MONITORING THE PHENOMENON OF SEAWATER INTRUSION IN THE ESTUARY AREA OF THE RIVER MAGRA AND IN THE ALLUVIAL PLAIN OF THE LOWER VAL DI MAGRA (SP)

Marco Sabattini, Francesco Ronchetti, Diego Arosio, Gianpiero Brozzo, Andrea Panzani

Abstract: Seawater Intrusion (SI) is a critical problem as a consequence of climate change. The progression of the salt wedge inland compromises the quality and quantity of groundwater, seriously damaging agriculture and gradually desertifying the territory. The alluvial aquifer of the Lower Val Magra (LVM) is one of the most important in Liguria (Italy). It supplies drinking water to the city of La Spezia. The main objective of this research is to determine the severity of the SI phenomenon in the LVM aquifer and in the River Magra estuary. Data from different databases (ACAM, Aral, Ispra) and new original data were used for this purpose. The analytical methods focused on multivariate statistics (HAC, PCA and PLS). It was found that the migration pattern of SI along the estuary is mainly controlled by river discharge and wind speed. The weir in Romito (8.5 km from the sea coast) is the current limit of the SI in the R. Magra. About the groundwater, the most salinized wells are concentrated in the Marinella plain. For the other part of the LVM, aquifer water quality is good, but will be deteriorate in the next years as a consequence of climate change.

Keywords: Seawater, Groundwater, Isotopes, Estuary, Monitoring

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Introduction and test site setting

Seawater intrusion (SI) in the Mediterranean area is a critical problem. Population growth and climate change increasingly expose coastal aquifers to salinization. The progressive intrusion of the salt wedge inland causes soil salinization, reducing soil permeability and severely damaging agriculture. This process impoverishes ecosystems, particularly in terms of plant species biodiversity, and ultimately leads to the desertification of the territory, with severe environmental, health, and economic consequences.

Liguria (Italy) is a region on the Tyrrhenian Sea coast. It is a hilly territory where alluvial plains are few, of limited extension and often densely populated. The aquifers in these flood plains are frequently of limited thickness (a few tens of metres).

The alluvial aquifer of the Lower Val Magra (LVM) (Figure 1) is one of the most important in the region. It supplies drinking water to the city of La Spezia and numerous municipalities in the area. The LVM is highly urbanised, industrialised and has extensive agricultural areas. The main features of the LVM aquifer are listed in Table 1 [1, 2, 11].

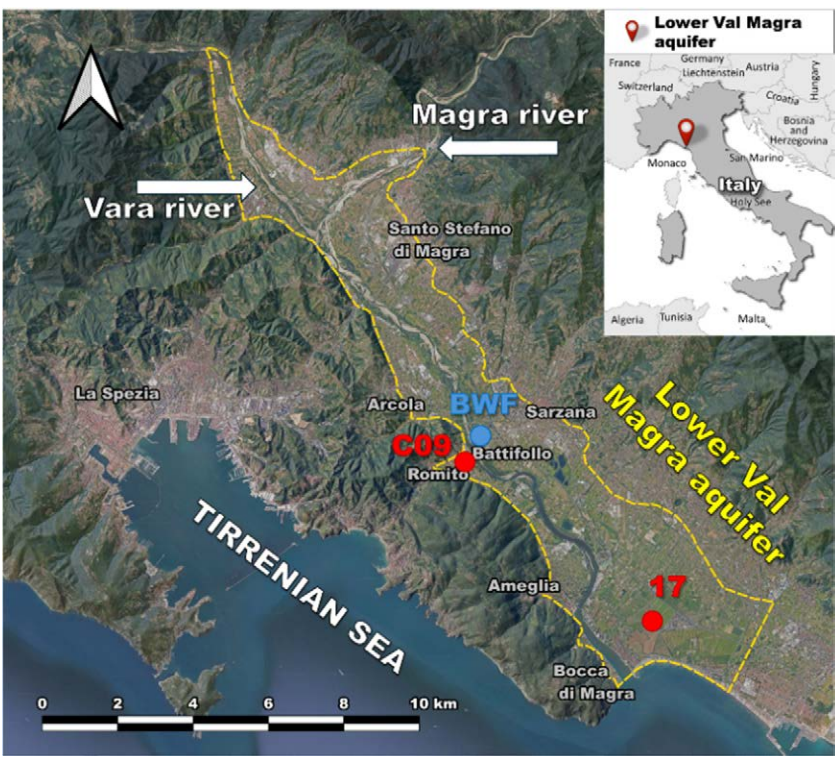

Figure 1 – Location and map of the research area and boundaries of the LVM aquifer. In red are represented the wells (C09 and 17) where the SI was detected. In blue is displayed the position of the Battifollo aqueduct Well Field (BWF).

