DOI 10.7343/as-2021-527

ACQUE SOTTERRANEE
Italian Journal of Groundwater
journal homepage: https://www.acquesotterranee.net/

2021-AS39-527: 35 - 46

Resilience to climate change: adaptation strategies for the water supply system of Formia and Gaeta (Province of Latina, Central Italy)

Resilienza ai cambiamenti climatici: strategie di adattamento per il sistema idrico di Formia e Gaeta (Provincia di Latina, Italia Centrale)

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ARTICLE INFO

Ricevuto/*Received*: 17 July 2021
Accettato/*Accepted*: 22 December 2021
Pubblicato online/*Published online*: 30 December 2021

Handling Editor:
Matteo Cultrera

Citation:
Lentini A, De Caterini G, Cima E, Manni R, Della Ventura G (2021) Resilience toclimate change: adaptation strategies for the water supply system of Formia and Gaeta (Province of Latina, Central Italy) - *Italian Journal of Groundwater*, 10(4), 35 - 46
https://doi.org/10.7343/as-2021-527

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Keywords: *coastal aquifers, climate change, resilience, groundwater supply, monitoring.*

Parole chiave: acquiferi costieri, cambio climatico, resilienza, approvviggionamento acque sotterranee, monitoraggio .

Riassunto

L'acquedotto che alimenta i comuni di Formia, Gaeta (provincia di Latina) di competenza del Servizio Idrico Integrato "ATO 4", si approvvigiona da due importanti sorgenti carsiche alimentate dalla struttura carbonatica dei Monti Aurunci occidentali: le sorgenti Mazzoccolo e Capodacqua di Spigno, con portate medie di 1100 l/s e 1300 l/s rispettivamente.

Nonostante queste fonti di approvvigionamento siano state utilizzate già in epoca romana e siano caratterizzate da un'acqua di ottima qualità, la variazione del regime delle precipitazioni, probabilmente collegata a cambiamenti climatici a più grande scala, ha causato ed accentuato nel tempo le seguenti problematiche: la diminuzione delle portate (causata dalla riduzione ciclica delle piogge invernali) e l'intensificazione dei fenomeni di torbidità (a seguito di piogge intense).

Per la mitigazione di questi problemi, che riguardano una popolazione residente di circa 150000 persone, Acqualatina S.p.A. (gestore del servizio idrico), ha promosso una serie di studi geologici e idrogeologici per migliorare la conoscenza del sistema geologico e per trovare ulteriori fonti di approvvigionamento che vadano a rinforzare il sistema esistente. La strategia è stata quella dell'incrementare la diversificazione delle fonti di approvvigionamento idrico, con l'individuazione sul territorio di nuovi acquiferi, in modo da mitigare le problematiche sopracitate. In questo lavoro si presentano i risultati degli studi eseguiti prima e durante la realizzazione del campo pozzi, chiamato "25 Ponti" situato nella piana di Formia, nella zona costiera, consistenti nei dati idrogeochimici di 130 campioni di acqua sotterranea e del monitoraggio dell'andamento piezometrico. I dati mostrano una variazione stagionale della idrochimica delle acque regolata dall'emungimento, che, in alcuni periodi dell'anno, va ad interessare le riserve regolatrici. Tale stagionalità è stata riscontrata anche durante il monitoraggio effettuato in assenza di emungimento.

Abstract

The aqueduct serving the municipalities of Formia and Gaeta (Latina province, Italy), an area under the enforcement and control responsibility of "ATO 4" Autorità d'Ambito Territoriale Ottimale – (Integrated Urban Water Management Agency), is supplied by two important karst springs. These springs, fed by the western Aurunci Mountains system are known as Mazzoccolo and Capodacqua having an average flow rates of 1100 l/s and 1300 l/s, respectively.

Although these sources have been used since ancient Roman times and the quality of their water is excellent, variations in the precipitation regime, possibly related to worldwide climate changes, has exacerbated the following problems: a decrease in the flow rates of the springs caused by the reduction in winter rainfall, and an increase of turbidity due to concentrated rainfall events.

In order to mitigate these problems, which affect a resident population of about 150,000 inhabitants, Acqualatina S.p.A. - the water utility company - promoted a series of geological and hydrogeological surveys. These studies aim at increasing the knowledge on the geological setting and to find additional sources to improve the existing supply. Within the framework of these activities, we studied a strategy aimed at diversifying the water supply by identifying new exploitable aquifers in the area, to reduce the aforementioned problems. This paper presents the results of research carried out before and during the construction of the water well field "25 Ponti" located in the coastal area of the plain of Formia. The research consisted in laboratory analyses of 130 groundwater samples and in monitoring of piezometric trends. The data show a seasonal variation in groundwater chemical composition caused also by aquifer exploitation, which in some periods of the year affects the regulated reserves. This seasonal phenomenon was however present in absence of pumping.

Inroduction

Pumping groundwater in urbanised coastal zones is extremily complicate because of poor water quality and quantity (Eftimi et al. 2017; Kouzana et al. 2007); moreover, worldwide and local climate change affect the rainfall quantity, which may trigger saltwater intrusion towards fresh groundwater (Beretta 2021; Farina et al. 2016; Freeze and Cherry 1979; Lukač Reberski et al. 2020; Pardo-Igúzquiza et al. 2019). Therefore, groundwater pumping in coastal zone needs to be monitored in order to avoid an increase of ions concentrations carrying to a variation in time and space of water quality in the aquifers (Azonsi et al. 2003, Kouzana et al. 2007).

The aqueduct that serves the municipalities of Formia, Gaeta (province of Latina, Italy), under the responsibility of "ATO 4" Autorità d'Ambito Territoriale Ottimale - Integrated Urban Water Management Agency, is supplied by two important karst springs which are fed by the western Aurunci Mountains (Fig. 1); these springs are well known as "Mazzoccolo" (9.5 m asl) and "Capodacqua di Spigno" (44 m asl).

Fig. 1 - a) Location of the "25 Ponti" wells and springs. b) 'Capodacqua di Spigno' spring during the turbidity period (2017) at left and during the water scarcity (2018) at right. c) A panoramic picture of '25 Ponti' water wells. d) Map showing the localization of wells and piezometers (base map from "Open Street Map").

Fig. 1 - a) Localizzazione del campo pozzi "25 Ponti" e sorgenti b) La sorgente Capodacqua di Spigno durante il periodo di torbida (2017) a sinistra e durante la scarsità idrica (2018) a destra. c) Una panoramica del campo pozzi "25 Ponti". d) Mappa che mostra l'ubicazione dei pozzi e dei piezometri (base cartografica di Open Street Map).

These springs were already exploited in ancient Roman times because of the excellent quality of their waters; however, since the beginning of the '50s heavy rains induce turbidity phenomena (Fig. 2), according to reported observation (Baldi et al. 2005, De Caterini - Acqualatina spa, unpublished data, 2010).

Such behaviour of these springs, similarly to other karst ones in the central Apennine carbonate area, are therefore affected by occasional turbidity phenomena due to heavy rainfall and are characterised by a sudden increase of the piezometric level (up to 13m), (Sappa et al. 2013). The water system exploiting these springs was equipped with a series of settling tanks and with 5 km of sub-horizontal and oblique wells, however without solving the turbidity problem (De Caterini - Acqualatina spa, unpublished data, 2010).

