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STRENGTH

D.2.3.2

Survey of the impact of saltwater intrusion on CBPF hydraulic network and Ferrara urban ecosystems

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2. Executive Summary

The territory of the Emilia-Romagna Region is divided among 8 land reclamation consortia, including the Ferrara Plain Reclamation Consortium (CBPF), established on October 1, 2009, pursuant to Regional Law No. 5/2009 of April 24, 2009. Today, it is recognized as the largest in Italy, both in terms of the number of contributors and the scale of the reclamation works (Figure 1).

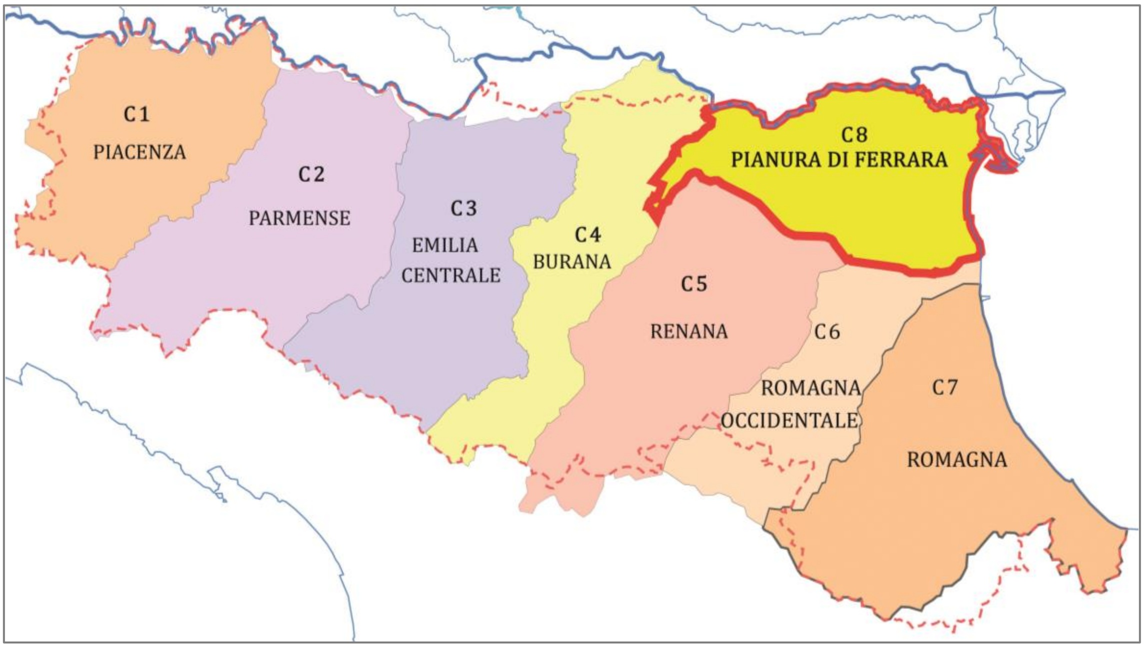


Figure 1 – The Land Reclamation Consortia of the Emilia-Romagna Region

The drainage basin managed by the CBPF covers an area of approximately 250,000 hectares and exhibits unique characteristics both at the national and European levels. The district's territory, which largely coincides with the Province of Ferrara, lies at the easternmost edge of the Po Valley and is bounded by major raised rivers: the Po to the north, the Reno to the south, and the Panaro to the west, while to the east it is bordered by the Adriatic Sea.

As shown in the elevation map in Figure 2, which illustrates the ground elevations relative to sea level divided into altimetric bands, the topography gradually decreases from west to east and from south toward the Adriatic Sea, ranging from a maximum elevation of approximately 25–30 meters above sea level in the area around Cento to negative elevations in the eastern zones near Comacchio, Codigoro, Lagosanto, Goro, and the Po River delta.

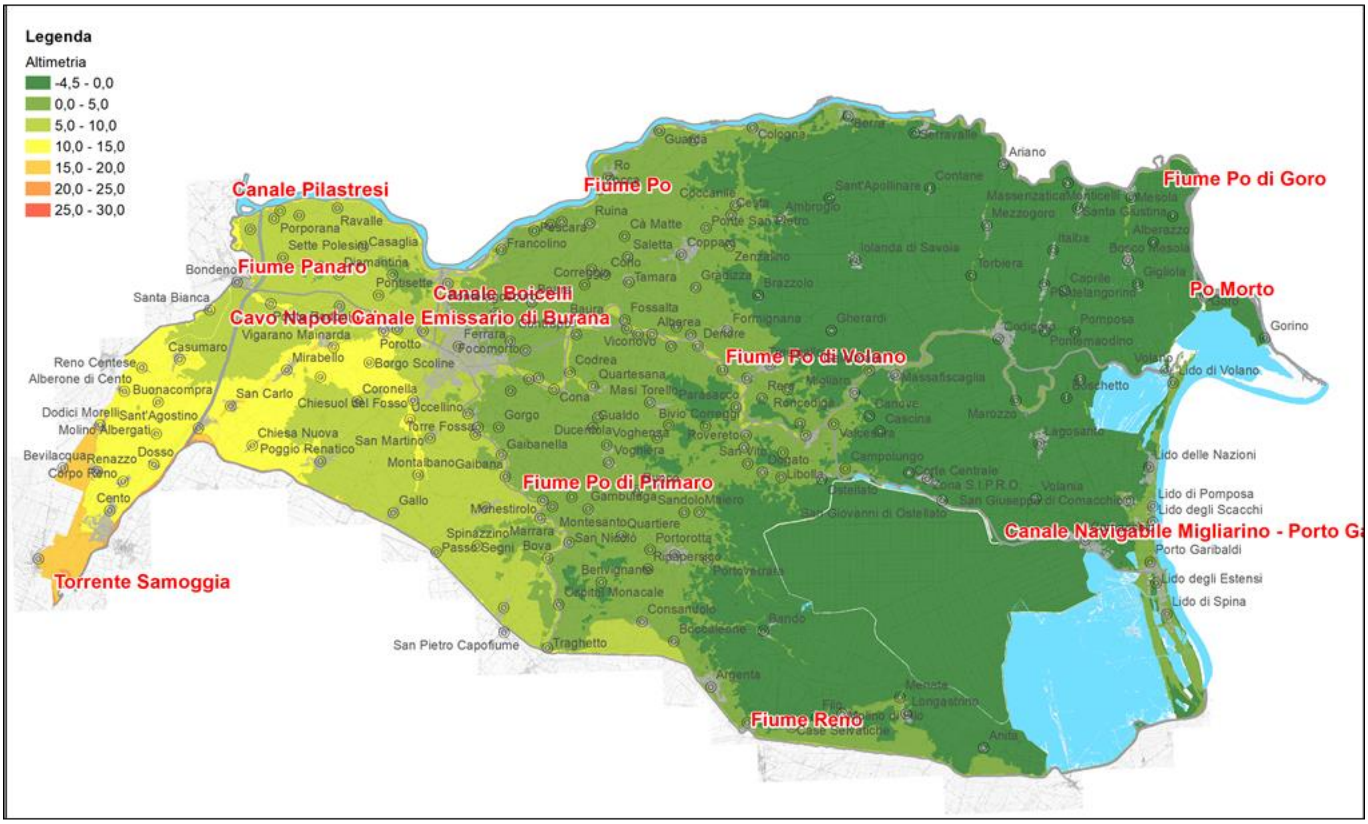


Figure 2 – Topographic elevation above sea level of the area managed by the CBPF

Overall, the territory managed by the CBPF is characterized by a vast low-lying or flat basin, with over 40% of its area lying below sea level (light green and dark green areas).
The central-eastern lands of the Ferrara Plain were formed as a result of the reclamation of ancient wetlands and lagoons that were once occupied by brackish or saline waters, often connected to the nearby Adriatic Sea or affected by tidal and saltwater intrusion phenomena.
This long historical reclamation process, initiated as early as the Roman period and intensified in the following centuries, made it possible to recover extensive areas for agriculture and human settlement.
However, the residual presence of salts in both soils and waters - due to the brackish origin of the sediments, low elevation, and limited natural percolation - means that these lands still exhibit high salinity levels today, with significant implications::

- For agriculture: specific cultivation practices are required to manage saline soils;
- For water management: continuous monitoring and maintenance of the reclamation canal network are necessary;
- For the environment: salinity influences the composition of vegetation and local ecosystems.

The coastal area of the Ferrara Province - particularly the section comprising the Northern Lidi (a group of four seaside resorts located north of the municipality of Comacchio, namely Lido di Volano, Lido delle Nazioni, Lido di Pomposa, and Lido degli Scacchi) and the Southern Lidi of Comacchio (namely Porto Garibaldi, Lido di Spina, and Lido degli Estensi) - currently represents one of the most vulnerable territorial zones along the entire northern Adriatic coast, both from an environmental and a hydraulic standpoint.
In this portion of the territory, the combined pressure of natural factors (saltwater intrusion, natural subsidence, low rainfall, prevailing dry winds, high summer evaporation rates, and soils poor in organic matter) and anthropogenic factors (excessive groundwater withdrawal, urbanization and soil sealing, intensive agriculture and inefficient irrigation, and climate change induced by greenhouse gas emissions) is leading to a progressive process of desertification, with increasingly significant impacts on ecosystems, agriculture, and urban livability.
One of the main scientific sources for long-term sea-level projections is the IPCC Sixth Assessment Report (AR6, 2021), which estimates the Global Mean Sea Level (GMSL) for the year 2100, under the high-emission scenario (SSP5-8.5), at 0.77 meters (with a likely range between 0.63 and 1.01 meters).
Therefore, the rise in the Adriatic Sea level, combined with the ongoing phenomena described above, is expected to lead to an increasingly pronounced saltwater intrusion along both surface and groundwater bodies, posing the risk of rendering the water unsuitable for irrigation and drinking purposes, and threatening local crops and water resources.

In this complex context, the coastal area of Ferrara can therefore be regarded as a true climatic and environmental hotspot, where it is urgent to implement mitigation and adaptation measures supported by up-to-date scientific data and continuous monitoring.
Based on these premises, there arises the need to carry out an in-depth investigation into the impact of saltwater intrusion on both surface and groundwater, with the aim of quantifying the phenomenon, understanding its effects at territorial and urban scales, and proposing integrated management and resilience solutions.

The study aims primarily to analyze salinity levels in surface waters, groundwater, and irrigation canals, in order to accurately map the areas affected by saltwater intrusion and to understand the extent and geographic distribution of the phenomenon.
In parallel, the assessment intends to evaluate the impact of saltwater intrusion on the hydraulic infrastructures managed by the Consortium, such as canals, pumping stations, and sluice gates, as these elements are particularly vulnerable to variations in water quality.

The consequences of saltwater intrusion could, in fact, be severe across multiple sectors: from agriculture—potentially affected in terms of crop productivity and quality—to the overall availability of water resources, and to the impacts on local ecosystems, which are often fragile and highly dependent on saline balance.
One of the main objectives of this work is to identify and propose effective mitigation and adaptation strategies capable of limiting current damages and preventing further critical issues in the future, which will be further examined in Deliverable 3.3.2.

3. Surface Waters

Agriculture represents one of the primary and most significant economic activities in the Province of Ferrara, not only due to the extensive area of cultivated land but also for the added value it generates. In 2020, the sector produced approximately € 468 million, accounting for 5.4% of the provincial gross value added (GVA) — a share more than double the regional average and nearly three times the national figure.
In addition, the sector has a substantial employment impact, with over 8,000 people employed, representing 5.2% of the total workforce in the province. The agricultural business structure is also highly consolidated, comprising about 5,000 farms, equivalent to 17% of all enterprises in the province (Source: Statistical and Economic Information, Ferrara Chamber of Commerce, 2024).