The Lower Val Magra region experiences both tectonic and sedimentary subsidence due to its graben structure. Tectonic downwarping has led to the accumulation of a thick sediment layer, forming the current alluvial deposit. This subsidence is more intense downstream of the Romito-Sarzana line, where a transverse fault disrupts the graben's continuity. South of Sarzana, where subsidence is greater, the sediment deposit exceeds 50 meters in thickness. This downwarping has historically created favorable conditions for transitional environments such as marshes, coastal lagoons, and bays [1, 2, 11].

Tectonic and sedimentary subsidence, along with recent sea level rise due to climate change, are increasing the intensity and accelerating the process of SI in the region. The estuarine morphology of the Magra River, the main source of aquifer recharge, serves as a preferential pathway for SI into inland areas [16]. The combination of these predisposing factors and the site's high significance makes seawater intrusion a tangible risk for the region.

Table 1 – Summarises the main characteristics of the LVM aquifer and its boundary.

Aquifer features
Unconfined
Water table closes the ground level (3-7 m depth)
Single-layer/multi-layer (towards the sea)
Aquifer texture: coarse deposits (high permeability)
Aquifer recharge by: river, rainfall and irrigations
SI is the main cause of water quality degradation in the area
Land use: urban area, industrial area, agricultural area

Recent monitoring of groundwater electrical conductivity (EC) in several wells has revealed rapid salinization related to SI phenomena, extending from the seacoast up to 8 km inland (Figure 2). The proximity of the CO9 well in Romito, which is periodically affected by these phenomena, to the Battifollo aqueduct Well Field (BWF) (Figure 1) has necessitated further investigation into SI in the Lower Val Magra (LVM) to protect the fresh groundwater resource.

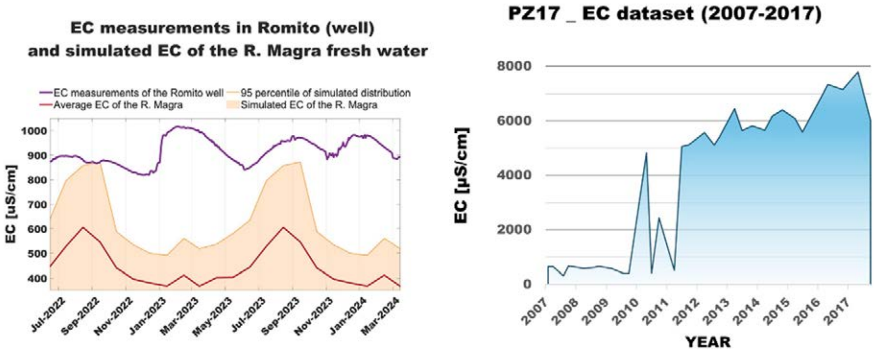

Figure 2 – Left: EC signal (continuous monitoring) of groundwater at well C09 in Romito (8 km from the sea coast) and comparison with freshwater EC values of the R. Magra. Right: EC signal (periodic monitoring) of groundwater at well 17 (1.2 km from the sea coast).

In order to protect people's health and to preserve BWF, this research has the following objectives:

- To update knowledge on SI in the LVM plain with a focus on the R. Magra estuary
- Conceptually define the saltwater migration process along the estuary
- Hydrochemical exploration of the floodplain to identify aquifer recharge areas
- Identify areas of the aquifer potentially exposed to SI
- Investigate salinisation dynamics of wells

Materials and Methods

The research was organised into 2 macro-themes:

1. R. Magra and surface water monitoring. For this purpose, 14 strategic monitoring points were identified along the R. Magra and in its estuary (Figure 3). At these stations, every 2 months, EC measurements of surface water were performed and samples were collected. The water samples were analysed using Isotope Ratio Mass Spectrometry (IRMS ISO) to measure the environmental tracer $\delta^{18}O$ [12]. Estuaries are highly dynamic systems governed by the interactions of tides, river flows and coastal currents [3, 16, 17]. Partial least square (PLS) regression technique was applied to model the data measured at the stations using the main environmental variables. The environmental variables considered in the model are: river discharge, tidal oscillations and wind direction and speed. These data come from the Arpal and Ispra databases.
2. Groundwater monitoring. For the objectives, a robust dataset was created by including hydrochemical data (major elements, trace elements and physical parameters) from 45 wells in the LVM (ACAM and Arpal sources) (Figure 3). The dataset was processed using multivariate analysis techniques: hierarchical cluster analysis (HCA) and principal component analysis (PCA) [6].