The groundwater turbidity is caused by modifications of the rainfall regime which, over the years, have worsened due to climate change (Sappa et al. 2018; Serra 2020), and are accordingly associated with a decrease in springs flow rates caused by the cyclical rainfall reduction (Fig. 2).

As a result, these problems affect the efficiency of water supplies, inducing the water authorities to reduce the amount of fresh water in the summer when the flowrates are at minimum (but when consumption increases due to tourism) and to declare the water undrinkability following heavy rains (Lobo Ferreira et al. 2014).

When turbidity phenomena occur, the waters of these springs exceed the turbidity tolerance and bacteriological values, which, according to Italian legislation (Legislative Decree no. 31 of 2001, which implements EU Directive 98/83/EC), should be < 4 NTU and total absence of bacteriological colonies, respectively (Di Matteo et al. 2016).

The study area has a high groundwater supply potential. However, the existing aqueduct, due to the outlined problems so far, can no longer ensure the quality required by the public water supply.

In order to mitigate these problems, which are affecting a resident population of about 150,000 inhabitants, Acqualatina S.p.A. carried out several studies, in order to improve the knowledge of hydrogeological aspects and to find additional sources that would enhance the existing system. This strategy aims to diversify the groundwater supply by connecting the adjacent areas to the main water network; moreover, it may identify new aquifers, that are not affected by the aforementioned issues.

The purpose of this study aims to verify if the hydrochemical variations are due either to the groundwater exploitation or due to seasonal changes (Lee et al. 2006, Sappa et al. 2019, Jamaa et al. 2020); moreover, it would lead to the definition of possible saltwater intrusion.

Materials and Methods

Between April 2017 and July 2020 different works were carried out to strengthen the resilience of the system, including the drilling of "25 Ponti" drilled water wells (Fig. 1), located in the plain of Formia (near Vindicio beach) in a)

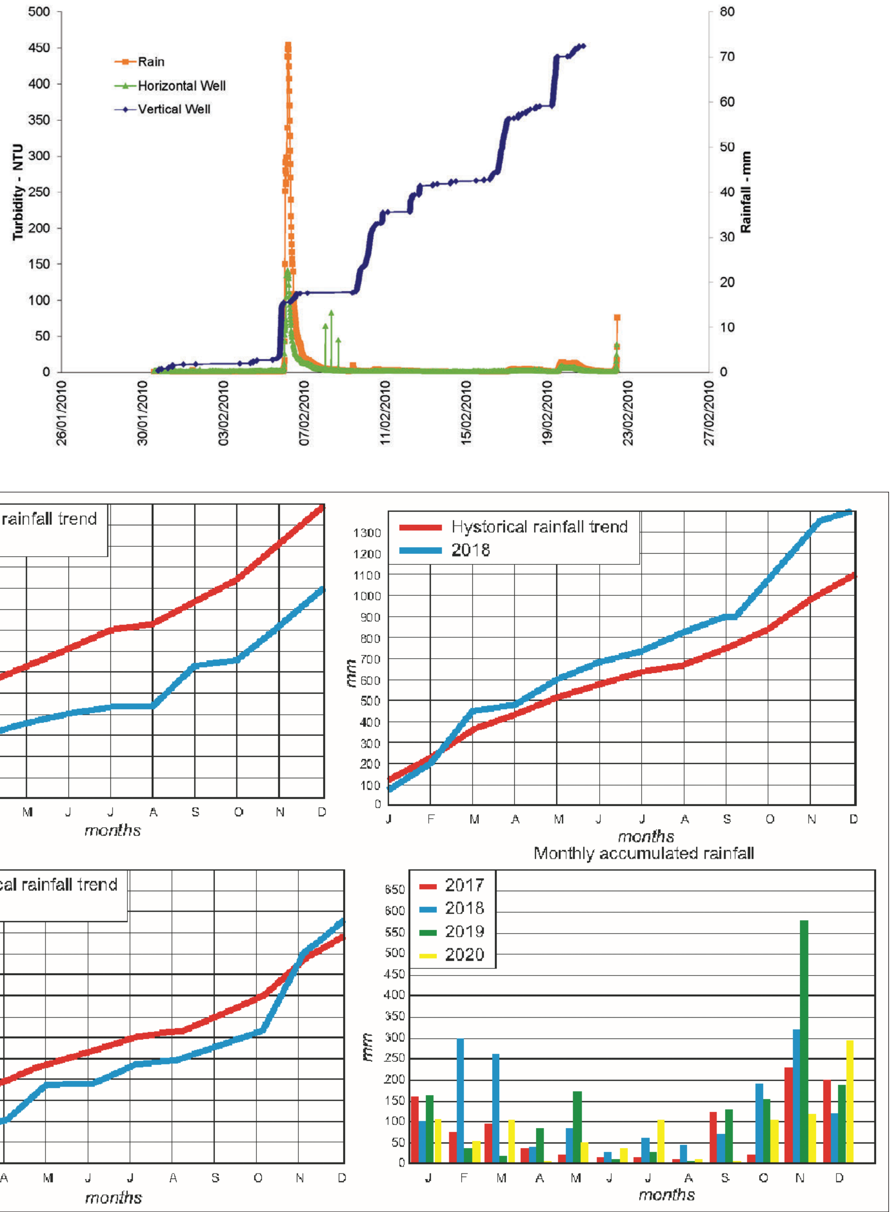

Fig. 2 - The diagram a) Shows the correlation between turbidity and intense rainfalls. b) The first three diagrams compare the accumulated rainfalls (mm) in the reference year with the historical mean, while the fourth diagram shows monthly accumulated rainfalls (mm) from January 2017 to April 2020. Graphs elaborated using the data from the SIARL Arsial portal http://www.arsial.it/

Fig. 2 - Il grafico a) Mostra la correlazione tra torbidità e precipitazioni intense. b) Nei primi tre grafici sono confrontate le precipitazioni accumulate (mm) nell'anno di riferimento con la media storica. Nel quarto grafico sono riportate le piogge mensili accumulate (mm) dal Gennaio 2017 ad Aprile 2020. Grafici elaborati con i dati ottenuti dal portale SIARL Arsial http://www.arsial.it/

the coastal area near Cicero's Tomb archaeological site, which is exploiting water from the deep carbonate aquifer (pumping rate of 200 l/s).

The construction of the '25 Ponti' drilled water wells encountered several difficulties related to:

- Proximity to the sea (about 500 m) and low altitude (between 17 and 21 m asl), which made it possible to interact with the saltwater wedge.
- Lack of a suitable geological model regarding the depth of the karst aquifer, its thickness and lithology of the surficial cover.

As shown by the plots in (Fig. 2), 2017 was characterised by very low rainfall.

In collaboration with D.I.C.E.A., the Department of Civil, Construction and Environmental Engineering of "La Sapienza" University in Rome, the drinking water of "25 Ponti' was monitored from 2017 to January 2021 to verify this hypothesis, and eventually find solutions to this problem.

The preliminary hydrogeochemical analyses carried out during the 2017 water crisis, showed an increase in salinity over time, potentially suggesting saltwater intrusion (Sappa 2019).

