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Groundwater monitoring in the archaeological site of Ostia Antica (Rome, Italy): first results

Monitoraggio delle acque sotterranee nel sito archeologico di Ostia Antica (Roma): primi risultati

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Riassunto: Il sito archeologico di Ostia Antica conserva i resti dell'antica città romana fondata nel VII sec A.C. sulla foce del fiume Tevere. L'importanza strategica di questa zona era fondamentale per Roma, non solo per il controllo del fiume e della sua foce, ma anche per il fiorente commercio del sale, prodotto nelle saline degli Stagni di Ostia. In seguito al declino dell'industria del sale, l'intera area venne bonificata nel XIX secolo. Nelle zone attualmente urbanizzate, un'articolata rete di canali e l'ininterrotta attività di pompaggio delle idrovore, impedisce la naturale inondazione delle zone situate al di sotto del livello del mare. Nel febbraio 2014, a seguito di eventi piovosi particolarmente intensi e prolungati, gran parte del sito archeologico è stato allagato costringendo la Soprintendenza per i Beni Archeologici di Roma a decretarne la chiusura per 15 giorni. Pochi mesi più tardi (luglio 2014) è iniziato un programma di monitoraggio delle acque sotterranee finalizzato allo studio della risposta della falda alle precipitazioni locali. L'attività ha previsto il monitoraggio della profondità della falda, della conducibilità elettrica (CE) e temperatura delle acque sotterrane e della composizione chimica delle acque (ioni maggiori). I risultati preliminari mostrano un'evidente relazione tra le fluttuazioni della falda e la distribuzione temporale delle precipitazioni. Il sito archeologico si trova ad una quota media di circa 2,5 m s.l.m. e la falda ha una soggiacenza media di circa 2 m con una direzione di flusso dal Fiume Tevere verso l'area bonificata, in accordo con le direttrici di flusso regionali. In tre pozzi sono state campionate acque dolci (600-1000 μS/cm) appartenenti alla facies bicarbonato calcica; in un pozzo, situato vicino ad un edificio che nel passato era un antico magazzino del sale, è stata rilevata acqua cloruro alcalina salmastra (4000 μS/cm). L'evoluzione chimica stagionale della composizione delle acque sotterranee suggerisce la possibilità di un contributo sotterraneo laterale da parte del Fiume Tevere, che, in prossimità del sito archeologico, scorre arginato a quote leggermente più elevate di quelle della falda.

Parole chiave: acquifero costiero, intrusione del cuneo salino, monitoraggio del livello di falda, patrimonio archeologico, Roma.

Keywords: *coastal aquifer, salt-wedge intrusion, water-table monitoring, archaeological heritage, Rome.*

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Abstract: *The archaeological site of Ostia Antica hosts the ruins of the ancient roman city called Ostia founded in the VII century B.C. near the mouth of Tiber River. The area was strategically important for Rome, not only for the control of the river, but also for some salt marshes (Ostia Pound). During the XIX century, the whole area was reclaimed and the salt production stopped. Nowadays drainage canals and pumps avoid the flood of zones placed below sea level, keeping dewatering below the ground surface.*

In February 2014, the site was largely flooded after an exceptional rainfall event and the Superintendence for Archaeological Heritage of Rome ordered the closure for 15 days. Few months later (July 2014) a groundwater monitoring project started with the aim of studying the aquifer response to local rainfall and prevent future damage and groundwater flooding. The activity consisted in water-table monitoring, groundwater electrical conductivity (EC) and temperature continuous measurements, coupled with chemical analysis of major ions. Preliminary results shows the link between water table fluctuations and rainfall distributions. The average elevation of the archaeological area is about 2,5 m a.s.l. and the local water-table depth is of about 0,5 m a.s.l.; groundwater flows from the Tiber River to the reclaimed area according to regional flowpath. Groundwater sampled from three wells is $Ca\text{-}HCO_3$ freshwater (600 - 1000 μS/cm), while the sample collected from a well located close to ancient salt storage warehouse (now Ostia Antica museum), is Na-Cl brackish water (about 4000 μS/cm). The chemical evolution of groundwater from summer to winter suggested a possible lateral inflow from the Tiber River, affected by salt-wedge intrusion. The inflow of Ca-Cl, SO_4 Tiber's water with an intermediate salinity could determine salinization of $Ca\text{-}HCO_3$ freshwaters and refreshing of Na-Cl brackish water.