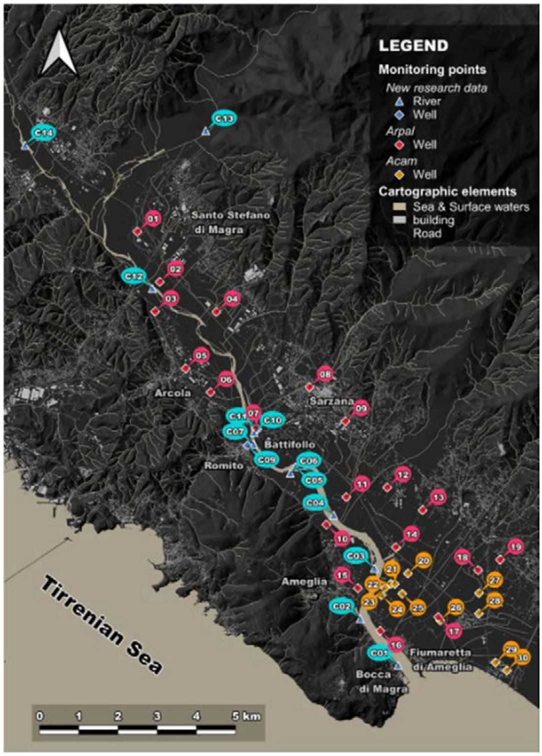

Figure 3 – Map displaying the location of the monitoring points. For some points the data come from databases published by other institutions (Arpal, ACAM), for other points new sampling was carried out (new research data).

Results

During the research years (2022 and 2023), a meteorological condition of intense and protracted drought was observed.

The Standard Precipitation Index (SPI) was used to quantify the magnitude of the drought phenomenon [10, 18, 19]. Data from the Sarzana weather station are used for the calculation. The station has an important historical record, with cumulated rainfall data from 1932 to the present.

Figure 4 shows as a matrix the SPI value for the years 2008-2023 (columns) calculated with aggregations of 3, 6, 12 and 24 months (rows). The chosen aggregation times provide information on the possible effects of drought in the short and long term [9, 10, 13, 15, 18, 19].

In the period 2022-2023, the index values (reaching -3) show severe (< -1.5) and extreme (< -2.0) drought conditions for all aggregation periods considered. This suggests probable negative effects on soil moisture, river discharge and aquifer recharge [9, 10, 13, 15, 18, 19].

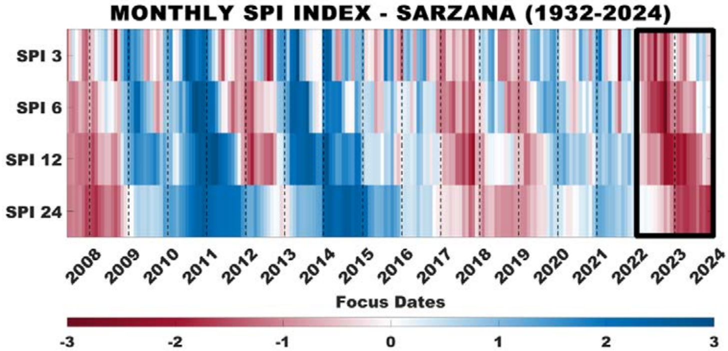

Figure 4 – SPI index matrix calculated for the Sarzana station. In the black rectangle is highlighted the research period.

During the same period, surface water EC values were measured periodically during 6 measurement campaigns involving all monitoring stations on the R. Magra. The collected data were reported in maps showing time-lapse images of the SI pattern along the estuary. SI pattern are the result of different climatic conditions and seasonality and summarise the dynamism of the estuary area.

The two extreme situations observed are shown in Figure 5: at left the EC pattern representing the minimum SI and at right the EC pattern representing the maximum SI along the R. Magra. The maximum observed SI reaches the natural weir located at the Romito toponym, 8.5 km from the mouth.