This study aims to further provide the monitoring activities

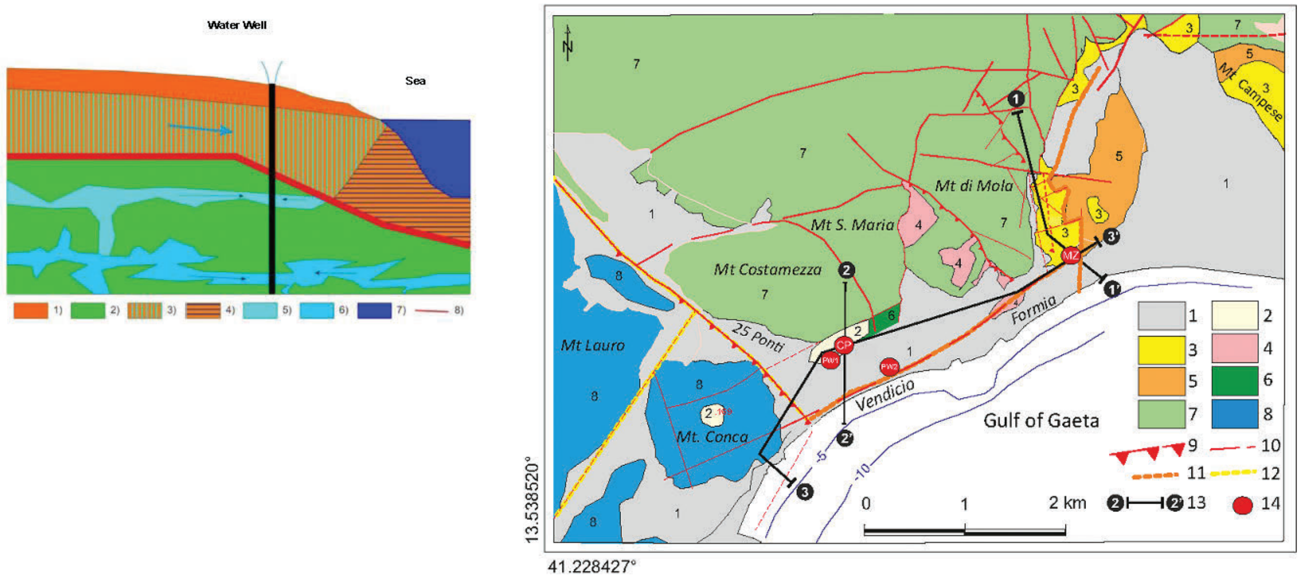

Fig. 3 - At left the theoretical diagram of '25 Ponti' area 1) Marine terrace (circulation of its compartmental aquifers); 2) karst aquifer; 3) Fresh water aquifer; 4) Salt water layer; 5) Karst aquifer; 6) Mineralized karst aquifer; 7) Seawater; 8) Limit of permeability. The arrows are showing the groundwater flow directions. At right the geological outline of the area: 1) Beach, river, eluvial and colluvial deposits (Upper Pleistocene – Holocene), 2) Sea Terrace - Sands consisting of quartz and reddish, yellowish feldspar, alternating with clays and silts (Middle-upper Pleistocene), 3) Conglomerates, detrital limestone and sandstone with allochthonous clasts (Lower Pliocene). 4) Chaotic clays and siltstones (Pliocene); Silty clays, marl and chaotic sandstone, marly limestone, sandstone. (Upper Cretaceous-Lower Paleocene) 5) Clays and silted clays with some fine layers of gypsum (Messinian) 6) Formia carbonatic hydrogeological Unit - 25 Ponti. 7) Aurunci M. Hydrogeological carbonatic Unit 8) Conca M. Hydrogeological carbonatic Unit 9) Reverse fault 10) Normal and transcurrent fault 11) Hydrogeological permeability limit (aquitard) 12) Permeability limit (aquiclude) 13) Geological cross section 14) Wells (private wells "Pw1" and "Pw2" and CP stand for "25 Pozzi" wellfield. Geological Map of Italy (1968) modified.

Fig. 3 - A sinistra lo schema teorico dell'area dei 25 Ponti 1) Terrazzo marino (circolazione di falde compartimentale proprie); 2) acquifero carsico; 3) falda acqua dolce; 4) falda acqua salata; 5) falda carsica; 6) falda carsica mineralizzata; 7) acqua di mare; 8) limite di permeabilità. Le frecce indicano le direzioni del flusso di acqua sotterranea. A destra l'inquadramento geologico dell'area: 1) Depositi costieri, fluviali, eluviali e colluviali (Pleistocene Sup. – Olocene), 2) Terrazzi marini, sabbie quarzose e cn feldspati, rossastre e giallastre, alternate con argille e silt (Pleistocene Medio—Sup.) 3) Conglomerati, calcari detritici e arenarie con clasti alloctoni (Pliocene Inf.) 4) Argille caotiche e siltiti (Pliocene); Argille limose, marne e arenarie caotiche, calcaree marnose, arenarie (Cretaceo Sup. – Paleoc. Inf.) 5) Argille and argille siltose con lenti fini di gessi (Messiniano) 6) Unità idrogeologiche carbonatiche della piana di Formia (25 Ponti) 7) Unità idrogeologiche carbonatiche dei Monti Aurunci 8) Unità idrogeologiche carbonatiche del M. Conca 9) Faglia inversa 10) Faglie dirette e trascorrenti 11) Limite di permeabilità Idrogeologica (aquitard) 12) Limite di permeabilità (aquiclude) 13) Sezione Geologica 14) Campo Pozzi (CP) e pozzi privati (Pw1 e Pw2). Carta Geologica d'Italia (1968) modificata.

performed by Sappa et al. (2019), in order to identify the causes of the groundwater variations and improve the geological model of the area.

Hydrogeological setting

The Formia Plain, where the '25 Ponti' water wells field is located, consists of a Quaternary succession of alluvial deposits, fans, transitional coastal deposits, marine terraces and red dunes (Aiello et al. 2007), whereas the bedrock is characterised by a series of carbonate platforms belonging to the Aurunci Mountains (Di Lorenzo et al. 2018), which consist of a series of limestone, such as detrital, microcrystalline, oolytic and organogenic limestone (Lias Lower - Upper Cretaceous) and bituminous dolomites at the bottom (Triassic - Lower Jurassic). These sedimentary rocks were affected by tectonic activities resulting in the formation of faults and folds (Upper Miocene, Tortonian-Messinian); the most important tectonic system is the Fondi-Itri-Formia fault (Iacurto et al. 2020; Servizio Geologico d'Italia 1968, Cipollari et al. 1991), (Fig. 3). The water wells field of '25 Ponti' intercepts this carbonate-rock aquifer; this karst groundwater system is also confined and show high geochemical variability (Fig. 3).

The Western Aurunci Mountains host a karst carbonate aquifer system (Boni et al. 1988; Capelli et al. 2012) which, due to the average elevation (in some case higher than 1500 asl, e.g. Petrella Mount at 1533 m asl, Fig. 1) and to the high karst permeability, catches a relevant rainfall fraction. At lower altitudes, the karst system feeds several springs with a significant flowrate and the largest ones are Mazzoccolo and Capodacqua di Spigno. The annual rainfall in the coastal zones of the Aurunci Mountains ranges between 700 and 1000 mm*y^{-1}, while, in the innermost areas, this amount increases between 1090 and 1350 mm*y^{-1} (Tallini 2013 and SIARL Arsial 2021). The Effective Infiltration calculated for the Western Aurunci mountains is between 400 and 600 mm*y^{-1} (Boni et al. 1988).