Introduction

In delta regions frequently the saturation level of fresh groundwater shows depth of few meters below the ground level, for this reason the groundwater contribution plays often a crucial role in flooding (McCarthy 2005, Wolski and Savenije 2006, Vazquez – Sune et al. 2007, Fan et al. 2013). The groundwater effect is even more marked in the reclaimed coastal areas, where some sectors are located at a lower altitude than the sea level. If the groundwater level was not kept below the ground surface by dewatering, these areas would be always groundwater-flooded (Yin and Li 2001, Camorani et al. 2005, Temmerman et al. 2013, La Vigna et al. 2016).

About 20 km from Rome, in the Tiber River delta plain, swampy areas, were located behind the dunes (Ostia ponds). The recharge of the marshland was ensured by runoff and also by groundwater, where the water table was above ground level (Mastrorillo and Mazza 2015). The ancient lagoon played a key role in the development of Ostia, a town of Roman age built on the Tiber River mouth. The ancient Ostia inhabitants started the exploitation of the Ostia ponds as salt works; this activity continued until the modern age, when the lagoon was reclaimed (Pannuzi 2013, Vittori et al. 2014). At that time, the relationship between Ostia and the water (town grown both on the sea side and on the river bank, and satisfied by an appreciable local drinking water supply) facilitated the prosperity of the town, even though several flooding events occurred (Calenda et al. 2005, Long 2008).

In the past, the main triggers of Ostia Antica floods were the Tiber River overflow and the outflow of very shallow groundwater (groundwater flooding). After the overflow protection works were completed (at the end of 18th century), the flooding of archaeological site has been caused mainly by groundwater's rise due to heavy rainfalls. This issue was well known by ancient inhabitants as much that in Ostia were no cesspits, and there was an extensive network of sewers below buildings and streets (www.ostia-antica.org). Nowadays in Ostia Antica the water-table has always been very shallow (1-2 m b.g.l.) and it outflows in the low-land areas, when the groundwater head increases. Therefore, the archaeological site is often flooded during rainy seasons. Almost every year, the lower excavations of the site are flooded by intense and prolonged rainfall events, making some monuments closed off to the visitors. In February 2014, the site was largely flooded after an exceptional rainfall event and the Superintendence for Archaeological Heritage of Rome ordered the closure of the whole site, for 15 days. These issues are producing a lot of inconvenience, first of all, a decrease of economic profit and an image damage of the archaeological site.

In 2015, a cooperation between the Superintendence and the Sciences Department of Roma Tre University started, with the aim of studying the aquifer response to local rainfall and preventing future damage. After the first years of study, it is possible to remark on preliminary results.

Study area and land use

The archaeological site of Ostia Antica is located in the southwestern suburbs of Rome on the Tiber River left bank, about 5 km away from the coastline (Tyrrhenian Sea). The site area is of about 1,5 km^2 and has an average elevation of about 2,5 m a.s.l. The geographic context surrounding the ruins of Ostia Antica is very different from the past (Fig.1).

During the Roman age, the Tiber River skirted the

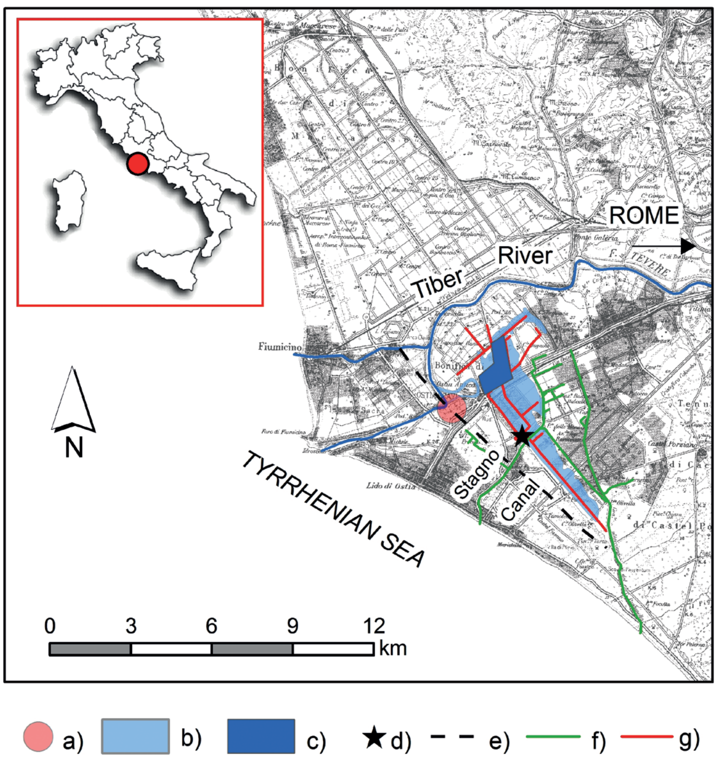

Fig. 1 - Location of study area. a) archaeological site of Ostia Antica; b) Ostia ponds; c) probable location of the salt pans d) drainage and pumping station; e) shoreline position 2700 yr BP (Milli et al. 2013); f) reclamation high canals system; g) reclamation low canals system.