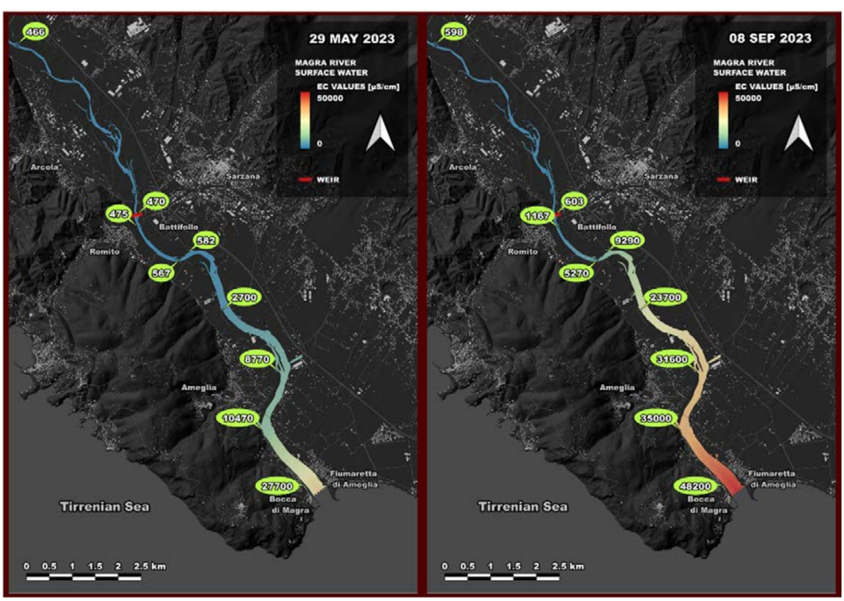

Figure 5 – At left: EC pattern representing the minimum SI observed along the R. Magra estuary. At right: EC pattern representing the maximum SI observed along the R. Magra estuary.

Regarding surface water isotopic monitoring, the graph in Figure 6 shows the EC- $\delta^{18}O$ pairs of all the monitoring stations downstream of the Magra-Vara confluence during all the measurement campaigns. For the stations located in the estuary area (C01-C07), the graph shows a clear linear correlation between the two parameters (R2 = 0.99). This correlation is the result of the freshwater-saltwater mixing that changes in time and space, from Bocca di Magra to Romito, as a consequence of winds, tides and river discharge.

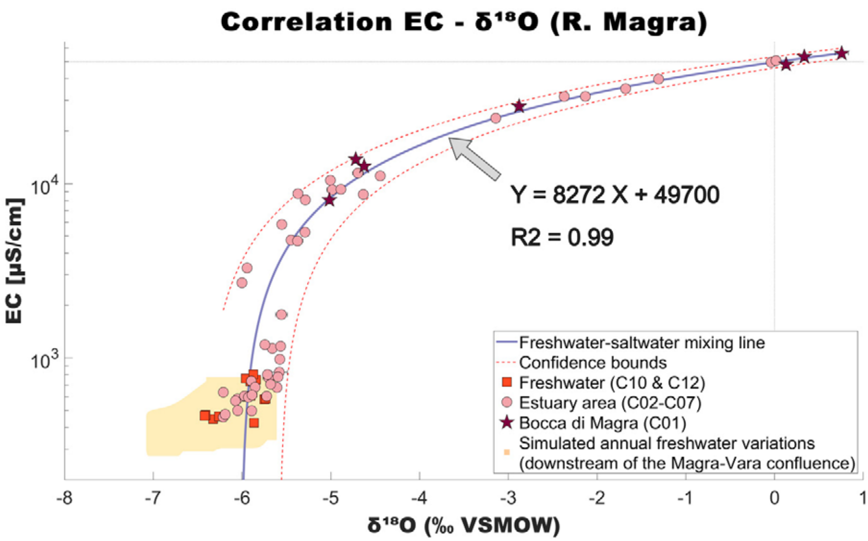

Figure 6 – EC- $\delta^{18}O$ bi-variate plot for all R Magra surface water samples collected.

The application of the HCA to the LVM groundwater hydrochemical dataset permitted the definition of 5 clusters. The map (Figure 7) shows the spatial distribution of the 5 clusters. Voronoi polygons are used for the spatial transposition of the data obtained. A difference in groundwater chemistry between the wells upstream and downstream of Battifollo is evident.

Finally, the map in Figure 7 shows the groundwater EC values measured in the wells. The map indicates that wells near the estuarine area have above-average EC, with the highest values located in the Marinella plain, north of Fiumaretta.