Mazzoccolo spring is located in the urban area of Formia, at the tectonic contact between the karst carbonate aquifer of the Western Aurunci and the clayey arenaceous, marly deposits (Messinian) located at the base of the aquifer and at its margins (Capelli et al. 2012). It is characterised by an extremely variable rate (200 l/s to over 1100 l/s) and, according to the stable isotope data (measured during this study and by Tallini 2013; Sappa et al. 2018), the recharge area is located approximately 800 m asl. This spring is affected by a quick reaction to heavy precipitations, which causes groundwater turbidity, linked to the karst system.

The karst aquifer system of the Western Aurunci mountains feds also Capodacqua di Spigno spring. A complex of clays (Pliocene – Pleistocene) and clays with gypsum (Miocene) defines the aquiclude of the karst system and the related springs This karst spring has the greatest flow rate of the area from 500 to 3400 l/s (Iacurto et al. 2021) and is also affected by turbidity issues. Vitruvio and Vetere groups represent other important springs in the study area (Fig. 1); again the Western Aurunci karst aquifer feds both of them and they occur at the contact with alluvial fans and debris (Lentini 2021).

Groundwater sampling and analysis

In this project 130 groundwater samples were analysed to identify their chemical parameters, and the piezometric trend was also monitored. Sampling operations were carried out during the commissioning of the wells (with pumping), with no pumping and after 8 months from the end of pumping. The results of the analysis were divided into wet and dry season (Lentini 2021).

The purpose of this methodology was to verify either the hydrochemical variation is caused by pumping or by seasonal variations (Lee et al. 2006; Sappa et al 2019; Jamaa et al. 2020).

Drilling operation and monitoring activities were carried out from April 2017 to January 2021 and included:

Drilling of four (4) water wells and four (4) monitoring piezometers (Fig. 1 and Tab. 1).

Collection and analysis of 130 groundwater samples (Tab. 1, Tab. 2, Tab. 3) while the piezometric trend, Electrical Conductivity (EC) and temperature were recorded by means of multi-parameter probes during the monitoring period (Tab. 4, Fig. 6). Additional samples were also collected from some private wells near the area and springs (Fig. 1). Sampling was carried out while the wells were pumping, in absence of pumping and after 8 months since the end of pumping activities The results of the groundwater chemical analysis were divided into wet and dry season.

The multi-parameter probe used for monitoring pressure, EC and water temperature was a DL.OCS/N/RS485 (STS Italia), a high-precision digital logger with an error of ≤ ± 0.05. The parameters were recorded with a 15-minute sampling frequency, starting from the end of 2017 for the Tulliola well and from 2018 for the Terenzia well, up to 2020 for both wells, including the dry and wet seasons. Groundwater was sampled from the wells by pumping (before, during and after the well testing and aquifer testing), using a flow cell. Samples were taken after at least 10 minutes pumping and after obtaining constant values of conductivity. Temperature, pH, and EC were measured in situ. Groundwater samples were filtered immediately after sampling for analysis of ions using 0.45 µm membrane filters. The samples were collected in the field in polypropylene bottles (50 ml). carefully filled without any air entrapment and were stored at 4°C The hydro-chemicals analyses were carried out at 'AcquaLatina Spa' and 'Arpa Lazio' laboratories, using a Dionex ICS 1000 Ion Chromatograph.

Results and Discussion

Table 1 shows the locations and the main features of the water wells, piezometers of the "25 Ponti" field and private wells. The private wells (range of flowrate between 1 l/s and 5 l/s) are exploited for domestic and field irrigation purposes.

Tab. 1 - "25 Ponti" water wells. Depths in m (Dz), Distance from the coast in m (Dx), elevations (El) in m asl, maximum flow rates (QM) and flow rates during pumping (Qo) in l/s, piezometric static levels in m asl, monitoring periods (month, year), number of groundwater samples (Ns).

Tab. 1 - Il campo pozzi "25 Ponti". Profondità in metri (Dz), distanza dalla costa in metri (Dx), altitudine (El) in m slm, portata massima (Qm) e portata in esercizio (Qo) in l/s, i livelli piezometrici statici (Ps) in m slm, il periodo di monitoraggio ed il numero di campioni (Ns).

Name/Type/year construction	Y (Lat)	X (Long)	D(z)	D(x)	El	QM	Qo	Sampl. Period	Ns
TUL_Tulliola/Well/2017	41.252237°	13.583979°	55	529	21	49	38	07/2017 to 10/2020	62
TER_Terenzia/Well/2018	41.252231°	13.583128°	90	567	20	17	13	07/2018 to 10/2020	50
CIC_Cicerone/Well/2020	41.252303°	13.584119°	100	534	22	61	50	08/2020 to 01/2021	2
MT_Marco Tullio/Well/2020	41.251978°	13.582981°	100	535	22	12	12	01/2020c to 08/2020	1
Tulliola1/Piezometer	41.252144°	13.583869°	45	525	21	21	-	-	-
Tulliola2/Piezometer	41.252369°	13.583969°	100	547	22	n.a.	-	-	-
Terenzia/Piezometer	41.251633°	13.583036°	100	498	21	20	-	-	-
Vindicio/Piezometer	41,245695°	13,580021°	85	177	10	n.a.	-	-	-
ColdirettiPW1/PrivateWell	41.251230°	13.581198°	80		20	2.5	n.a.	02/03/2020	1
CircoloLaVelaPW2/PrivateWell	41.249873°	13.589844°	535	80	4	n.a.	n.a.	02/03/2020	1

Table 2 shows the maximum and minimum values of the different ions and chemical-physical parameters analysed from the samples collected from the wells. The table contains the results of the samples collected during pumping or with no pumping or after 8 months from pumping; they were finally distinguished into groundwater samples of wet and dry seasons.

Tab. 2 - Hydrochemical analyses carried out with and without water pumping from 2017 to 2020 (in dry and wet seasons). EC at 20°C in μS/cm, ions are in mg/l.

Tab. 2 - Analisi chimico-fisiche effettuate sia durante il pompaggio che in assenza di estrazione di acqua dal 2017 al 2020 (sia nei periodi di precipitazioni scarse che in quelli piovosi). EC a 20°C in μS/cm, ioni in mg/l.