Fig. 1 - Ubicazione dell'area di studio. a) sito archeologico di Ostia Antica; b) stagni di Ostia; c) probabile ubicazione delle saline; d) stazione di pompaggio; e) posizione della linea di riva 2700 anni fa (Milli et al. 2013); f) canali di drenaggio delle acque alte; g) canali di drenaggio delle acque basse.

northern side of the inhabited area while nowadays it scarcely affects a portion of the western sector (as a consequence of the disastrous flood of 1557) (Bellotti et al. 2011). Moreover, the shoreline was originally close to the town but due to the debris accumulation of the river over the past 2,000 years, it is now 4 km away from the old position (Milli et al. 2013). The mouth progradation allowed the development of swamps behind the dunes (Ostia ponds), in the inner part of the delta plain. Romans built Ostia town on the shoreline in the 6th century B.C. and at that time the Ostia pond has been began to be used as saltworks. The saltpans were linked to sea by the Stagno Canal that ensured the seawater recharge (Fig.1). The salt production activity was carried out until '700 (Arnoldus-Huyzendvel 2014) and in 1884 the areas located below the mean sea level were reclaimed. The reclamation drainage system consists on both a network of canals collecting rainwater and draining groundwater to a drainage station and a system of pumps, which avoid the low lands flooding, keeping groundwater below the ground surface.

After the reclamation activities, the modern Ostia grew up, replacing the coastal dune environment and surrounding the archaeological site. The original connection between the Ostia Antica drain canals and the reclamation drainage system has been abandoned for about 40 years, and nowadays the local "idrovora" (pumping station of the reclamation system) is out of order.

Hydrogeological setting

The roman coastal aquifer is a freshwater multilayer aquifer made mostly of Pleistocene and Holocene sandy sediments constituting the Tiber River delta plain. The left bank of the plain coincides with the contact between the Pleistocene transitional deposits and the Holocene coastal and alluvial deposits. In the inner sector of the plain, the stratigraphic composition is made of silty sands, clay and gravel deposited during several Pleistocene transgressive cycles. The outer part is characterized by Holocene deposits, mainly coastal and eolic sands, passing laterally to the alluvial sediments of the Tiber River (Funiciello et al. 2008). The eteropic contact between Pleistocene and Holocene deposits is buried under swamp deposits (peat, silt and clay) outcropping due to reclamation. The deepest boreholes drilled in the area passed through the sands and reached the shale bedrock (Plio-pleistocene marine shale) at an approximate depth of 50 m and deepening towards the sea (Capelli et al. 2007) (Fig. 2)

Groundwater flow is limited at the bottom by the low permeability aquiclude (Plio-pleistocene clay bedrock) and the recharge, exclusively from rainfalls, is ensured by the presence of permeable sands with a higher effective infiltration (Banzato et al. 2013; Mastrorillo and Petitta 2009).

In the inner part of the plain, groundwater flows preferentially in the gravel layers of the Pleistocene deposits