In a territory such as the Ferrara area, which is largely flat and in many cases below sea level, **water supply management assumes a strategic importance** - both to ensure agricultural productivity and to prevent soil salinization phenomena, increasingly frequent as a consequence of climate change and marine intrusion.
For this reason, it is essential to guarantee not only an **adequate quantitative availability of irrigation water, particularly during the summer months, but also to ensure its qualitative suitability**. The presence of dissolved salts, when exceeding certain thresholds, can severely compromise crop yields, either by directly damaging the plants or by causing complete crop losses—as high salinity reduces the root water uptake capacity, leading to leaf necrosis, growth inhibition, and yield reduction. Moreover, excessive salinity can cause significant and semi-permanent degradation of soil properties, undermining long-term agricultural sustainability.

When the sodium concentration in the soil exceeds certain thresholds, this element tends to replace calcium and magnesium ions adsorbed on clay particle surfaces. Such a process profoundly alters the soil's physicochemical balance, leading to particle dispersion and structural compaction.

The immediate consequence is a loss of structural stability: the soil becomes less porous, water infiltration decreases, and surface ponding occurs, while air circulation within the deeper layers is severely restricted. Over time, these processes cause progressive and often semi-permanent degradation of the soil profile. Ultimately, the soil may lose its agricultural functionality entirely, becoming an impermeable and sterile surface, unsuitable for sustaining any type of crop.

Qualitative monitoring of irrigation water is therefore of fundamental importance, particularly with regard to the measurement of dissolved salt concentration, which is often indirectly estimated through electrical conductivity (EC) measurements, expressed in mS/cm.

In general, there are no universal threshold values that define whether water is suitable for irrigation use, as salinity tolerance varies depending on crop species, phenological stage, irrigation techniques, and soil characteristics.

However, based on field experience and specific local conditions within the Ferrara district, it is generally considered that the use of irrigation water with electrical conductivity (EC) values below 1.5–2.0 mS/cm does not cause significant issues. Water with EC values between 2.0 and 3.0 mS/cm can still be utilized with caution, whereas values exceeding 3.0 mS/cm make irrigation strongly inadvisable, as such salinity levels can drastically reduce plant water uptake, impair growth, and, in extreme cases, lead to complete crop failure.

Some crops, such as wheat or olive trees, exhibit a higher tolerance to saline conditions, but most high-value crops typical of the Ferrara area—including processing tomatoes, fruit trees, and vegetables—require low-salinity water to maintain high productivity and quality standards.

As a useful reference, the Po River water typically shows an electrical conductivity of around 0.5 mS/cm, whereas seawater generally exceeds 30–35 mS/cm.

In a context such as that of Ferrara, where agriculture is an integral component of both territorial identity and the local economy, ensuring the availability of high-quality, low-salinity water is not merely an agronomic necessity, but a strategic priority for the resilience and competitiveness of the entire agricultural sector.

The complex hydraulic network managed by the Ferrara Plain Reclamation Consortium, which extends over 4,000 km of canals and includes more than 170 pumping stations operating during the irrigation season, plays a crucial role in maintaining this balance. The system ensures not only the drainage of excess water, but also the distribution of freshwater resources for irrigation purposes, thereby supporting both soil conservation and agricultural sustainability.

The agricultural water supply of the aforementioned network is sourced from the main watercourses crossing the coastal area of Ferrara and discharging into the sea - specifically, from north to south, the Po di Goro, Po di Volano, the Migliarino–Ostellato–Porto Garibaldi navigable canal, and the Reno River (Figure 3).

The Ferrara Plain Reclamation Consortium derives a total annual volume of approximately 450 million m^3 from this system of abstraction points. Irrigation water supplying the Province of Ferrara originates almost entirely from the Po River.

The main abstraction points are as follows:

- Pilastresi pumping station, managed by the Burana Reclamation Consortium, with a maximum licensed discharge of 47 m^3/s, of which 44 m^3/s are allocated to the Ferrara Plain Reclamation Consortium and 3 m^3/s to the Reclamation Consortium. A share of 8 m^3/s of the total 44 m^3/s may be drawn from the new Pontelagoscuro station, connected to the new navigation lock.
- Palantone pumping station, managed by the CER Reclamation Consortium, which allocates 5.9 m^3/s of its maximum licensed discharge of 68 m^3/s to the Ferrara Plain Reclamation Consortium.
- An additional share, with a combined discharge capacity of 42 m^3/s, is derived through the siphon systems of Guarda, Contuga, Berra, and Garbina.

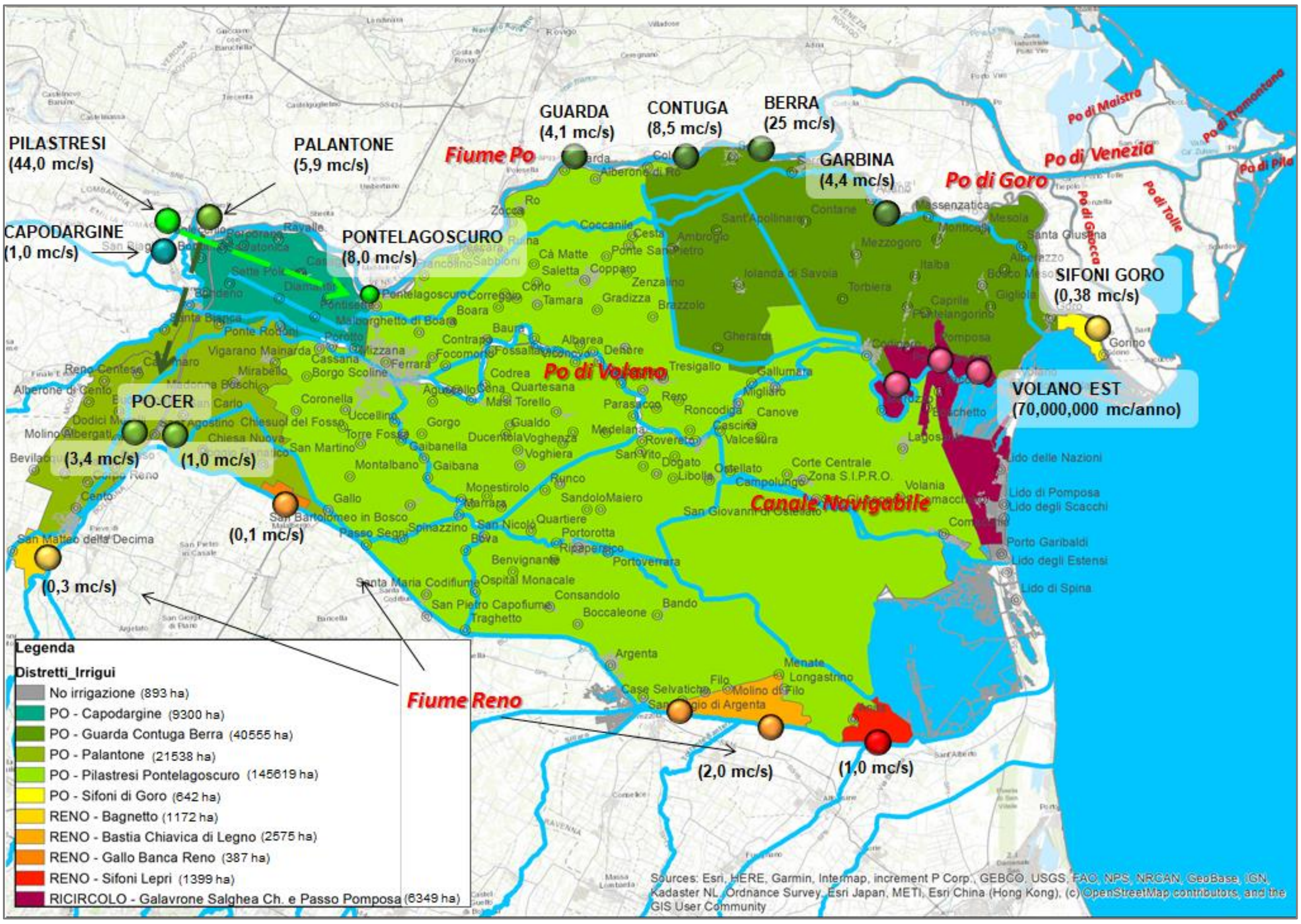


Figure 3 – Irrigation Macro-Districts of the Consortium

The upstream progression of the saline wedge along these hydraulic channels may pose a significant issue, as—beyond a certain distance—it can limit or entirely prevent water abstraction, depending on the location of the intake points and their proximity to the river mouth.

The implementation of anti-salinity barriers, together with the use of real-time monitoring systems for salinity level control, represents a key component in the sustainable management strategy of water resources. These measures are essential to safeguard freshwater availability, particularly during low-flow and drought conditions, and to preserve the long-term functionality of the irrigation network.

3.1. Monitoring Network of Watercourses in the Province of Ferrara

The quality of surface waters is assessed according to the principles established by the EU Water Framework Directive 2000/60/EC, transposed into Italian legislation through Legislative Decree No. 152/2006.

This regulation introduced a new approach to water resource management, based on ecological and sustainable criteria, with the objectives of protecting aquatic ecosystems, promoting the rational use of water, reducing pollution, ensuring water availability, mitigating the impacts of extreme events such as droughts and floods, and actively involving citizens and stakeholders in environmental planning processes.

At the core of this strategy lies the **ecosystem-based approach**, which regards the river as a living organism to be safeguarded in its entirety—encompassing both its physico-chemical integrity and biodiversity. Within this framework, **monitoring networks** are not merely technical tools for data collection, but constitute key instruments for territorial governance.

By measuring qualitative and quantitative parameters, it becomes possible to plan remediation actions, assess the effectiveness of implemented measures, and support adaptive management of water bodies in line with sustainable development goals.

The legislation requires **the classification of water bodies according to their ecological and chemical status**, defining five quality classes: high, good, moderate, poor, and bad.

The overarching goal is to achieve at least "good status" for all water bodies, or to maintain "high status" where it already exists.

This assessment is based on a range of parameters, including the composition of aquatic flora and fauna, the presence of nutrients, temperature, salinity, and the morphological characteristics of the watercourses, as well as the concentration of pollutants.

Monitoring activities are carried out on three- or six-year cycles, and are divided into the following categories:

- **Surveillance monitoring**, for water bodies not considered at risk;
- **Operational monitoring**, for at-risk water bodies or to evaluate the effectiveness of specific measures;
- **Investigative monitoring**, aimed at identifying and analysing the causes of environmental degradation.