ID	Sampling	pH	EC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO^{3-}	Cl^{-}	Br^{-}	SO_4^{2-}	NO_3^{-}
TUL_1	Dry 2017 **(pumping)**	7.1-7.52	607-684	62.9-99.5	9.8-15.7	16.7-29.9	0.4-12.4	244-366	42.8-56.8	0.04-0.05	27.2-32.3	14.8-18.6
TUL_2	Wet 2017 (without pumping)	7.1-7.3	740-858	92.9-120.6	13.4-17.8	23.9-36.7	1-2.4	353.8-427	80.9-137.3	0.2-0.4	29.6-30.8	353.8-427
TUL_3	Dry 2019 (without pumping)	6.91-7.82	737 -846	106.1-116.4	16.3-18.8	35.2-40.4	1-3.1	293-305	80-136.7	0.4-0.6	21.8-32.5	10.9-14.7
TUL_4	Wet 2018 (without pumping)	7.88-7.93	303-306	75-84	5.9-7.9	35.6-36.7	0.4	186.199	9.7-10.1	<0.05	30.9-31.9	1.7-1.9
TUL_5	Wet 2019 (without pumping)	7.2-7.5	706-726	99.9-107.9	16.8-18.2	32.2-36.8	1.8-2.4	305-323.3	80-119	<0.05	20.8-37	1.7-7.9
TUL_6	Wet 2020 **(pumping)**	7.39-7.81	585-687	86.7-99.5	14.6-19	29.6-40.7	1.5-4.4	250-329	35-131.6	0.03-0.05	9.1-28.4	2.9-8.4
TUL_7	Wet 2020 (after 7 months without pumping)	7.67	648	91.6	16.8	40.4	1.4	323	75	0.35	26	8
TER_1	Dry 2018 (without pumping)	7.23-7.48	1102-1146	133.3-140.1	32.9-34.1	55-58	1.4-2	305	196-218.3	0.05-1.2	69.2-69.6	27.6-28.5
TER_2	Wet 2019 (without pumping)	7.7-7.84	872-941	122.2-125.1	28-32.8	33.3-38.6	3.3-3.8	320	92.2-92.5	0.9-1.1	59.4-81.9	21.1-24.5
TER_3	Dry 2019 **(pumping)**	7.1-7.29	980-1055	120.3-134	32.6-34.9	48.6-65.5	2.3-3.4	305-314	153.2-194.1	0.05-1.5	57.9-83.8	22.2-45.7
TER_4	Wet 2019 **(pumping)**	7.2-7.74	1043-1057	118.3-123.5	27.8-32.8	58.5-70.4	2.4-5.4	317.2-335.5	115.6-180.2	0.05-0.9	29.9-49.9	2.5-18
TER_5	Wet 2020 **(pumping)**	7.4-7.83	772-941	93.4-125.1	24.1-32.4	33.3-70.9	1.2-3.8	320-336	48.7-118.5	0.05-1.1	19.6-81.9	3.2-24.5
TER_6	Wet 2020 (after 7 months without pumping)	7.68	760	94.8	23.7	46.1	1.6	336	79	0.41	34	13
CIC_1	Dry 2020 (without pumping)	7.2	582	97,4	13,2	28,6	1,5	300	51	0,19	15	5
CIC_2	Wet 2020 (without pumping)	7.8	615	92,5	17,1	32,3	1,4	299	62	0,23	15	6

 DOI 10.7343/as-2021-527

Table 3 summarises the hydrochemical values measured on the same day from the different wells of the '25 Ponti' water wells, to compare them with the neighboring private wells and with the main sources in the area.

The MT well is the closest to PW2 (about 200m of distance) and its chemistry is consistent with PW2. The water wells drilled which belong to Acqualatina catch the same confined carbonate aquifer; whereas the completion characteristics of the private wells is still uncertain. They presumably mix the kast carbonate confined aquifer with those of the marine terrace.

Tab. 3 - A comparison of chemical-physical analyses of the groundwater sampled at the water wells ('25 Ponti' water wells and private wells) and springs (in light blue). EC is electrical conductivity at 20°C in μS/cm, ions are in mg/l and temperature is in °C. Abbreviations: Tulliola (TUL), Terenzia (TER), Cicerone (CIC), MarcoTullio (MT), Mazzoccolo (MZ), Vitruvio (VITR), Vetere (VET), Capodacqua di Spigno (CA_Sp), private wells Pw1 and Pw2.

Tab. 3 - Comparazione delle analisi chimiche dell'acqua sotterranea campionata nei pozzi ('25 Ponti' e pozzi privati) e nelle sorgenti (evidenziate in celeste). CE è la conducibilità elettrica a 20°C in μS/cm, gli ioni sono espressi in mg/l e la temperature è in °C. Le sigle: Tulliola (TUL), Terenzia (TER), Cicerone (CIC), MarcoTullio (MT), Mazzoccolo (MZ), Vitruvio (VITR), Vetere (VET), Capodacqua di Spigno (CA_Sp), private wells Pw1 and Pw2.

ID	Sampling Date	pH	EC	T	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	CO_3^{2-}	Cl^-	Br^-	SO_4^{2-}	NO_3^-
TUL	2 March 2020	7.38	615	17.3	96.4	16.7	35.8	1.7	317	0	59.5	0.27	20.4	8
TER	2 March 2020	7.39	787	16.9	97.9	28.5	57	3	329	0	89.6	0.5	41.1	19.6
CIC	3 Agust 2020	7.44	615	16.9	92.5	17.1	32.3	1.4	299	12	62	0.23	15	6
MT	3 Agust 2020	7.06	981	n.a.	68.9	12.5	6.3	1.4	310	0	137	0.92	66	38
Pw1	2 March 2020	7.9	307	18.4	58.3	9.8	5.8	0.5	220	12	13.3	0.46	21.9	22.6
Pw2	2 March 2020	7.53	1095	n.a.	161.2	41.4	44.1	6.2	354	0	53.3	3.25	164	184.3
CA_Sp	2 March 2020	7.56	301	13.5	38.6	8.8	9.7	0.9	198	0	13.5	< 0.05	3.2	1.3
MZ	2 March 2020	7.87	307	13.5	58.5	10.4	6.8	0.6	213	6	13.9	0.06	5.6	2.8
VET	2 March 2020	7.67	487	n.a.	84.3	12.7	15.3	0.8	305	0	17.1	-	5.4	2.7
VITR	2 March 2020	7.58	456	n.a.	89.4	18.4	12.4	1.9	305	0	17.5		7.8	6.2

Table 4 shows piezometric levels of the water wells Tulliola (from December 2017 and July 2018) and the water well Terenzia (from November 2019 to February 2020) compared to the rainfalls, EC and temperatures (periodical seasonal variation). In order to make easier the data understanding, dry and wet periods are also defined (minimum and maximum of rainfalls, respectively).

Tab. 4 - The values of T, EC and Piezometric Level (P.l) of Tulliola, Terenzia water wells and the rainfalls.

Tab. 4 - I valori di T, EC e livello piezometrico (P.l.) dei pozzi Tulliola e Terenzia e le precipitazioni.

Well/ period	T (°C)	EC (uS/cm)	P.l. (m a.s.l.)	Rainfalls (mm)
TUL_Wet 2017	17.2	718.3-765.20	-5.8 - 6.13	920-2093
TUL_Wet 2018	15.5-17.3	626 - 779.7	6.05-12.83	2085.45 2093.19
TUL_Dry 2018	16.9-17.30	646.6 - 708.7	5.31-11.89	2010.65 2669.39
TER_ Dry2019	17.20-17.5	819.00-1146.60	-14.70-3.26	n.c.
TER_ Wet2019	17-19.60	371.80-1139.40	-14.84-11.52	n.c.
TER_ Wet2020	14.7-17.4	434-6644.4	-14.83-4.26	n.c.

The Geological model

The geological model of the study area (Fig. 4) shows the outcrop of the Pleistocene marine terrace (clays, organic clays alternating with sand levels deposited in the coastal and lagoon environment), overlying the carbonate fractured substrate presumably dating back to the Jurassic period (below the hydrogeological Formia unit), which is located at a depth between 4 m and -5 m asl at the '25 Ponti' drilled water wells and about -50 asl at Vindicio beach (Fig. 4, section 2-2').

The stratigraphy explored by wells drilling can also be described, from top to bottom, as consisting of a sequence of sediments covering a limestone bedrock. The top sediments are formed by anthropogenic fill materials of clay bricks, calcareous pebbles and brown soil about 2m thick, lying above the sediments from the fluvial terrace (thickened red sands with hight iron content, white sands alternating with grey clays with peaty layers) overlying the carbonatic substrate. At the sand levels, an ephemeral aquifer was found, and, in fact, there are many old wells and cisterns in the area which exploited this aquifer. The limestone substrate consists of mudstones, hazel to whitish wackestone (with regular 20-50 cm layering), very fractured and karsified with the presence of spathic calcite, red residual clay and greenish clayey levels. Many levels of residual clay alternate with these karsified limestone.