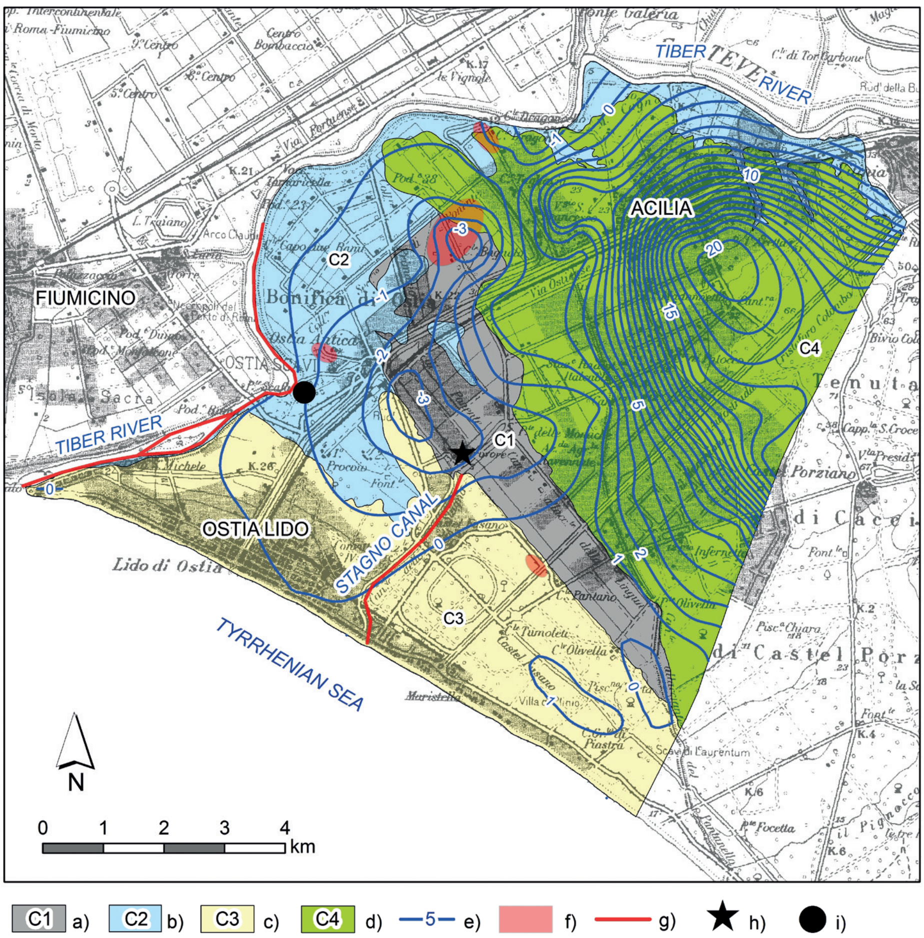

Fig. 2 - Left bank of the Tiber River delta: hydrogeological setting. a) Heterogeneous deposits to backfill quarries HOLOCENE; b) Sandy, silty and clayey alluvial deposits HOLOCENE; c) Sandy beach deposits HOLOCENE; d) Heterogeneous clastic deposits (Sandy- silt and clay deposits interbedded with gravels) PLEISTOCENE; e) piezometric surface (equidistance: 1 m); f) high salinity areas; g) the seawater's rise in the Tiber River and Stagno Canal; h) Ostia reclamation's water pumping station; i) archaeological site of Ostia Antica.

Fig. 2 - Assetto idrogeologico del settore sinistro del Delta del Fiume Tevere. a) Depositi di bonifica OLOCENE; b) Depositi alluvionali sabbiosi, siltosi e argillosi OLOCENE; c) Depositi sabbiosi di spiaggia OLOCENE; d) Depositi clastici eterogenei (depositi sabbioso-siltosi e argillosi intercalati con ghiaie) PLEISTOCENE; e) superficie piezometrica (equidistanza:1 m); f) salinizzazioni della falda localizzate; g) risalita del cuneo marino nel Fiume Tevere e nel Canale dello Stagno; h) Stazione di pompaggio delle Idrovore di ostia; i) sito archeologico di Ostia Antica.

in semi-confined conditions. The hydraulic connection of the groundwater is ensured by the spatial continuity of the gravel horizons interbedded with the sand and silty layers. In the coastal area, groundwater laterally flows to the Holocene sands and the aquifer becomes unconfined. The aquifer shows the highest heads about 20 m a.s.l and a progressive lowering of the hydraulic gradient towards the sea (from 1% to approximately 0.3%) as a consequence of the baseflow level approach. The hydraulic gradient lowering is also related to the changes of the groundwater hydrodynamic conditions from a semi-confined to an unconfined state (Mazza et al. 2015).

In the northwestern part of the plain the water table frequently changes its pattern, showing relatively low head areas (-3 m a.s.l) where the depression level of the water table is kept by the current pumping reclamation activities in order to keep the groundwater below the ground surface and to avoid the formation of swamps.

The groundwater quality shows variable values of "marine" salinization ranging from 0.35 and 7.5 g/L. Nevertheless the water with higher salinity was found in the inner portion of the area and not by the coastline where it would normally be expected it to rise due to the saltwater intrusion effects. Some of the groundwater high salinity areas are present near the Tiber river bank (3.1 g/L) and in the Ostia Antica area (3.8 g/L). These spots of saltwater contamination could be probably caused by river-groundwater flux exchange processes, because of the rise of the seawater in the Tiber River up to 8 km from the mouth (Manca et al. 2014). The mixing between freshwater and saltwater could be also due to a contamination of the shallow groundwater t with the not-fully-exhausted effect on the soil of former salt production activity that lasted approximately 2500 years (Mastrorillo and Mazza 2015)