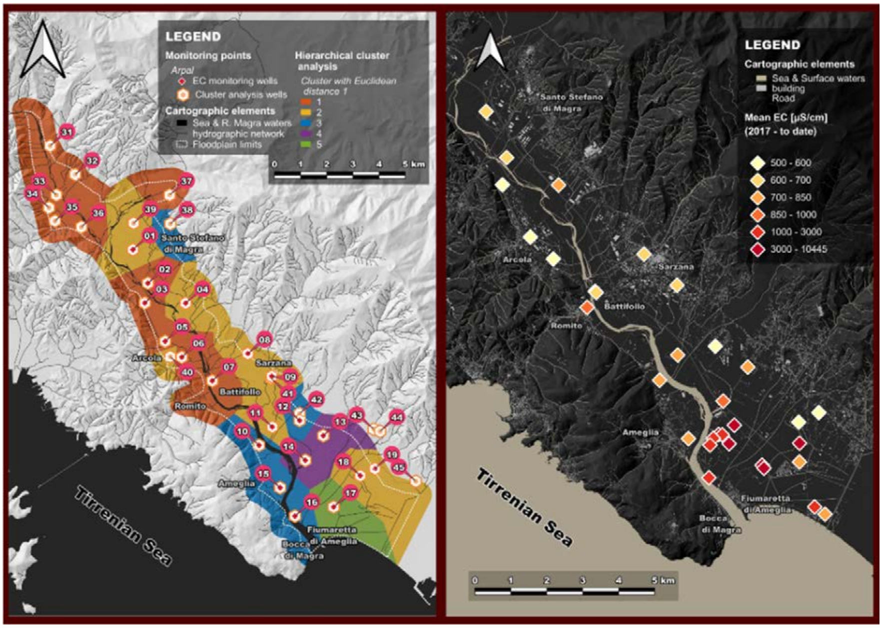

Figure 7 – At left: map showing the spatial distribution of the 5 clusters obtained through HCA. At right: map of groundwater EC values measured in wells (EC value: average from 2017 to date).

Discussion

The distribution maps of electrical conductivity (EC) in surface waters (Figure 5) show constant values upstream of the natural weir at Romito, while downstream, the EC values progressively increase due to the presence of seawater. The weir creates a higher hydrometric level upstream, forming a natural barrier for SI in surface waters. During the investigations, the weir marked the limit of SI along the R. Magra, 8.5 km from the coast.

The natural weir at Romito is the only altimetric protection for the BWF. However, future sea level rise scenarios, published by NASA and corresponding to global eustatic variations, indicate that the weir will be insufficient to contain SI along the R. Magra. (Figure 8) [4, 5, 7]. These scenarios become even more critical considering the ongoing tectonic and sedimentary subsidence in the area.

A strong correlation between EC and $\delta^{18}O$ was obtained in surface waters in the estuarine area. This suggests that both parameters can be used as predictors of freshwater-saltwater mixing and consequently to monitor the SI. This is true for surface water as well as groundwater (Figure 9).

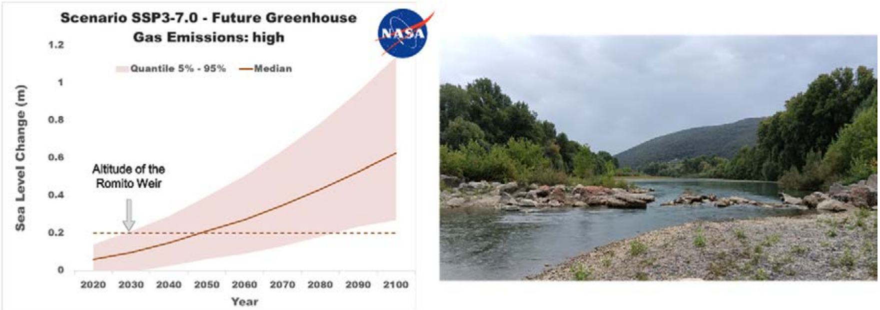

Figure 8 – At left: sea level rise scenario (NASA) and comparison with the altitude of Romito Weir. At right: photo of Romito Weir.

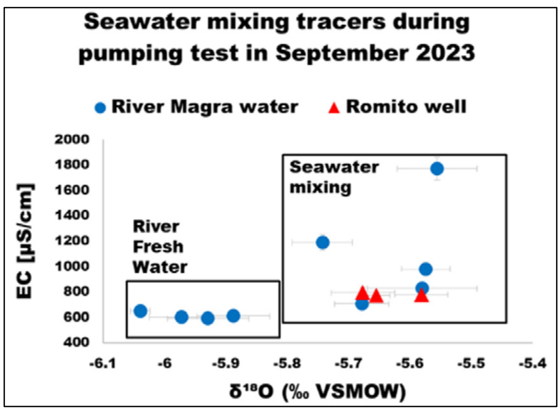

Figure 9 – Application of the EC- $\delta^{18}O$ pair to identify SI in groundwater in the Romito well. The EC- $\delta^{18}O$ values of the groundwater are compared with the values measured in the surface waters of the R. Magra in the same days and representing freshwater-saltwater mixing.