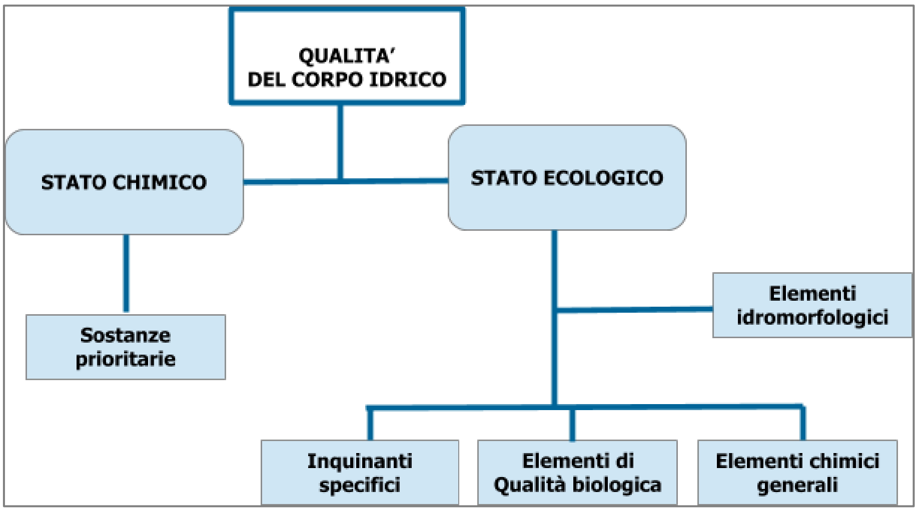


Figure 4 - Classification Criteria for the Water Quality Status of Surface Water Bodies (Source: ARPAE Report – "Surface Water Quality in the Province of Ferrara", Years 2017–2018)

In the specific case of the Ferrara area, the hydromorphological characteristics of local water bodies - which are predominantly artificial, with muddy riverbeds and steep banks - do not allow for a comprehensive biological assessment in accordance with the criteria established by the Directive.
For this reason, only chemical monitoring is carried out on these watercourses.
An exception is represented by the Po River, which, although not wadeable, allows for the analysis of certain biological components (such as macrobenthos and diatoms) through the use of artificial substrates.

The regional monitoring network of surface watercourses in the Province of Ferrara, managed by ARPAE – Ferrara Section (APA Center), is organized into three distinct systems:

1. **The Environmental Quality Network** on the Po River and the main artificial canals, comprising 16 sampling stations;
2. **The Functional Network for Cyprinid Fish Life**, consisting of 3 monitoring stations;
3. **The Network for the Control of Raw Water for Potabilization**, active at 2 points along the Po River.

In particular, the Environmental Quality Network for surface waters has been designed to include both primary and secondary hydrographic systems, thus providing a comprehensive representation of the different water body typologies present across the provincial territory.
Based on the presence of pressure factors - such as pollution or morphological alterations - the monitored water bodies are classified into three risk categories: "Not at risk", "Potentially at risk", "At risk" with respect to the achievement of environmental objectives. This classification

determines the type of monitoring to be applied: surveillance monitoring for "not at risk" water bodies, and operational monitoring for those "at risk". In the Province of Ferrara, all monitoring stations fall within the operational monitoring category.
Monitoring activities also differ in frequency and analytical profiles, depending on the specific characteristics of the water bodies. For those suitable, both physico-chemical and biological analyses are foreseen - although, in practice, biological assessments are carried out only at three stations along the Po River.
The environmental monitoring network of the Province of Ferrara includes 16 control stations (Figure 5): 3 on the Po River, 2 on the Po di Volano, 3 on the Canal Bianco, and the remaining 9 within the Burana Navigabile basin.
The monitoring program, with its detailed schedule and analytical procedures, is defined in Table 1. It is worth noting that Profile 1 – Base, applied to all monitoring stations, represents the minimum analytical set of physico-chemical and microbiological parameters used to assess surface water environmental quality, including temperature, pH, and electrical conductivity.

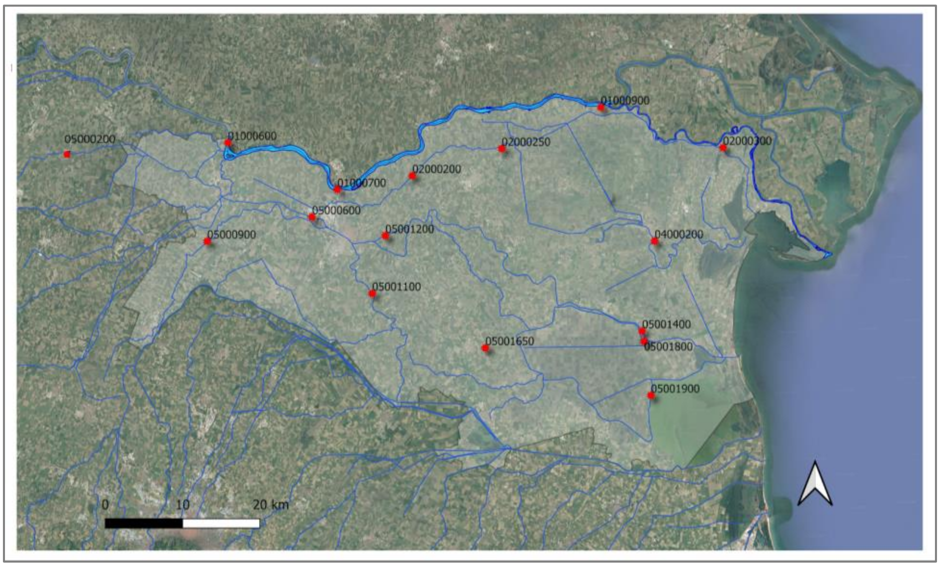


Figure 5 - ARPAE Surface Water Monitoring Network
(Source: ARPAE Report – "Surface Water Quality in the Province of Ferrara", Years 2017–2018)

In the monitoring of saline wedge intrusion within the Ferrara territory, a strategic role is played by the stations located along the main hydraulic axes that constitute the primary water supply sources for the reclamation district, in particular:

– 01000900 – Po River, Serravalle di Berra;
– 04000200 – Po di Volano River, Ex Ponte Varano (Codigoro);
– 05001400 – Navigable Canal, Upstream of Valle Lepri Lock.

Codice	Bacino	Asta	Toponimo	Programma	2017	2018	2019	Frequenza	Profilo analitico
01000600	PO	Fiume Po	Stellata di Bondeno	Operativo	ch	tutto	ch	12	1+2+3
01000700	PO	Fiume Po	Pontelagoscuro Ferrara	Operativo	ch	tutto	ch	12	1+2+3+ POT+ PFAS
01000900	PO	Fiume Po	Serravalle di Berra	Operativo	ch	tutto	ch	12	1+2+3+ POT+ PFAS
02000200	C.BIANCO 1° tronco	Canal Bianco	Ruina	Operativo	ch	ch	ch	8	1+2
02000250	C.BIANCO 1° tronco	Canale Cittadino Naviglio	Ponte a valle di Coccanile*	Operativo	ch	ch	ch	8	1+2
02000300	C.BIANCO 2°tronco	Canal Bianco	Ponte s.s. Romea Mesola	Operativo	ch	ch	ch	8	1+2+3
04000200	PO DI VOLANO	Po di Volano	Ex Ponte Varano Codigoro	Operativo	ch	ch	ch	8	1+2+3
05000200	BURANA NAVIGABILE	Canale Quarantoli	Passo dei Rossi	Operativo	ch	ch	ch	8	1+2
05000600	BURANA NAVIGABILE	Canale Burana Navigabile	Cassana	Operativo	ch	ch	ch	8	1+2
05000900	BURANA NAVIGABILE	Canale di Cento	Casumaro	Operativo	ch	ch	ch	8	1+2
05001100	BURANA NAVIGABILE	Po di Primaro	Ponte Gaibanella S.Egidio	Operativo	ch	ch	ch	8	1+2
05001200	BURANA NAVIGABILE	Canale Burana Navigabile	Passerella Focomorto Ferrara	Operativo	ch	ch	ch	8	1+2
05001400	BURANA NAVIGABILE	Canale Burana Navigabile	A monte chiusa Valle Lepri	Operativo	ch	ch	ch	8	1+2+3
05001650	BURANA NAVIGABILE	Collettore S.Antonino	Portoverrara*	Operativo	ch	ch	ch	8	1+2
05001800	BURANA NAVIGABILE	Canale Circondariale Bando Valle Lepri	Idrovora Valle Lepri	Operativo	ch	ch	ch	8	1+2+3
05001900	BURANA NAVIGABILE	Canale Circondariale Gramigne Fosse	A monte Idrovora Fosse	Operativo	ch	ch	ch	8	1+2+3

* Attive al 2015

Table 1 ARPAE Environmental Quality Network – 2017–2019 Monitoring Programme (Source: ARPAE Report – "Surface Water Quality in the Province of Ferrara", Years 2017–2018)

3.2. Po di Goro river

As shown in Figure 3, the Po di Goro river represents the first and largest distributary of the Po River, which—together with the Po di Maestra, Po di Tramontana, Po di Pila, Po di Tolle, and Po di Gnocca—forms the Po River Delta.

This watercourse branches off from the right bank of the main Po channel near the town of Serravalle and flows into the Adriatic Sea after a course of approximately 45 km, near Gorino

Ferrarese, within the Municipality of Goro. Its channel defines the easternmost section of the boundary between Veneto and Emilia-Romagna.

Unlike the other hydraulic branches described in the following sections, the Po di Goro is not regulated by control structures or barrages and is therefore directly affected by saline wedge intrusion. The extent of the saline front's advancement or retreat depends solely on the transiting river discharge and on marine tidal dynamics.

With regard to the Ferrara bank of the Po di Goro, two water abstraction points are present (Figure 6):

- Goro Siphons: a system of five small-capacity siphons, located close to the coastline, which normally abstract water to supply the Goro irrigation district (642 ha) until late spring. Given their proximity to the sea, it is expected that salinity levels increase during the summer months. These variations are systematically monitored by the Reclamation Consortium at the abstraction points; when salinity values exceed the irrigation suitability threshold (typically > 2 mS/cm), water withdrawal is suspended, and the irrigation supply for the area is ensured through a dedicated pumping station capable of transferring freshwater from the Canal Bianco system.
- Garbina Pumping Station: located approximately 36 km from the coast, also equipped with an electrical conductivity sensor, with an abstraction capacity of up to 4.4 m^3/s. Together with the Berra and Contuga stations, it supplies the Canal Bianco, the main irrigation channel of the Berra–Contuga District (40,555 ha).

The ARPAE Serravalle monitoring station, located approximately 45 km upstream from the river mouth, does not record any significant variations in electrical conductivity, precisely due to its distance from the coastal zone.

As shown in Figure 7, conductivity values remain consistently below 1 mS/cm, indicating that the influence of the saline wedge does not extend to this river reach.

For the effective monitoring of saline wedge intrusion, it has therefore been necessary to install stations closer to the river mouth, where the influx of saline water is more pronounced and variable.