Data and methods

Data presented here come from the monitoring activity started in July 2014 and consists of water-table monitoring, groundwater electrical conductivity (EC-25°C) and water temperature measurements, coupled with the chemical analysis of major ions. The monitoring network, shown in figure 3, consists of six measurement points:

- **P1** ("Museum well") is an old domestic well used up to early 1960's.
- **P2** ("Diana's house") is an original roman domestic well located in an original roman house.
- **P3** ("Old idrovora") is a no longer used pumping point of the reclamation system.
- **P4** ("Castle's well") is the courtyard's well of Castle of Giulio 2nd dates back to 15th century.
- **P5** ("Tiber River's dock") where elevation of river's level measurements started in July 2015.
- **P6** ("Scafa Bridge") where one chemical sample of Tiber's water was collected in May 2015.

Three of these points (P1, P3 and P4) are equipped with automatic probes (DL70N-Multi STS) to record the hydrogeological data, in a continuous mode. In P3 and P5, data are acquired quarterly by manual measurements (periodic monitoring). In all points, seasonal chemical samples were collected; in P6 only one sampling has been used to identify the chemical composition of salt-wedge intrusion in Tiber mouth.

Rainfall data are acquired by Ostia thermopluviometric station managed by Regional Hydrographic Service.

The manual measurements were made using a conventional water table meter, to evaluate groundwater table depth, and a portable pH-conductivity-meter, to collect data about pH (pH, ± 0.01), Electrical Conductivity (EC, in μS/cm ± 0.5%, normalized at 25°C).

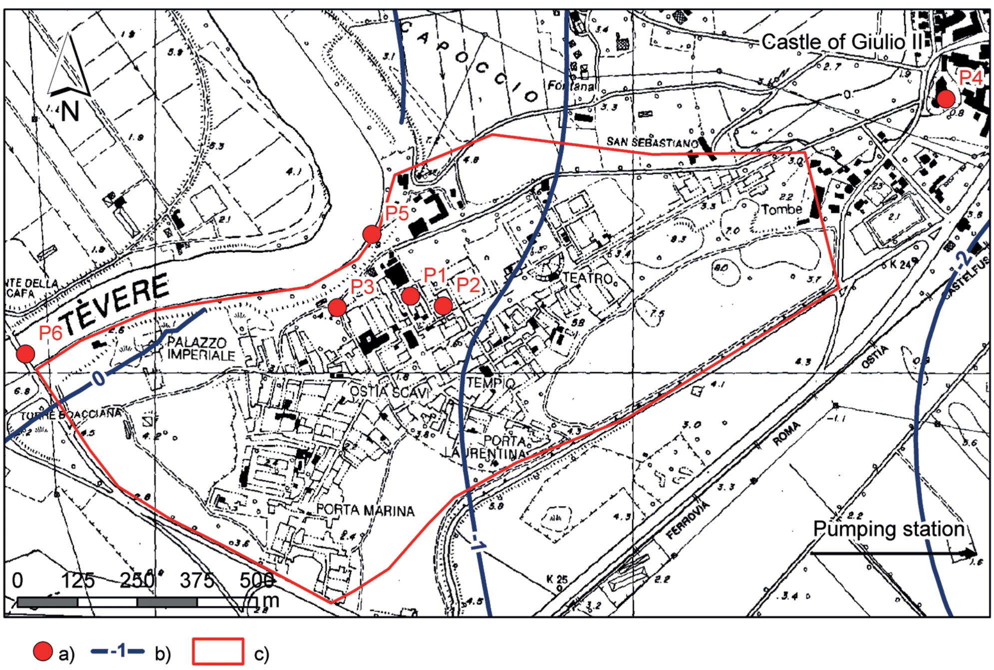

Fig. 3 - Water monitoring network in Ostia Antica's Archaeological site. a) measurement points; b) regional piezometric surface (equidistance: 1 m); c) boundary of arcaheological site

Fig. 3 - Rete di monitoraggio delle acque nel sito archeologico di Ostia Antica. a) punti di misura; b) superficie piezometrica regionale (equidistanza: 1 m); c) confine del sito archeologico.

Water sampling was carried out using a 0.5 L Niskin bottle and transferred to HDPE containers. Water samples were collected at the third drop in the well, to avoid the contamination due to the previous water samples. For each sampling station, two water samples were taken. One of the samples was acidified using a 1 ml nitric acid (HNO_3), to lower the pH <2 and to avoid the cations precipitation. Groundwater samples were collected for chemical analyses of major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}). Calcium, magnesium and hydrogen carbonate concentration were determined by titration with EDTA 0,01 N (Ca and Mg) and HCl 0,02 N (Cl). Sodium and potassium were measured via flame emission spectroscopy, sulphate ion through a colorimeteric method using turbidimetric techniques and chloride with an ion- selective electrode (APHA 2005).