The piezometer drilled near Vindicio Beach (Vindicio) crossed 20 m of silty sandy peaty succession of lacustrine deposits, 50 m of red clays alternating with sandy silty clayey levels in dune facies and layers of calcareous pebbles (mudstones and wackestone) belonging to the Aurunci series. At the bottom of this formation, fine sands and silt are intercepted. Finally, at the depth of 75 m, the limestone substrate was found.

The geological section 1-1' (Fig. 4) shows that, to the north, the karst aquifer of the Aurunci mountains (Fig. 4 in green) crops out and feeds the Mazzoccolo spring (MZ), which, in the central part, emerges with the Pliocene aquifer, made up of puddingstone with allochthonous clasts (Fig. 4 in yellow), lying on clays and silty clays deposits with some fine layers of gypsum dating back to the Messinian (in orange) that reach a depth of about -50m a.s.l. These Messinian deposits protect the aquifers from marine intrusion. To the south there are beach deposits.

The geological section 2-2' (Fig. 4), is focused on the '25 Ponti' water wells area. The carbonate substrate aquifers (in green and blue) is affected by the Fondi-Itri-Formia fault, which separates the structure of Lauro Montains (Calcare Massiccio, Lower Jurassic) from the M. Aurunci West Unit. Due to possible intense fracturing, these faults can play a potential aquitard role. The carbonate aquifer is covered by

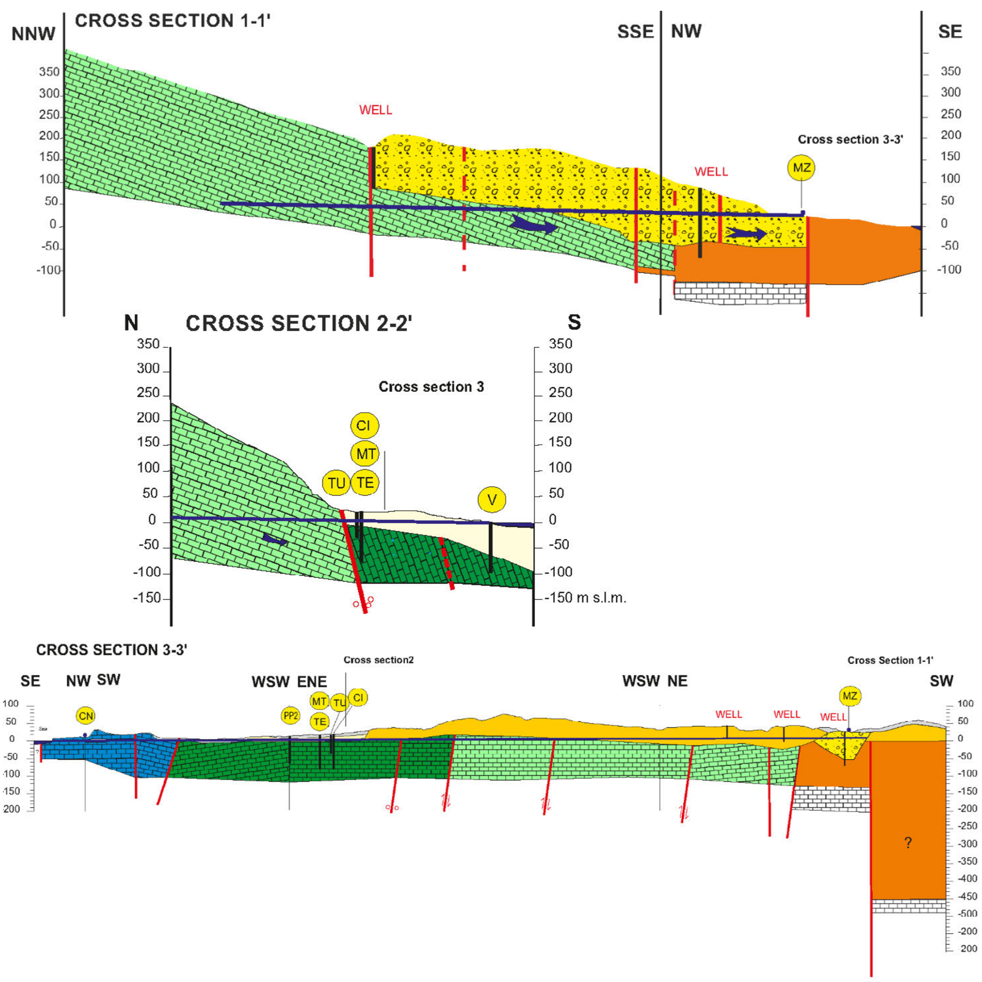

Fig. 4 - Geological sections (locations in Figure 3).

Fig. 4 - Sezioni geologiche (l'ubicazione in Figura 3).

marine terrace deposits made up of clays, silty sands and carbonate pebbles in clays matrix with a 75 m thickness in the Vindicio beach sector and 20 m near the mountains. It contains some small aquifers in the most permeable parts; however, it acts as an aquitard with the deeper aquifer. To the south, there are the Messinian deposits of clays and silty clays with some fine layers of gypsum (in orange) protecting the aquifer from marine intrusion.

The geological section 3-3' (Fig. 4) shows that, in the SW sector, the carbonate structure of M. Conca (in blue) is in contact with the sea, and, in fact, there are underwater springs showing higher mineralization (e.g. S. Maria della Conca, Boni et al. 1988). However, the faults belonging to the Fondi-Itri-Formia system protect the aquifer exploited by the '25 Ponti' water wells. Finally, on the south-eastern side, there are Messinian deposits (in orange) protecting the aquifer from marine intrusion.

The geological sections in Figure 4 (whose location is shown in Fig. 3) were developed based on stratigraphic data from the drilled wells and on a literature review.

Hydrogeology and Hydrogeochemistry

The '25 Ponti' water wells field intercepted a confined, which lays at the bottom of Pleistocene marine terrace deposits (aquiclude); its thickness ranges between 20m and 75m. This aquifer is characterised by high secondary permeability due to fractures and karst phenomena, by a multilayer hydrogeological circulation with clear artesian/confined characteristics and strong sensitivity to the seasonal trends.

The different productivity and hydrochemistry of the water wells (Tab. 1, Tab. 2, Tab. 3 and Fig. 5) is due to the complexity of the geological and structural setting. Tulliola and Cicerone wells intersect more fractured lithologies than Terenzia and Marco Tullio. Table 3 shows the chemical and physical data of waters from the '25 Ponti' water wells and the springs, sampled on 2nd March 2020 (after a pumping break for 8 months). Only Cicerone and Marco Tullio wells were sampled at a later stage (on 3rd August 2020).

The ion composition is dominated by Ca, Mg and HCO_3 and the waters of Marco Tullio (MT) and private well Pw2 show the highest EC (Fig. 5).

Water well monitoring shows that the water level of the main aquifer was intercepted at about -25 m from ground level, and rose up to 4 m above sea level, which roughly corresponds to the top of the aquifer. The observed piezometric level, therefore, fluctuated between around 12 m a.s.l. in the wet season of 2020 (Tab. 4) and 4 m a.s.l. in the dry season of 2017 (Sappa et al. 2019).