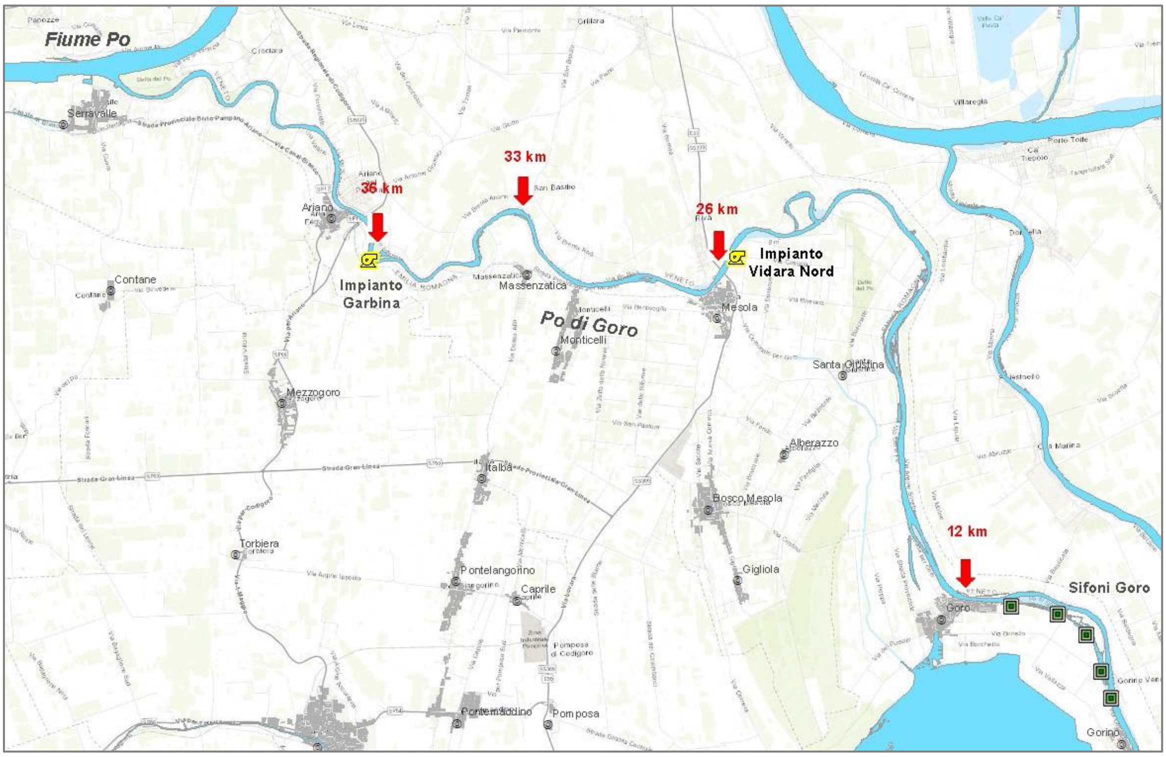


Figure 6 – Water Abstraction Points on the Ferrara Bank of the Po di Goro

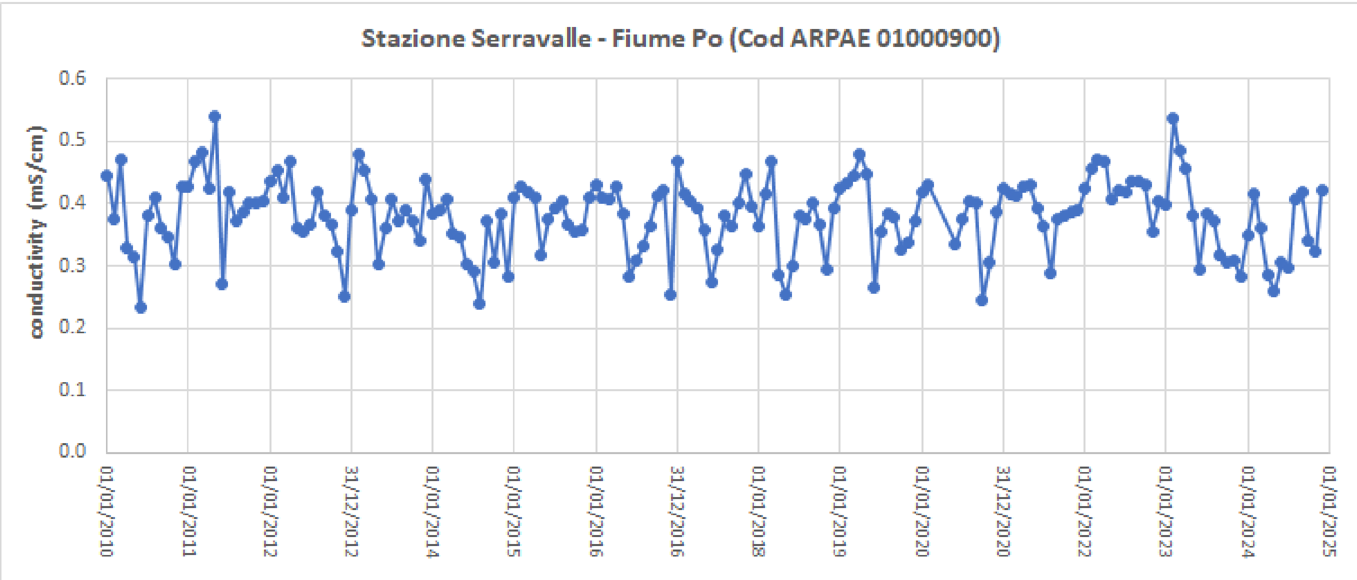


Figure 7 – Serravalle Station on the Po River: Electrical Conductivity Trends (2010–2025)
(Source ARPAE: https://www.Arpae.it/it/il-territorio/ferrara/report-a-ferrara/acqua/acque-superficiali/ferrara-rete-di-monitoraggio-2008-2019/view)

In 2003, Europe was struck by an exceptional heatwave, both in intensity and duration. The increasingly severe drought conditions and the consequent saltwater intrusion prompted the Environmental Department of the Province of Ferrara to initiate a systematic monitoring programme of the saline wedge in the Po Delta branches flowing into the Sacca di Goro, which was subsequently conducted on an annual basis.

However, based on the initial results, monitoring activities on the Po di Volano were discontinued in 2006, since—as described in the following section—it is a regulated watercourse, used primarily for irrigation purposes, where salinity variations are only marginally influenced by the Po River discharge at Pontelagoscuro (Ferrara). This decision allowed the monitoring efforts to be focused on the remaining delta branches, which are more significantly affected by marine intrusion phenomena.

Following the enactment of Regional Law No. 13/2015 of Emilia-Romagna, these functions were transferred to ARPAE, which conducted field surveys in 2016, 2017, and 2022—the latter being another year marked by severe water scarcity across the Po River basin.

During the 2023–2025 period, the monitoring network has been and will continue to be kept operational thanks to funding provided under the cooperation agreement pursuant to Article 15 of Law 241/1990, signed with the Po River Basin Authority for the monitoring activities supporting the implementation of Directive 2000/60/EC (the RasPo – Strategic Environmental Network of the Po River Basin).

The monitoring stations were installed at easily identifiable reference points, such as bridges or other fixed hydraulic structures, to ensure rapid identification and accessibility.

Accordingly, well-known locations (e.g. bridges, sluices, pumping stations) were selected, and GPS coordinates were recorded for each site.

The monitoring points were established starting from the river mouths, at regular intervals of approximately 3 km upstream along the various delta branches.

The location of the 41 monitoring stations is shown in Figure 8.

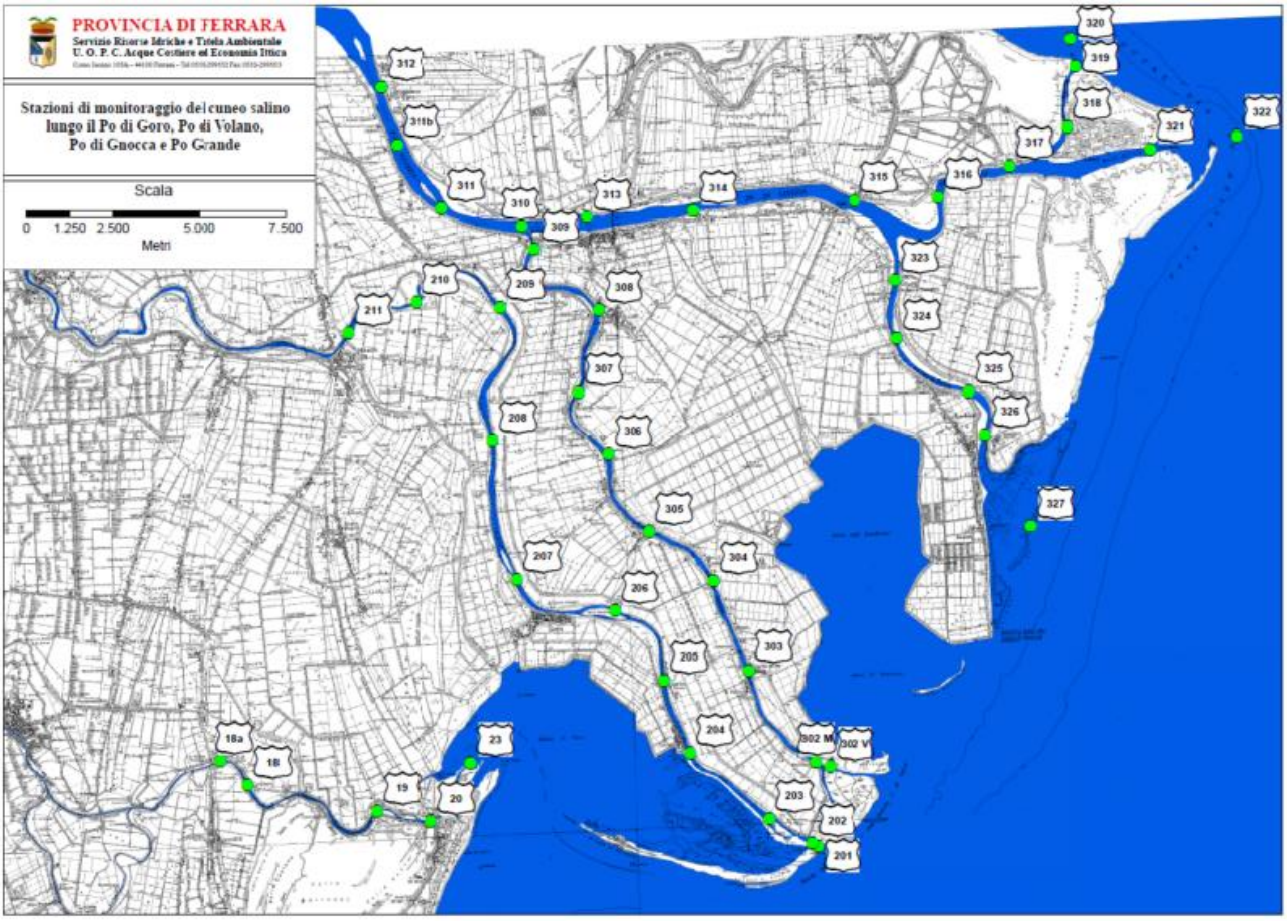


Figure 8 – Saline Wedge Monitoring Network in the Po River Delta

Once the designated monitoring location is reached, a multiparametric probe (Figure 9) is deployed, capable of recording several parameters — including pressure, temperature, salinity, dissolved oxygen, pH, electrical conductivity, and chlorophyll — throughout the entire water column.

The pressure parameter allows the correlation of all measured variables with depth, enabling the reconstruction of vertical profiles and the identification of stratification patterns within the water body.