Results

The local distribution of water-table elevation measures (from 0.50 m a.s.l to 1.50 m b.s.l.) evidences a groundwater flow from Tiber River to the reclaimed area according to regional flowpath (Fig. 3). After the first year of monitoring, preliminary results show the link between water table fluctuations and rainfall distributions (Fig. 4). In P4, the closest to Ostia's idrovora pumping station, the steady trend of water level and EC is probably related to pumping activity.

The direct relationship between the groundwater and precipitation is confirmed by the drops of EC values in correspondence to each intense rainfall event. In September 2014, an anomaly was observed in P1 where the first autumnal rain was followed by an EC increase (Fig. 5).

According to the classification of Freeze and Cherry

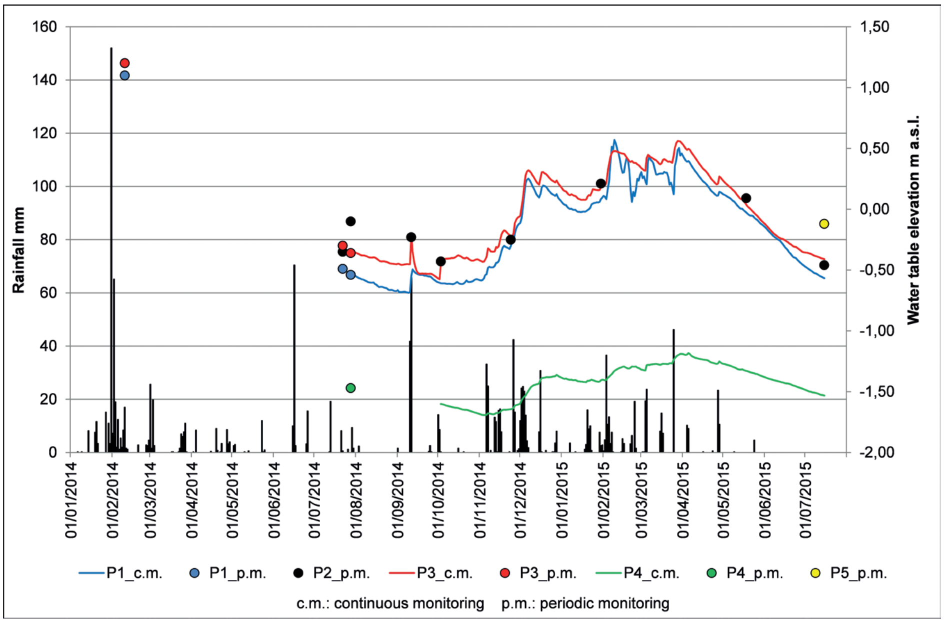

Fig. 4 - Rainfall histogram vs. water table elevation. At the top left the exceptional rainfall event in February 2014.

Fig. 4 - Confronto fra l'andamento delle piogge (istogramma) e il livello di falda. In alto a sinistra il livello raggiunto dalla falda in occasione delle precipitazioni eccezionali del Febbraio 2014.