Due to these variations of the piezometric level, in the dry season regulatory reserves tend to decrease (Fig. 4). It was observed that dynamic levels induce drops down to -13 metres asl, that recalls waters from the surroundings areas and depths.

In Table 2, Table 4 and Figure 6, the water analyses during water pumping show a progressive and limited increase of their mineral content. Such mineral pattern tends to decrease as rainfall seasons begin and when pumping is stopped for 8 months; it then increases again (in the dry season) until it stabilises at the initial values (after an 8-month break from pumping).

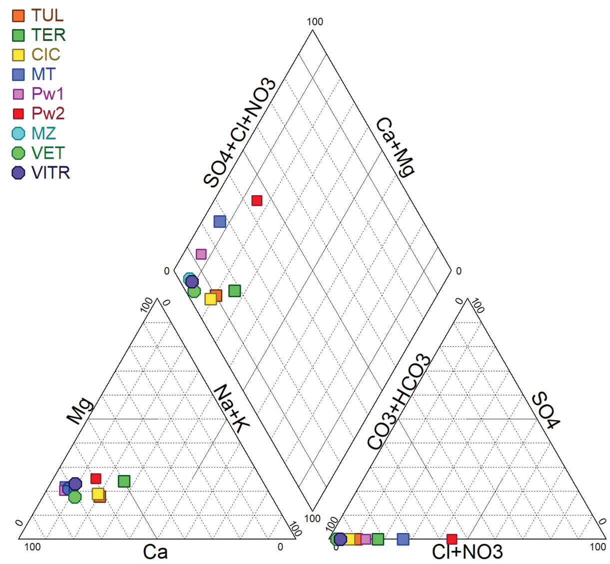

Fig. 5 - Piper diagram of data in Table 3. MT and Pw2 show the most mineralized waters.

Fig. 5 - Diagramma di Piper dei dati della Tavola 3. MT e Pw2 mostrano le acque maggiormente mineralizzate.

Figure 6 shows the trend of the piezometric level of the static aquifer (the pumping ended in December corresponds to the knee of the curve), of the temperatures and of the EC as a function of rainfall which, that are mainly concentrated in the winter season.

This diagram shows how the influx of fresh water, coming from rainfalls in the period between February and April, induces an increase in the piezometric level, a decrease in EC and temperature.

With a decrease in rainfall, the piezometric level begins to drop asymptotically until it stabilizes at a value of 7 metres a.s.l. (in August 2017 the initial level was 4 metres a.s.l.) and the EC decreases back to a value of about 700 µS/cm. In the dry season, the aquifer progressively loses its hydraulic load and the waters of the well field tend to draw mainly from permanent reserves.

The EC variation progressively decreases over time in the wet season, despite the fact that the well is continuously operated, which proves that the parameter is influenced by rainfall.

This phenomenon can also be observed in the diagram below, which shows the trend of the same parameters mentioned above relating to the Terenzia well in the period between November and February 2020 (end of the aquifer test).

As we can clearly see, the groundwater level between November, the period in which the well is not in operation and which corresponds to the peak of the dry season, the EC level is 950 µS/cm. As the rain season beginsll, the piezometric level increases and the EC drops abruptly to stabilize around 680 µS/cm. With the beginning of the extraction activities (rate of flow = 13 l/s) the EC remains constant while the piezometric level decreases to about 16m. At the end of the well drawing, the EC values stabilises at 650 µS/cm, which is less than the initial values.

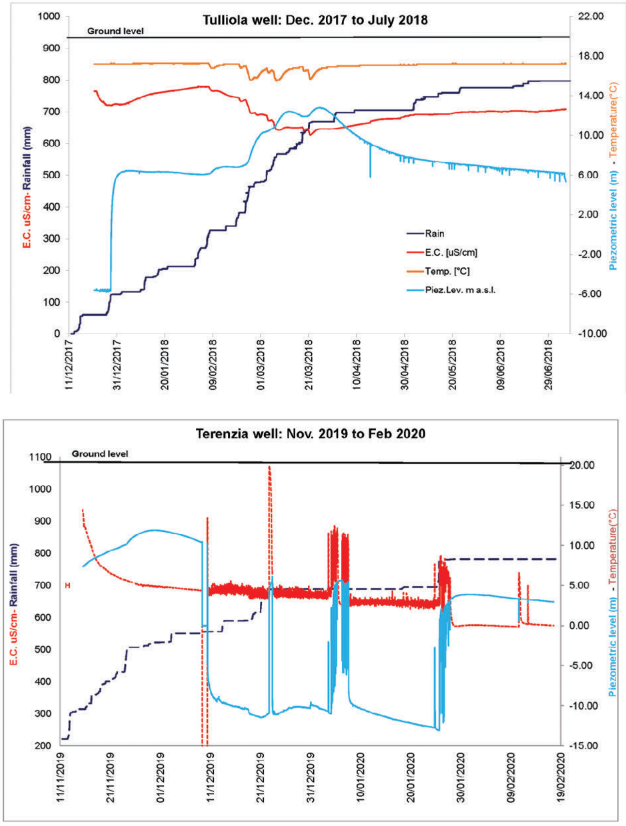

Fig. 6 - Monitoring of Tulliola (a) and Terenzia (b): variation of EC, accumulated rainfall, temperature and piezometric height, from December 2017 to July 2018 and from November 2019 to February 2020, respectively.

Fig. 6 - Monitoraggio Tulliola (a) e Terenzia (b): variazione dei parametri CE, piogge accumulate, temperatura e altezza piezometrica, rispettivamente nei periodi da Dicembre 2017 a Luglio 2018 e da Novembre 2019 a Febraio 2020.

According to the trend of the parameters, the aquifer measured under static conditions, except for the first few days of monitoring, is strongly influenced by rainfalls, mainly concentrated in autumn and winter.

The results obtained show that the measured increased mineralization follows a seasonal trend, influenced by the drinking water extracted from the wells, that, in some periods of the year reduces regulated reserves and requires extraction from permanent reserves. This seasonal phenomenon was also confirmed when monitoring was performed without pumping (Fig. 7). Therefore, in the dry season the contribution of regulated reserves, which slowly tend to drain and stop at a static level of about 4 m asl, is more important.

It is believed that the portion of the aquifer characterised by permanent reserves, are affected by greater mineral content, since the highest EC values are located approximately at this height.

At the end of the 7-month pumping tests the mineralization of the water was found to be exactly the same as the initial one (Fig. 7).

The hydrochemical analyses carried out mainly within Tulliola and Terenzia wells, except for the first analysis of Tulliola well in July 2017 (Tab .2 and Fig. 7) show that the ion concentrations are always significantly higher in the summer, while being lower in winter when there is an abundance of water. This phenomenon was observed regardless of the activity of the wells (Fig. 7). In fact, at the end of monitoring operations which lasted 8 months in the wet season, the concentration of ions observed at Tulliola and Terenzia waters was lower, compared with the first analysis carried out after the construction of the wells and with the one prior to the monitoring activity (8 months earlier), FIG.7.

The piper and ions correlation graphics are also highlighting that the seawater intrusion in the "25 Ponti" aquifer area occurs (Fig. 7); indeed, the ions concentration correlation during the dry season keeps its pattern also during the wet season.

Finally, the study made it possible to identify an EC alarm threshold to be used as a reference during water wells exploitation. This level corresponds to the maximum salinity value found in the Terenzia well (1146 in µS/cm in summer 2018 without pumping operations).