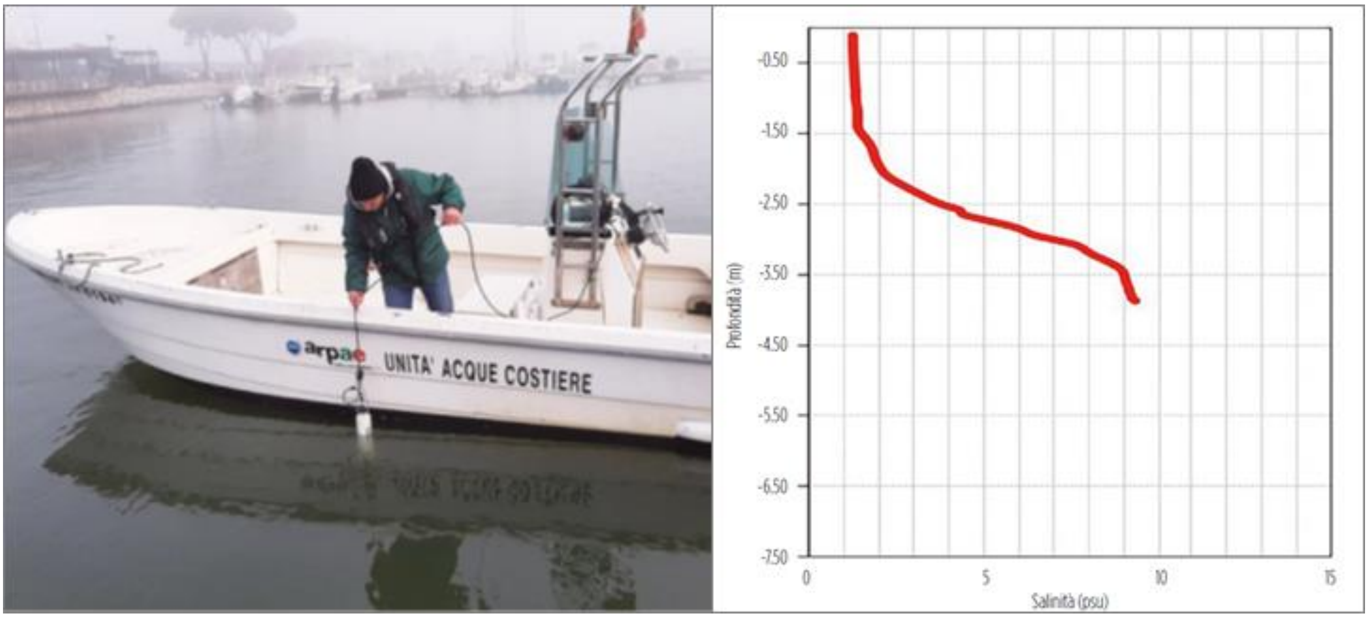


Figure 9 Measurement Activities of Physicochemical Parameters via Multiparametric Probe and Vertical Salinity Profiling (Source: Rivista Ecoscienza, no. 6/2023)

For data processing aimed at identifying the river reach unaffected by saline wedge intrusion, a threshold value of 1 mS/cm is commonly adopted to distinguish freshwater from brackish water. This salinity level represents the upper limit beyond which irrigation problems may occur.
In other words, the end of the saline wedge is defined as the river cross-section where salinity values below 1 mS/cm are recorded throughout the entire water column.

Figure 10 shows a plan view of the Po River Delta, highlighting the river sections affected by the saline wedge intrusion and the different salinity levels recorded along each reach in July 2022—a period marked by an exceptional drought event, remembered as one of the most severe in recent decades.
Data processing revealed that the saline wedge intrusion reached maximum distances of 34.3 km along the Po di Goro and 40.1 km along the Po di Venezia, corresponding to an average daily discharge at Pontelagoscuro (Ferrara) of approximately 110 m^3/s, the lowest value ever recorded.

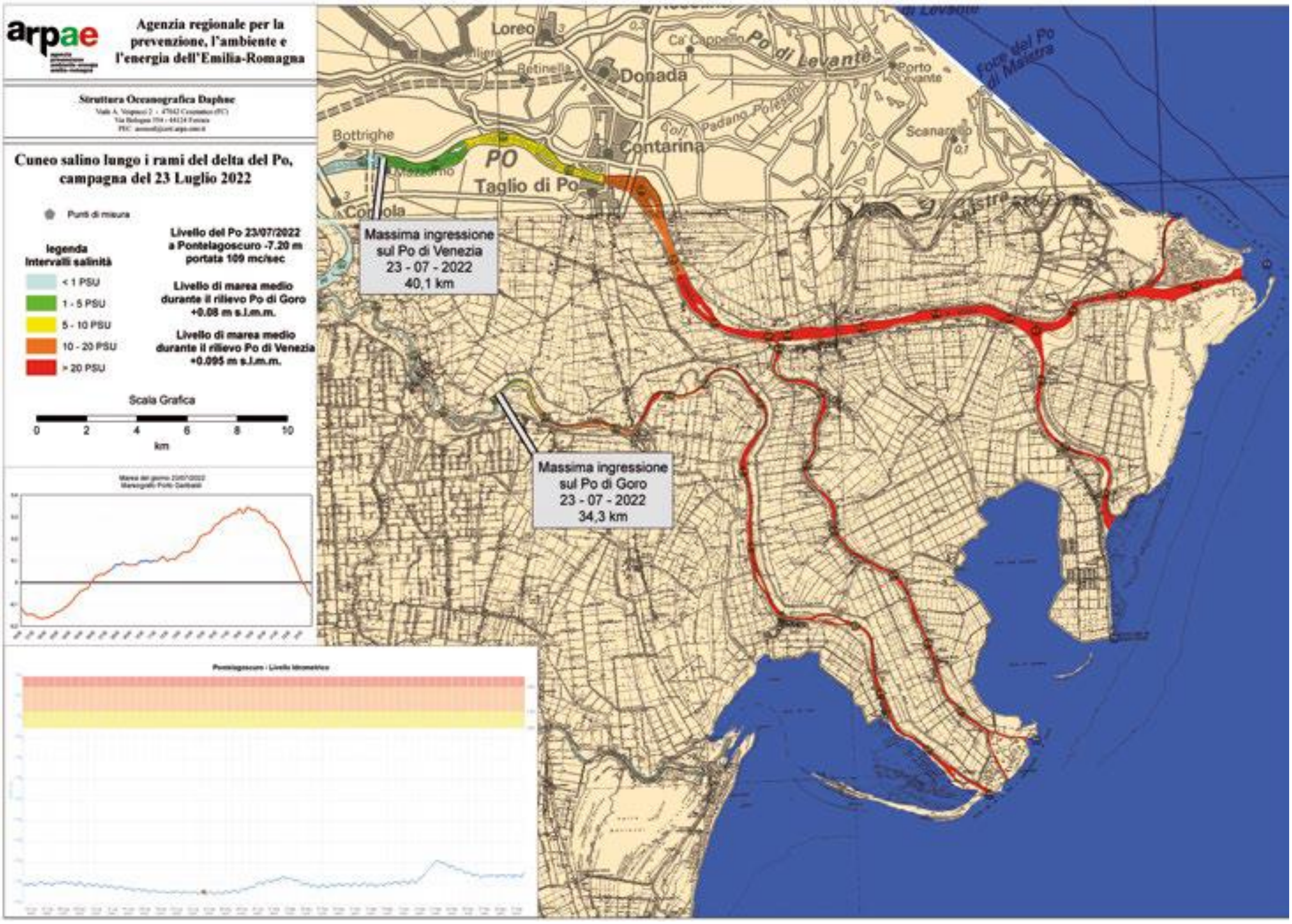


Figure 10 - Plan View Map of the Saline Wedge – 23 July 2022 (Source Rivista Ecoscienza n.6/2023)

This significant reduction in river discharge measured at the Pontelagoscuro gauging station resulted, in July 2022, in a saltwater intrusion that reached unprecedented levels.

The following graph shows the measured upstream distances (in kilometres) of the saline wedge progression along the Po di Goro.

Although the saline wedge intrusion had already been observed with considerable intensity in 2003, 2005, 2006, and 2012, the year 2022 recorded the most extensive upstream penetration ever measured.

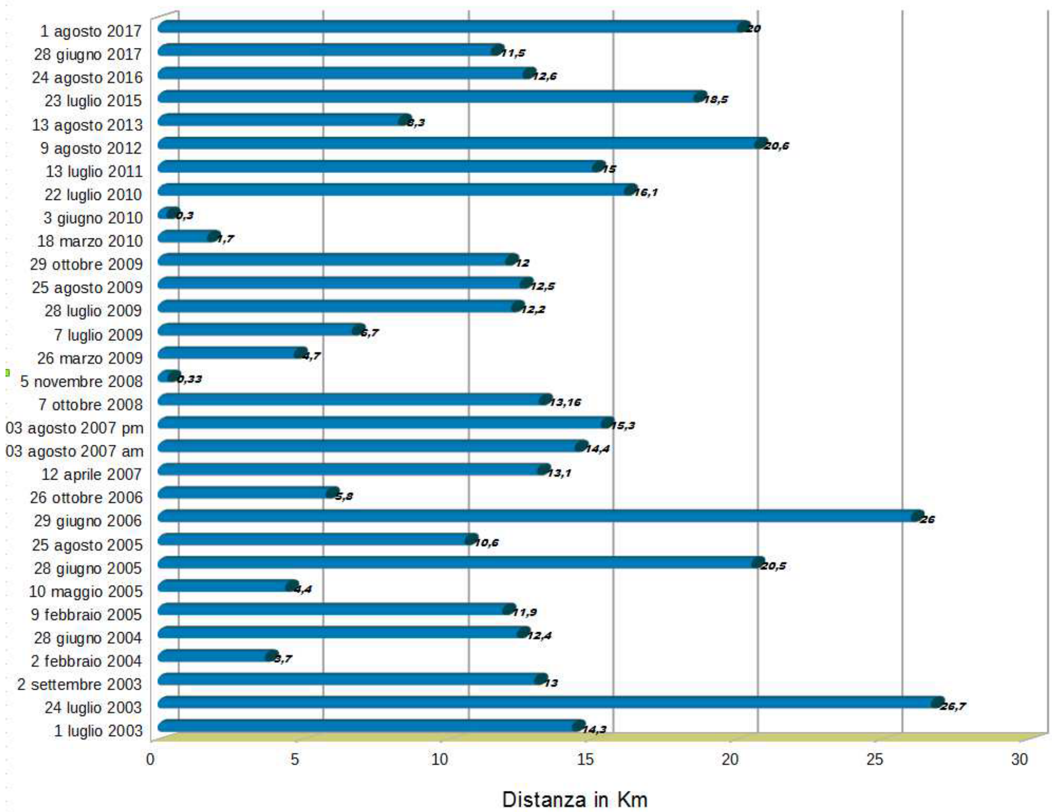


Figure 11 – Comparison of Saline Wedge Intrusion in the Po di Goro
(Source: ARPAE – Measurement Campaign for the Assessment of Saline Wedge Intrusion in the Po River Delta, Conducted on 1 August 2017)

During the summer of 2022, a more extensive monitoring campaign of the river's electrical conductivity was carried out by the Ferrara Plain Reclamation Consortium, involving measurements at locations farther upstream than those usually surveyed.

In particular, four sampling points were established along the river course, progressively increasing in distance from the river mouth (Figure 6): Goro town (12 km), SS Romea bridge (26 km), San Basilio (33 km), and the Garbina pumping station (36 km).

Spot measurements were performed approximately 0.5 metres below the river water level, with the objective of obtaining a preliminary indication of the presence and distribution of dissolved salts in the water (Table 2).

More detailed investigations were also conducted, as illustrated in Figure 12. Specifically, on 6 July, 21 July, and 21 October 2022, electrical conductivity measurements were taken at different depths (1, 2, and 3 metres), considering that saline wedge intrusion typically occurs through vertical stratification.

On these occasions, the monitoring was extended to a larger number of sampling points, with an average spacing of approximately 3 km along the river course.
In addition, on 6 July, a specific measurement campaign was carried out under different tidal conditions by Consortium staff, in order to assess the influence of tidal dynamics on the upstream progression of the saline wedge.