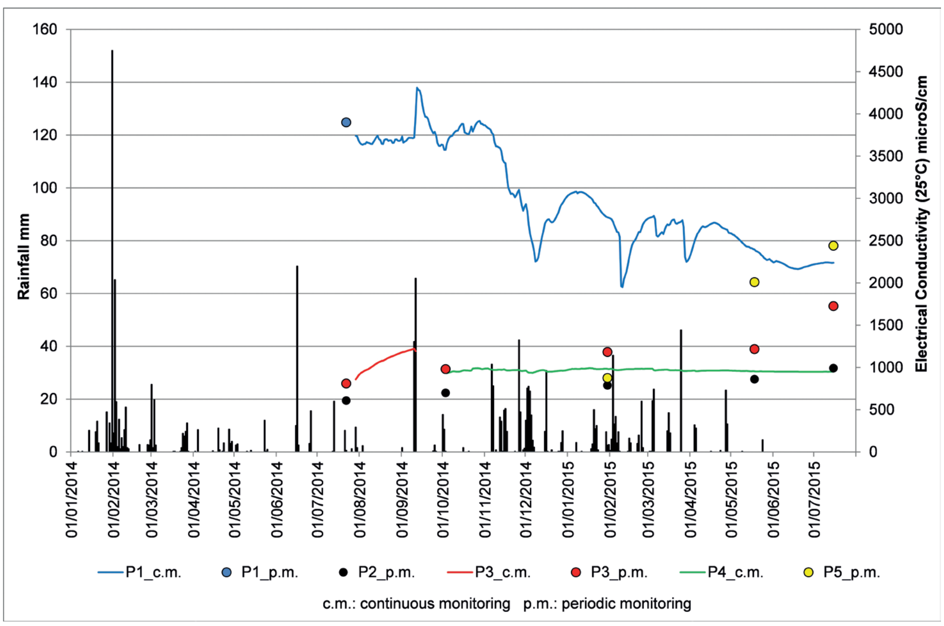

Fig. 5 - Rainfall histogram vs. electroconductivity (25°). In September 2014, an anomaly was observed in P1 where the first autumnal rain was followed by an EC increase.

Fig. 5 - Confronto fra l'andamento delle piogge (istogramma) e i valori di conducibilità elettrica della falda. A settembre 2014 nelle acque del P1 all'aumento delle piogge corrisponde un anomalo incremento dei valori di conducibilità elettrica.

(1979), only groundwater of P1 can be classified as brackish water type (2500 ≤ EC <46700 μS/cm); in the other EC measurements points, freshwater (EC < 2500 μS/cm) always was observed. Groundwater and Tiber River compositions changed throughout the year. P2, P3 and P4 were fresh groundwater with a Ca, Mg – HCO_3 composition in winter 2015, but became Na, K – HCO_3 waters (blue arrow in figure 6) in late spring and summer 2015, with a clear salinization, as shown by the BEX index (Cruz et al. 2011), given by [Cl - (Na+K)] / Cl, with composition expressed as meq/L.

P1 groundwater, is very different from other samples. It is brackish, with a Na, K - Cl, SO_4 composition and a negative BEX (winter 2015). It moved to Na, K - HCO_3 field, with a similar negative BEX in late spring and summer 2015 (blue arrow in figure 6), but its water type was next to the boundary between Ca, Mg - Cl, SO_4 and Na, K - Cl, SO_4 waters (red arrow in figure 6) with a much less negative BEX during the previous summer. These different trends are probably due to climatic changes between the two years, with summer 2014 characterized by more frequent rainfalls during the spring and the early summer compared to the following year.

Tiber River (P5), sampled next to the location of P1, P2 and P3 well, was a fresh Ca, Mg - Cl, SO_4 water in winter 2015 and became a brackish Na, K - Cl, SO_4 water in late spring and summer 2015 (see green arrow in figure 6). The river was also sampled in late spring 2015, about half kilometer downflow Ostia Antica archaeological area. It was a saline water with the composition of sea-water.

Discussion

According to the presented hydrogelogical setting, the Ostia Antica's alluvial sands hosts a phreatic aquifer at a depth of 2 -3 meters b.g.l. with seasonal water table fluctuations of about 1m and recharge from zenith infiltration. Due to the low depth of groundwater, intense and prolonged rainfall events trigger groundwater outflow, in the archaeological low lands. After depletion of rainfall events, the residence time of the flooding conditions depends on decreasing velocity of groundwater level.

Near the mouth, the Tiber River flows within artificial embankments, at higher elevation than the local groundwater table. According to the spatial distribution of piezometric elevation shown in figure 3, different hydraulic head between the Tiber River and groundwater level in correspondence of the alluvial plain could determine a lateral inflow of Tiber seawater to coastal aquifer, triggered by the drainage pumping system. That is because in the Tiber River mouth sector a salt-wedge intrusion was noticed inside the river thalweg (Manca et al. 2014), the lateral inflow could induce a groundwater salinization process. The chemical evolution of groundwater from winter to summer confirms this hypothesis. The inflow of progressively more saline water from Tiber River (from 875 to 2490 μS/cm) from January to July 2015 produces an increase of salinity of P2, P3 and P4 groundwater, with a relative growth of Na+K, with respect to Ca+Mg ions. This mixing is probably associated with a base exchange process.