Conclusions

This study aims to understand if the EC increase might be either linked to the saltwater intrusion or to the groundwater from the confined aquifer. In this study area the ions correlation and their trend concentration showed an increase of mineralization which is linked mainly to confined aquifer groundwaters.

The geological model was first derived from a literature review and then improved through stratigraphic models obtained during field studies., The combination of hydrogeochemical data and piezometric observation at different locations (Tab. 1), supported the definition of eventual saltwater intrusion; moreover, data interpretation supports the decision makers on how to prevent such issue.

The derived hydrogeological model also shows that between the seawater and the confined carbonate aquifer there are low permeable sediments (about 75 m thick) that defines an aquitard which separates saltwater from fresh groundwater. At the water wells, the bedrock is made of clays and silty clays with fine layers of gypsum which contribute to the protection of the aquifer from saltwater intrusion.

A significant variation of the hydrochemistry content was observed; such variation could be related not only to the pumping activities, but also to the rainfall seasonality trend; as a result, the climate changes would drive to additional impact on the hydrochemistry content.

The mineral content in the groundwater changes according to seasonal trends. As a result, the groundwater exploitation has to be lowered during the dry seasons and permanent reserves are therefore needed. Furthermore, the presence

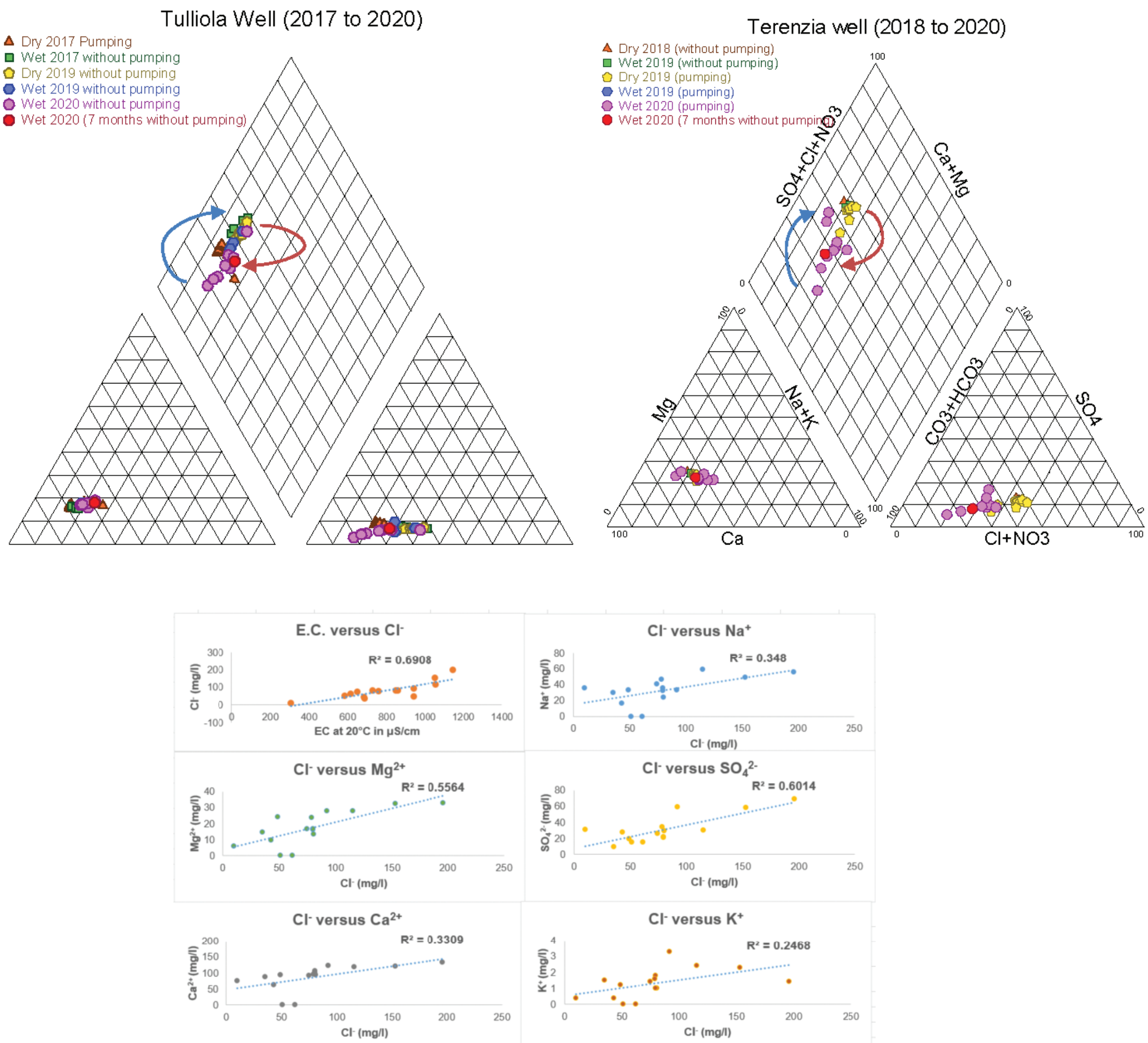

Fig. 7 - Piper diagrams showing the evolution of chemism over time and ions correlation diagrams. The blue arrows in the piper diagrams are showing the chemical evolution of the water during the pumping in the wells (year 2020, wet period, violet points), however the red arrows are showing that at the end of the 8-month pumping tests the mineral content of the water was found to be exactly the same as the initial one (red points).

Fig. 7 - Diagrammi di Piper relativi all'evoluzione nel tempo del chimismo e diagrammi di correlazione tra gli ioni. Le frecce blu nel Piper indicano l'evoluzione idrochimica durante il pompaggio ai pozzi (nel 2020, stagione delle piogge, punti viola), mentre quella rossa indica che ad 8 mesi dalla fine del pompaggio la mineralizzazione era scesa ai valori iniziali (punti rossi).

of distinct hydrogeological systems recharged by different catchment basins drives the increase of complexity of the whole system .

The study showed that the '25 Ponti' water wells field managed to achieve those strategic objectives which are aimed to the increasing of the resilience of the aqueduct system to the new challenges to come.

The '25 Ponti' water wells field is currently providing 200 l/s of fresh water with no issues in terms of water quantity and turbidity; this well field is therefore a valuable resource to be used in support to the main aqueduct.

Finally, the EC alarm threshold has been set during water well extraction, in order to prevent possible saltwater intrusions.

Author contributions

The authors contributed equally to this work. All the authors read and approved the final manuscript.

Competing interest

The authors declare no competing interest.

Funding

Project financed by Regional Legislative Decree M.00005 del 08/08/2018 of the President of the Lazio Region as commissioner delegated for the water supply crisis of drinking water (OCDPC n.474/2017).

Acknowledgement

The authors would like to thank the team of Acqualatina S.p.A. for their valuable help: Professor G. Sappa for his scientific contribution. Surveyors P. Venturo and G. De Santis for their support on the field. Dr. M. Abatecola and A. Terraciani for chemical analyses. Dr. L. Leccese for her communication policy. Mr. M. Gallo. Mr. M. Formato. Mr. A. Parente for the execution of works.

Additional information
Supplementary information is available for this paper at https://doi.org/10.7343/as-2021-527
Reprint and permission information are available writing to acquesotterranee@anipapozzi.it
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