$\delta^{18}O$ is calculated from stable isotopes of the water molecule. This means they are little affected by factors such as the presence of pollutants. This characteristic is among the advantages of $\delta^{18}O$ over EC and for this reason $\delta^{18}O$ was chosen in this research as the target for PLS.

PLS was applied to investigate the effects of some environmental factors (river discharge, tidal oscillations and wind direction and speed) on the SI migration in the surface waters of the R. Magra. The multivariate regression model suggests that discharge and wind speed are the main factors controlling the pattern of SI along the estuary. The dominant winds from the sea to the inland (Figure 10) and the low river discharge are the main predisposing factor for SI. In contrast, tidal fluctuations are less relevant and only contribute at the extremes of the estuary area (C01, C06 and C07).

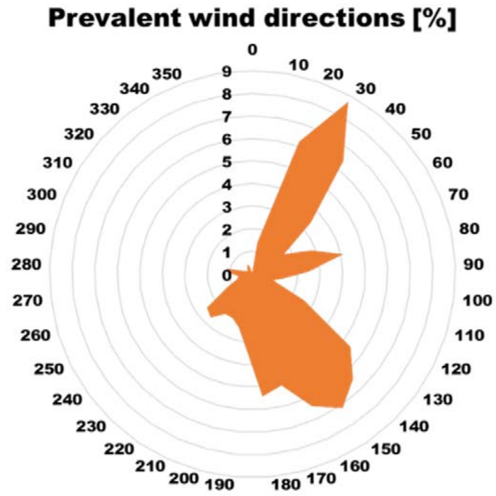

Figure 10 – Direction of dominant winds from 2010 to date in the study area (La Spezia tide gauge).

HCA was applied for the exploration of the groundwater hydrochemistry dataset (major elements, trace elements and physical parameters). The HCA distinguished five main clusters. PCA on the same dataset identified the characteristics describing these clusters and suggest a possible interpretation:

- Cluster 1 - low-salt waters directly connected to the R. Magra;
- Cluster 2 - waters with a higher salt content than Cluster 1, but still connected to the waters of the R. Magra;
- Cluster 3 - waters chemically different from the first two clusters and related to streams coming from the valley slopes;
- Cluster 4 - waters with a high carbonate content and related to streams coming from the valley slopes;
- Cluster 5 - waters with a high salt content, especially chlorides, resulting from mixing with seawater.

The HCA shows a clear hydrochemical distinction in groundwater between the wells upstream and downstream of the natural Romito weir.

Moreover, the HCA supports the hypothesis developed by some authors that the alluvial deposit downstream of Battifollo is not gravelly-sandy but is predominantly pelitic [11]. According to this hypothesis, towards the sea the aquifer became multi-layer. The most superficial layer is associated to the presence in the fine deposit of sandy cords (old seacost) and of the ancient river system of the Magra (Roman age). The EC values of the groundwater support this hypothesis and suggest a relationship between these ancient environments and the SI in the Marinella plain.

Conclusion

The research was conducted during an intense and anomaly drought period that characterized all the Mediterranean area in the years 2022-2023. Climate change may favour these periods of extreme drought with increasing frequency and severity. This drought phenomenon can facilitate SI and compromise the quality of superficial water and groundwater in the coastal area.

In our test site, about superficial water, results highlighted as the migration of salt water along the estuary of the R. Magra is mainly controlled by river discharge and wind speed. The natural weir in Romito (8.5 km from the sea coast) is the current limit of the SI and the only protection of the BWF. Future scenarios of relative sea level rise (resulting from subsidence and climate change) could soon invalidate this natural protection for the BVF [4, 5, 7].

Nowadays, about the groundwater, the most salinized wells are concentrated in the Marinella plain. There is probably a relation between their spatial distribution and the ancient Magra river system and sea coast line. For the other part of the LVM, aquifer water quality is good, but will be deteriorate in the next years. According this risk, the main suggestions that the research recommended are:

- Implementation of a continuous monitoring network (EC) for the aquifer in the LVM, and in particular in the Marinella plain and in the BVF area.
- Design of a new weir where the Romito natural weir is localized.

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