	Garbina	*San Basilio*	*Ponte SS Romea*	*–*
Distanza dal mare	*36 Km*	*33 Km*	*26 Km*	*12 Km*
26-giu			480	20.000
28-giu			600	18.000
1-lug			496	20.000
5-lug			478	20.000
8-lug			460	20.000
12-lug			850	20.000
15-lug			700	20.000
19-lug			650	20.000
21-lug			8.500	39.000
26-lug	490	500	11.000	40.000
29-lug	500	500	3.500	40.000
2-ago	505	500	500	10.300
5-ago	500	500	520	10.000
9-ago	500	555	8.150	20.000
12-ago	500	505	510	10.000

Table 2 – Survey of Electrical Conductivity (µS/cm) at 0.5 m Depth along the Po di Goro River during Summer 2022

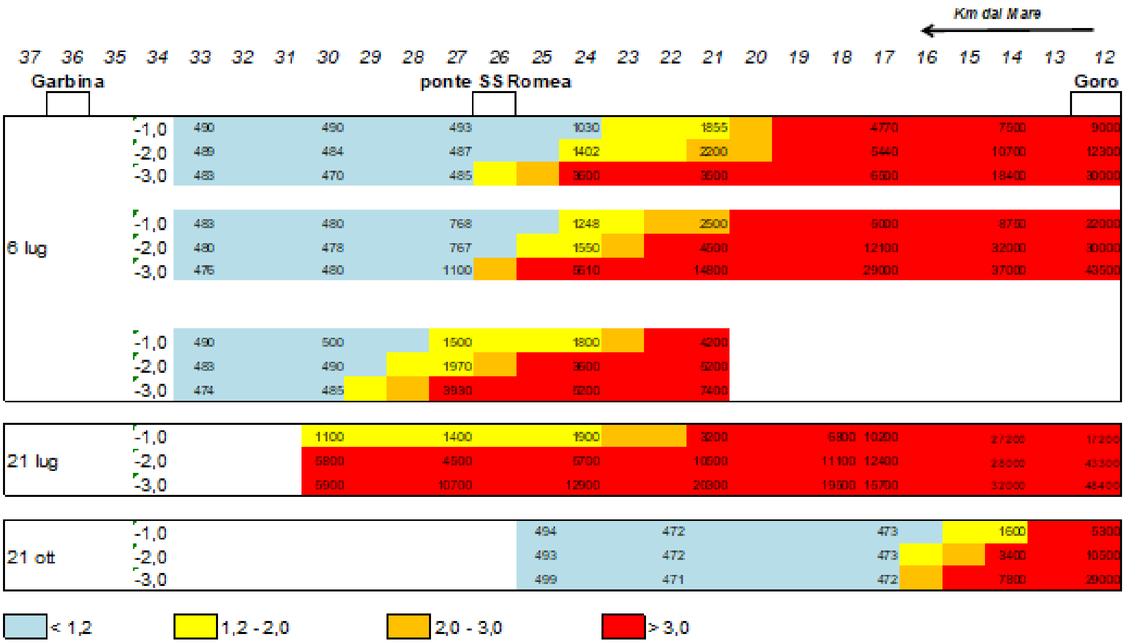


Figure 12 Detailed Survey of Electrical Conductivity (µS/cm) at Different Depths (1, 2 and 3 m) along the Po di Goro River on 06/07/2022 – 21/07/2022 – 21/10/2022

Figure 12 highlights the vertical stratification of saline waters, as demonstrated by the increase in electrical conductivity values at greater depths.
Referring to the survey of 6 July, the effect of tidal influence on the upstream progression of the saline wedge can be estimated at approximately 3 km: conductivity values below 1,000 µS/cm, recorded at all three measured depths, appear shifted from around 27 km to 30 km from the river mouth.
With regard to the maximum upstream extent of saltwater intrusion, it is assumed that this occurred during the second decade of July, coinciding with both the lowest hydrometric level and minimum discharge of the Po River at Pontelagoscuro.
Although the 21 July survey was carried out shortly before this critical period, the data suggested that the saline wedge may have reached 33–34 km from the river mouth, consistent with ARPAE's monitoring results (Figure 10).
Of particular concern is the proximity of the Garbina pumping station, located only 2–3 km upstream from the hypothetical point of maximum saline front intrusion.
Up to 2022, even during the most critical years (such as 2003 and 2006), the saltwater intrusion had been detected only up to approximately 27 km from the river mouth. In that context, although the phenomenon was recognized as significant, the Garbina station was considered to be safely located.
In 2022, however, due to the exceptional advancement of the saline wedge, a precautionary suspension of water abstraction was implemented for several days.
Measurements carried out during that period indicated that the saline front advanced to within a few kilometres of the pumping station, highlighting a potentially critical situation.

3.3. Po di Volano river

Moving further south, in the central part of the Province of Ferrara, flows the Po di Volano (Figure 13). At a distance of approximately 25 km from its mouth, in the locality of Tieni, there is a control structure (barrage) originally built for navigation purposes.
This structure has remained closed since the mid-1980s, effectively dividing the river into two sections: the upstream reach, where water levels are artificially maintained at approximately +1.5 m a.s.l., and the downstream reach, which is directly connected to the Adriatic Sea and characterized by lower water levels influenced by tidal fluctuations (±0.30 m a.s.l.).

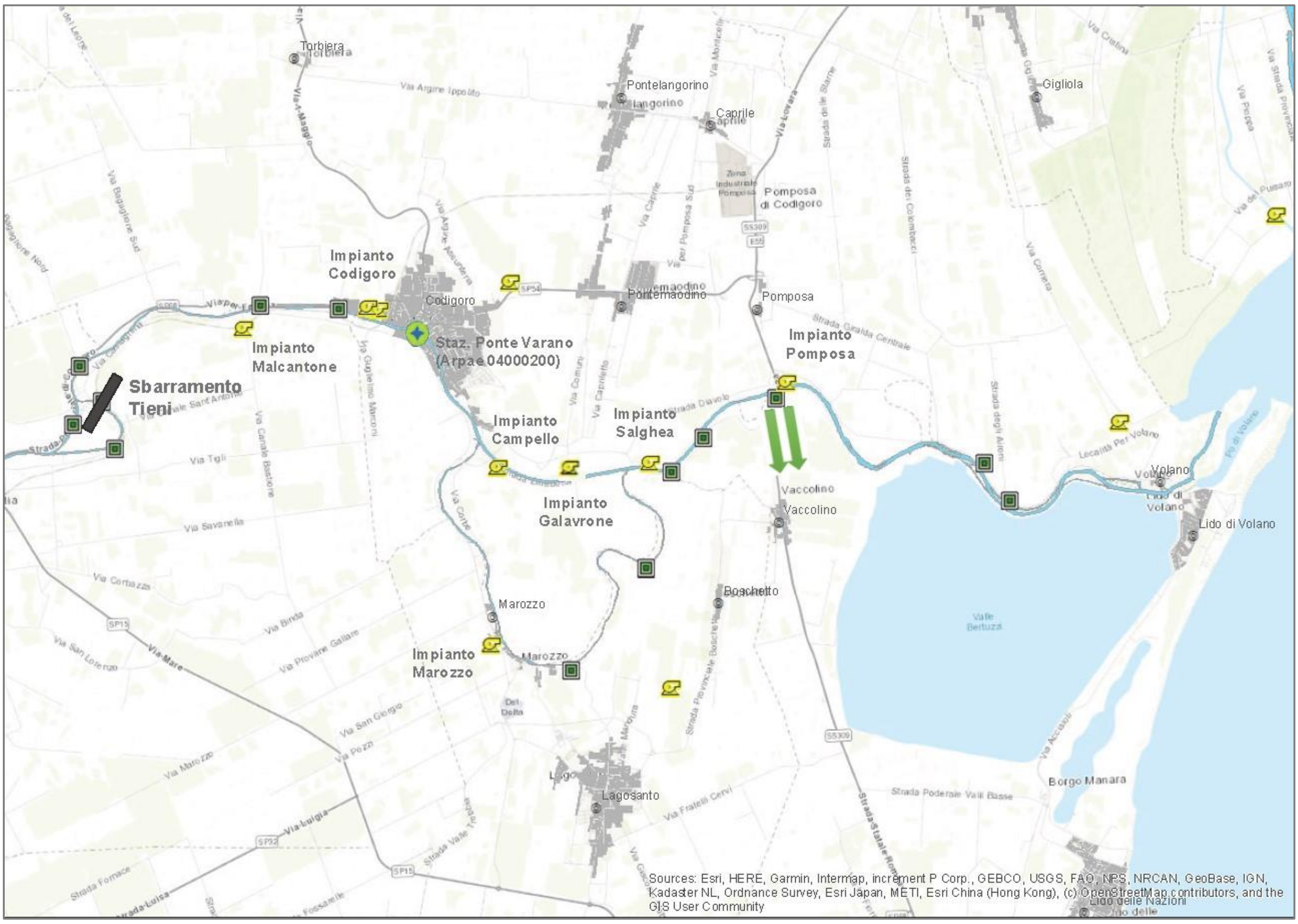


Figure 13 – Key Hydraulic Structures along the Po di Volano river

In the upstream reach of the barrage, freshwater is present, supplied during the irrigation season through abstractions from the Po River at Pilastresi and Pontelagoscuro.
Conversely, in the downstream reach, the water is in direct connection with the Adriatic Sea and therefore exhibits much higher salinity levels, often approaching those typical of seawater (around 40 mS/cm).
It should be noted, however, that discharges from several Reclamation Consortium pumping stations into this stretch significantly affect conductivity variations throughout the year.
In particular, the Codigoro Acque Basse pumping station, during the irrigation period, receives and discharges into the lower section of the Po di Volano the return flows from a large agricultural area characterized by high water demand. Among the most representative crops are rice fields,

which generate substantial volumes of drainage water, released either into the drainage network or into the mixed network, depending on operational conditions and agricultural practices.
This continuous and prolonged inflow of freshwater considerably reduces the conductivity of the Po di Volano waters, making their secondary use for irrigation in the downstream areas feasible.
As shown in Figure 14, the conductivity values measured in 2022 at Pomposa intake remained stable between April and September, within the range compatible with irrigation use (1.0–1.5 mS/cm).