The high salinity values of P1 (Na, K – Cl, SO_4 brackish

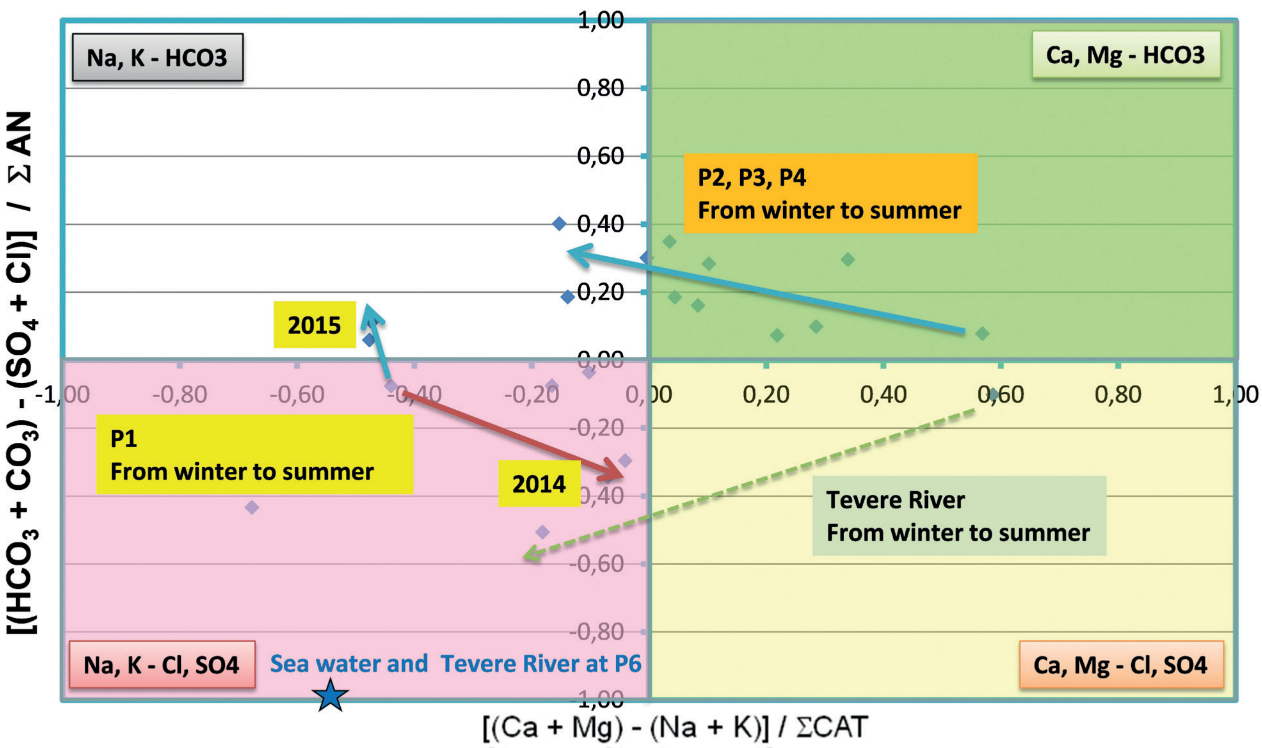

Fig. 6 - Composition expressed in terms of meq/L and chemical evolution (from winter to summer) of groundwater and Tiber River water in the Ostia Antica archaeological site.

Fig. 6 - Composizione chimica delle acque di falda e del Fiume Tevere e loro evoluzione stagionale (dall'inverno all'estate).

water, about 4000 µS/cm in September 2014) could be explained by the well location, close to the ancient salt storage warehouse (now Ostia Antica museum). It is possible that residual salt, trapped in the soil, was leached into local aquifer, producing a temporary increase of EC during the first autumnal recharge. The dissolution of precipitated salts in the area of P1 well has been probably recorded by the chemical composition of groundwater of July 2014, which seems to be affected by a process of base exchange with an increase of $Cl+SO_4$ concentration and the sorption of Na+K by sediments with associated release of Ca+Mg. This process has not taken place in July 2015, a very dry and hot season, when P1 well seems to follow a chemical trend comparable to that of other wells, with a simple mixing with the Tiber River.

Conclusion

The first results of Ostia Antica groundwater monitoring highlighted that the former pumping ad canals system of the archaeological site should be restored in order to try to keep the groundwater always below the level of the archaeological excavations. For the purpose of this project, the space distribution of the water table fluctuations inside the site is being defined and compared with the framework of the former drain system. One of the aims of the research project is to realize a map of areas of potential flooding in relation to the water table head. To achieve this objective another year of studies has been planned by the research team. In the next year the groundwater monitoring network will be increased with more piezomiters.

Of interest is also to understanding the supposed hydraulic connection between the groundwater and Tiber River. The water sampling will continue and further chemical analyses could be improved by the evaluation of some minor ions (as Bromine and Radon) concentrations for identifying the salinization sources due to the different values they assumes for seawater intrusion, and halite (crystallized in the ancient salt-works) dissolution processes (Davis et al. 1998). Soil samples will be also analyzed to confirm the salt dissolution in the soil around the ancient salt storage warehouse and to define the ion exchange processes between soil and water.

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