vitale, Rossella Maria Gafà, Claudio Papiccio and Francesco La Vigna, writing and review. Isidoro Bonfà, Maria Pia Congi, Lucio Martarelli, Gennaro Maria Monti and Angelantonio Silvi specific contribution on their role in the monitoring system, and text review.

All authors have read and agreed to the final version of the manuscript.

Additional information

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REFERENCES

Bono, P., & Boni, C. (1996) Water supply of Rome in antiquity and today Environmental Geology, 27, 126–134. https://doi.org/10.1007/BF01061685

Bonsor, H., Dahlqvist, P., Moosman, L., Classen, N., Epting, J., Huggenberger, P., Garica-Gil, A., Janza, M., Laursen, G., & Stuurman, R. (2017) Groundwater, geothermal modelling and monitoring at city-scale: Reviewing european practice and knowledge exchange: Tu1206 cost sub-urban wg2 report.

Capelli, G., Mazza, R., & Papiccio, C. (2007) Intrusione salina nel Delta del Fiume Tevere. Geologia, idrologia e idrogeologia del settore romano della piana costiera. *"Seawater Intrusion in the Tiber River Delta. Geology, Hydrology and Hydrogeology of the Roman Sector of the Coastal Plain"*, Giornale di Geologia Applicata, 5, 13-28.

ESRI (2024) ArcGIS Enterprise. Deliver industry-leading mapping and analytics to your infrastructure and the cloud. Online resources: https://enterprise.arcgis.com/en/. ESRI BeLux: https://images.app.goo.gl/S8qEhcXKA7tbPcXeA (accessed on 14 September 2024).

ESRI (2023) Collect data in Field Maps. Field Operation. Online resources: https://www.esri.com/arcgis-blog/products/field-maps/field-mobility/try-data-collection-in-arcgis-field-maps/ (accessed on 14 September 2024).

Gaitanaru, D., Gogu, C. R., Boukhemacha, M. A., Litescu, L., Zaharia, V., Moldovan, A., & Mihailovici, M. J. (2017) Bucharest city urban groundwater monitoring system. Procedia engineering, 209, 143-147.

Howard, K. W. F., Hirata, R., Warner, K., Gogu, R., & Nkhuwa D. (2015) Resilient Cities & Groundwater. In IAHStrategic Overview Series; Foster, S., & Tyson, G., Eds.; International Association of Hydrogeologists: London, UK. Available online: https://www.iges.or.jp/en/pub/resilient-cities-groundwater/en (accessed on 15 June 2022).

La Vigna, F., Alberti, L., Da Pelo, S., Ducci, D., Fabbri, P., Gargini, A., Lasagna, M., Pappalardo, G., Polemio, M., & Rusi S. (2024) Exploring the aquifers shaping Italy's sub-urban landscape. Acque Sotterranee – Italian Journal of Groundwater. https://doi.org/10.7343/as-2024-806

La Vigna, F. (2022) Review: Urban groundwater issues and resource management, and their roles in the resilience of cities. Hydrogeol J., 30, 1657–1683. https://doi.org/10.1007/s10040-022-02517-1

La Vigna, F., Bonfà, I., Coppola, A. G., Corazza, A., Di Filippo, C., Ferri, G., Martelli, S., Rosa, C., & Succhiarelli, C. (2016) 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, 4(4), 59-70. DOI: 10.7343/AS-132-15-0159

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, R. M., Lacchini, A., Mancini, M., Martelli, S., Mastrorillo, L., Monti, G. M., Procesi, M., Roma, M., Sciarra, A., Silvi, A., Stigliano, F., & Succhiarelli, C. (2016) Groundwater of Rome. Journal of Maps, 12(sup1), 88–93. 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.

Lentini, A., Meddi, E., Galve, J. P., Papiccio, C., & La Vigna, F. (2022) Preliminary identification of areas suitable for Sustainable Drainage Systems and Managed Aquifer Recharge to mitigate stormwater flooding phenomena in Rome (Italy). Acque Sotterranee, 11(4), 43–53. https://doi.org/10.7343/as-2022-590

Lee, J. Y., Choi, M. J., Kim, Y.Y., & Lee, K. K. (2005) Evaluation of hydrologic data obtained from a local groundwater monitoring network in a metropolitan city, Korea. Hydrological Processes: An International Journal, 19(13), 2525-2537.

Lo Russo, S., & Taddia, G. (2009) Groundwater in the Urban Environment: Management Needs and Planning Strategies American Journal of Environmental Sciences, 5(4):494-500. DOI:10.3844/ajessp.2009.493.499

Manca, F., Capelli, G., La Vigna, F., Mazza, R., & Pascarella, A. (2014) Wind-induced salt-wedge intrusion in the Tiber River mouth (Rome–Central Italy). Environmental Earth Sciences, 72, 1083-1095.

Mastrorillo, L., Mazza, R., Tuccimei, P., Rosa, C., & Matteucci, R. (2016) Groundwater monitoring in the archaeological site of Ostia Antica (Rome, Italy): first results. Acque Sotterranee - Italian Journal of Groundwater, 5(1). https://doi.org/10.7343/as-2016-192

Mazza, R., La Vigna, F., Capelli, G., Dimasi, M., Mancini, M., & Mastrorillo, L. (2015) Hydrogeology of Rome. Acque Sotterranee - Italian Journal of Groundwater, 4(4). https://doi.org/10.7343/as-129-15-0156

Mazza, R., & Mastrorillo, L. (2013) L'idrogeologia regionale nella pianificazione e gestione della risorsa idrica sotterranea. Il dominio vulcanico laziale (Italia centrale) *"Regional hydrogeology for groundwater resource management policies. The Latium volcanic domain (central Italy)"*. Acque Sotterranee - Italian Journal of Groundwater, 2(4), 41-53. https://doi.org/10.7343/as-050-13-0077

Menberg, K., Bayer, P., Zosseder, K., Rumohr, S., & Blum, P. (2013). Subsurface urban heat islands in german cities. Science of the total environment, 442, 123-133.

Patton, A., Farr, G., Boon, D., James, D., Williams, B., James, L., Kendall, R., Thorpe, S., Harcombe, G., & Schofield, D. (2020) Establishing an urban geo-observatory to support sustainable development of shallow subsurface heat recovery and storage. Quarterly Journal of Engineering Geology and Hydrogeology, 53(1), 49-61.

Prinos, S. T., Lietz, A., & Irvin, R. (2002) Design of a Real-Time Ground-Water Level Monitoring Network and Portrayal of Hydrologic Data in Southern Florida. U.S. GEOLOGICAL SURVEY Water-Resources Investigations Report 01-4275. Prepared in cooperation with the SOUTH FLORIDA WATER MANAGEMENT DISTRICT. 108 pp.

Zhou, Y., Dong, D., Liu, J., & Li, W. (2013) Upgrading a regional groundwater level monitoring network for Beijing plain, China. Geoscience Frontiers, 4(1), 127-138.

Working group ISPRA, & Roma Capitale (2023) https://www.isprambiente.gov.it/it/attivita/suolo-e-territorio/idrogeologia/monitoraggio-acque-sotterranee-di-roma-capitale