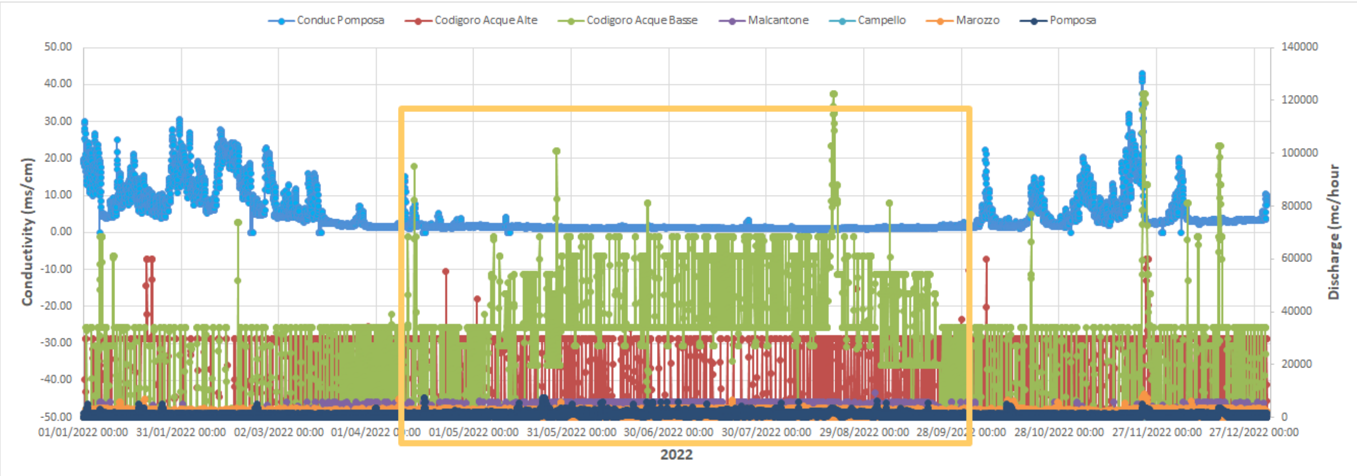


Figure 14 – Po di Volano – Year 2022: Electrical Conductivity Values Recorded at the Pomposa intake and Discharges from the Main Drainage Pumping Stations

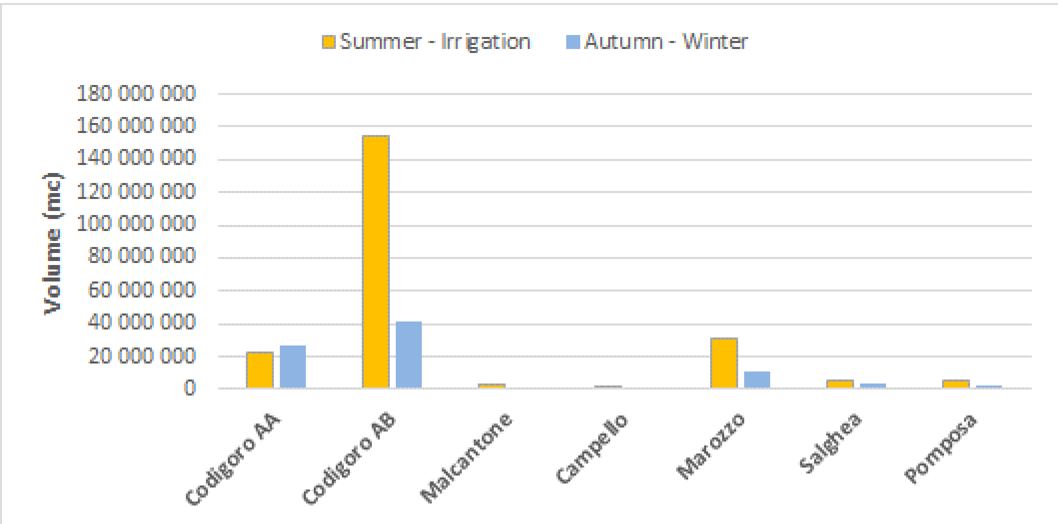


Figure 15 – Po di Volano – Year 2022: Volumes Discharged by the Main Drainage Pumping Stations during the Summer (Apr–Oct) and Winter (Jan–Mar and Nov–Dec) Seasons

Since this system operates independently from the hydrological regime of the Po River, the salinity values recorded in 2022 do not differ significantly from those measured in previous years.
A third sensor has recently been installed at the Galavrone reversible pumping station, designed to operate both as an intake, drawing water from the Po di Volano and lifting it toward another water body, and as a drainage outlet, discharging water back into the canal.
This facility is located 3.7 km upstream from the Pomposa sluice, thus slightly farther from the river mouth. For this reason, it is less affected by the saline wedge intrusion during the autumn–winter period, when drainage discharges from neighbouring pumping stations are less significant, reaching maximum conductivity values of about 5 mS/cm, as shown by the comparison between the two intake points in 2023 (Figure 16).
Further upstream, near the town of Codigoro, lies the Ponte Varano monitoring station managed by ARPAE, which appears to be almost unaffected by saline intrusion, with peak conductivity values of only 2 mS/cm. More precisely, over the 2010–2024 monitoring period, the highest recorded value was 3.2 mS/cm, measured on 24 January 2012.

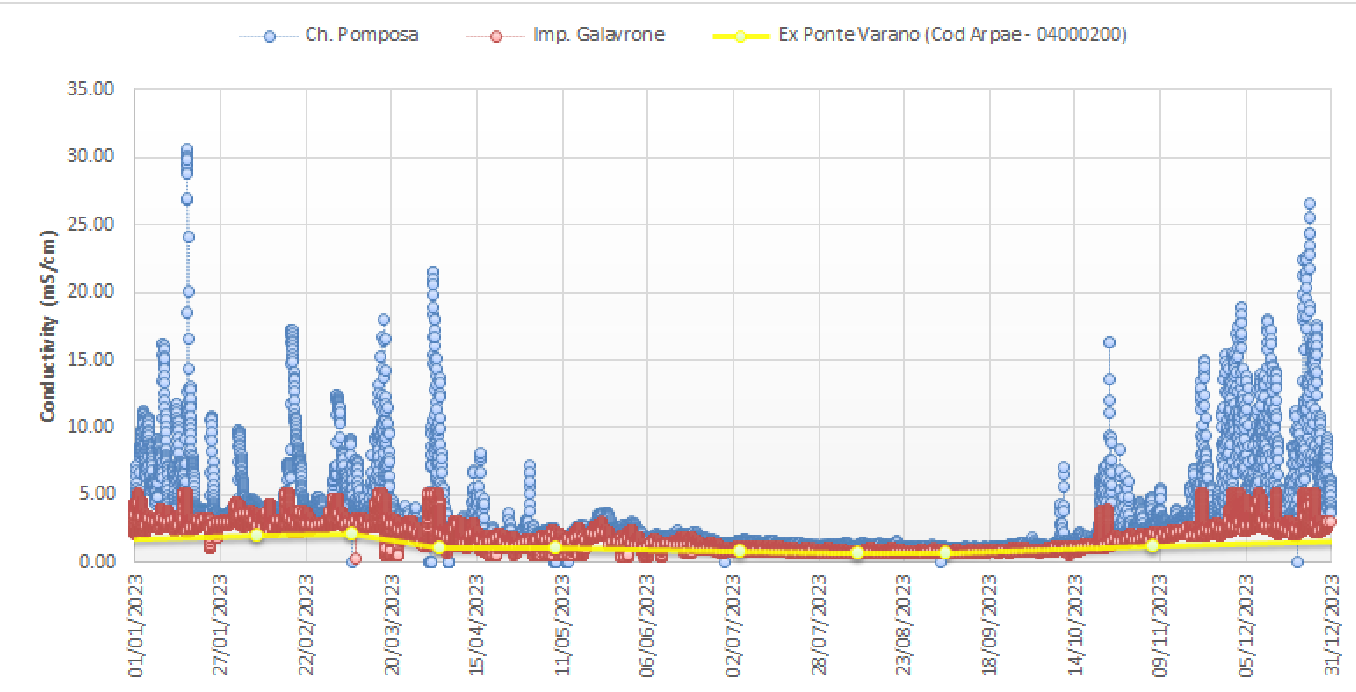


Figure 16 – Po di Volano – Year 2023: Electrical Conductivity Values Recorded at the Pomposa and Galavrone Intakes and at the ARPAE Ponte Varano Monitoring Station

3.4. Migliarino - Porto Garibaldi Navigable Canal

Similarly to what has been observed for the Po di Volano, the Navigable Canal (Canale Navigabile) also features a control structure (barrage) located at Valle Lepri, approximately 14 km from the sea (Figure 17).

This structure divides the watercourse into two sections, with the downstream reach directly connected to the Adriatic Sea.

Unlike the Tieni barrage, however, during rainfall events it is sometimes necessary to open the structure to discharge excess water to the sea.

All Consortium intake works are therefore located upstream of the Valle Lepri barrage, as the discharges from the nearby drainage pumping stations are insufficient to ensure an adequate reduction of canal salinity.

These intake points uniformly supply the entire irrigation area, including the lands situated east of the barrage, thereby significantly reducing the vulnerability of the area to saline intrusion from the sea.

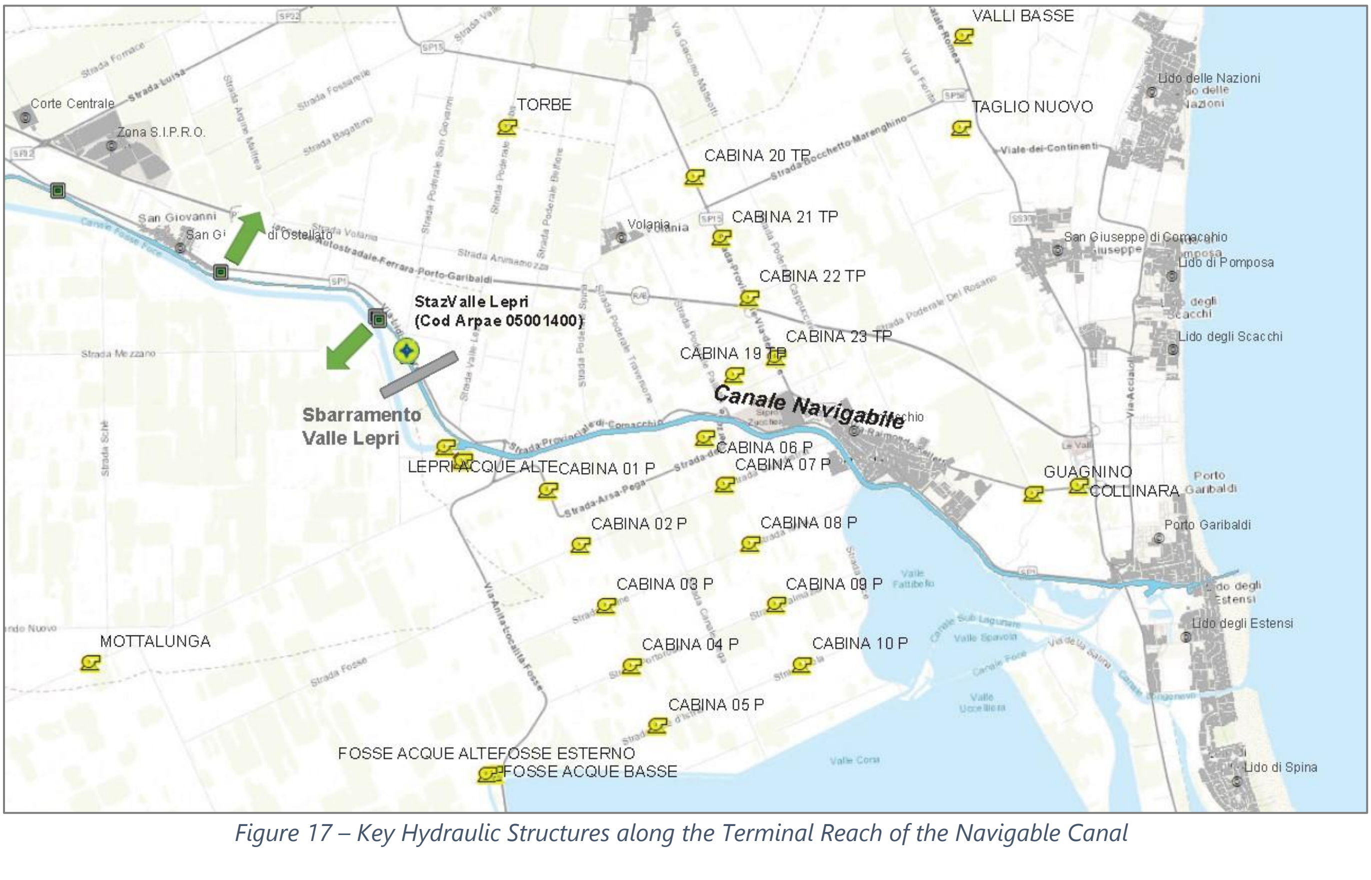


Figure 17 – Key Hydraulic Structures along the Terminal Reach of the Navigable Canal

The Consortium installed a conductivity sensor upstream of the Valle Lepri barrage in June 2024, near the reference point identified by ARPAE for surface water monitoring (ARPAE Code 05001400).

As shown in Figure 18, the electrical conductivity values recorded by ARPAE over the 2010–2024 period have remained consistently below 2 mS/cm, with a slight decrease during the irrigation months.

Figure 19 confirms the consistency of the data acquired by the Consortium, despite some variability in sampling frequency.

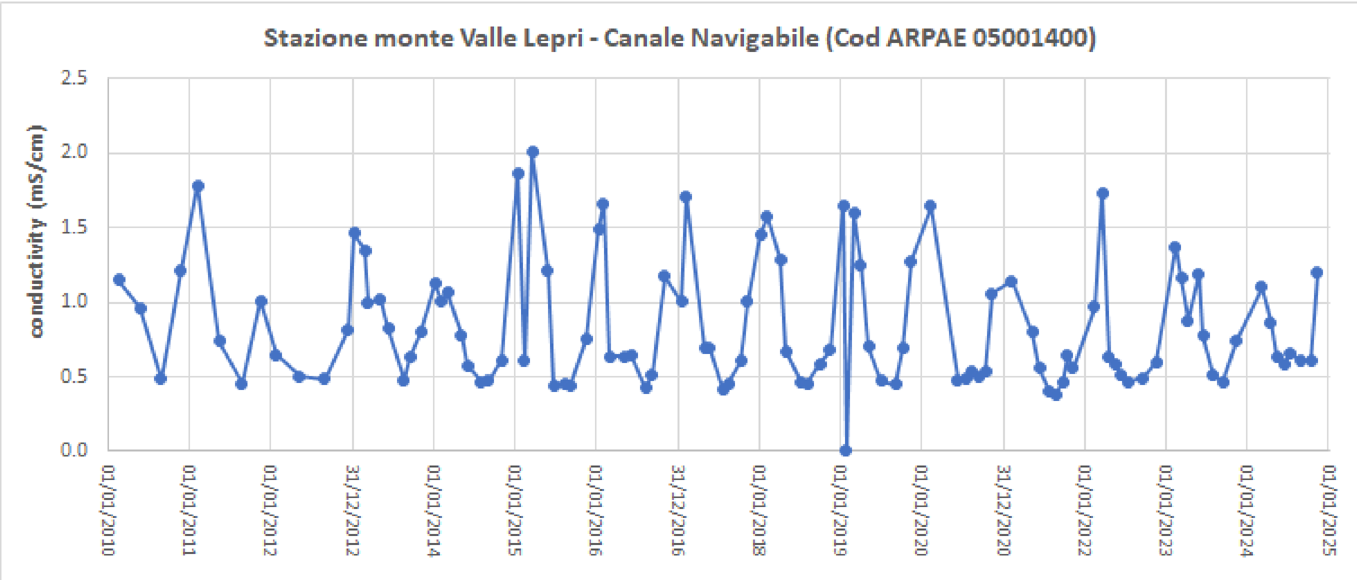


Figure 18 – Valle Lepri Station on the Navigable Canal: Electrical Conductivity Trends (2010–2025)
(Fonte ARPAE: https://www.Arpae.it/it/il-territorio/ferrara/report-a-ferrara/acqua/acque-superficiali/ferrara-rete-di-monitoraggio-2008-2019/view)

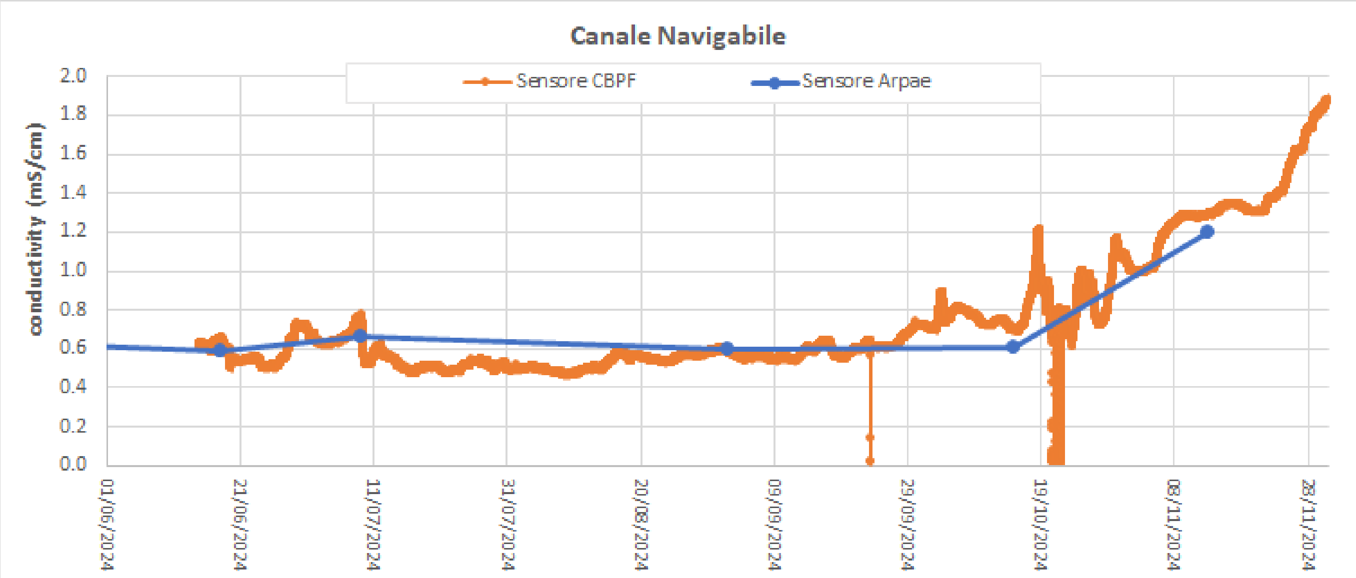


Figure 19 – Valle Lepri Station on the Navigable Canal: Comparison of Electrical Conductivity Measurements by the Consortium and ARPAE

3.5. Reno river

The Volta Scirocco barrage is located on the Reno River, approximately 6 km from the sea, and is managed by the Second-Level Reclamation Consortium for the Emilia-Romagna Canal (CER Consortium), of which the Ferrara Plain Reclamation Consortium is a member (Figure 20).

In the terminal reach between the barrage and the sea, which is affected by saline wedge intrusion, there are no intake structures, and therefore no issues related to the salinity of the available water are observed.

Upstream of the barrage, the main challenges concern the amount of water available for abstraction.

The torrent-like hydrological regime, typical of Apennine rivers, is characterized by rapid and relatively short rises in water levels during rainfall events, followed by extended low-flow periods with limited discharge.

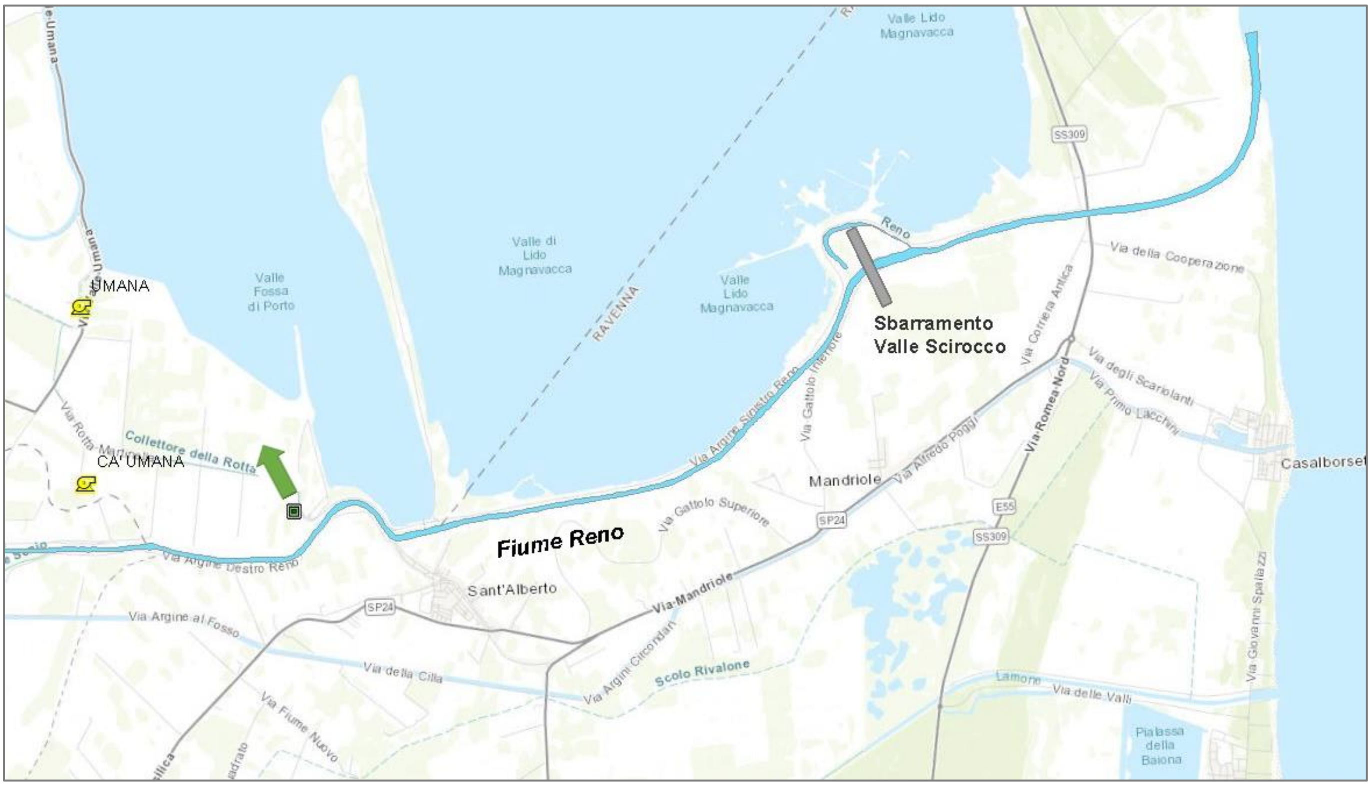


Figure 20 – Key Hydraulic Structures along the Terminal Reach of the Reno River

4. Groundwater

Groundwater represents a strategic resource for water supply on a global scale, playing a fundamental role in the domestic, agricultural, and industrial sectors.
It circulates and accumulates within aquifers, i.e. geological formations characterized by high permeability—typically composed of sands, gravels, or fractured rocks—that are capable of storing and transmitting water efficiently.
The increasing anthropogenic pressure associated with population growth, the rising demand for water for civil, agricultural, and industrial uses, and the overexploitation of groundwater resources poses a concrete threat to the equilibrium of the coastal aquifer system in the Ferrara area.
To this, one must add the growing impacts of climate change—notably the reduction in precipitation, the increase in temperature, and higher evapotranspiration rates—which collectively alter the natural water balance and promote saltwater intrusion within the phreatic aquifer in coastal zones of the study area.
In this context, it has become essential to undertake a comprehensive hydrogeological study and modelling activity aimed at developing an updated understanding of the Ferrara phreatic aquifer, with a focus on its main physical properties, groundwater flow dynamics, and particularly its vulnerability to saline intrusion.

Following a geological and sedimentological overview of the coastal aquifer at the regional scale, the report proceeds with the description of the monitoring networks implemented to date for the analysis and assessment of the qualitative and quantitative status of the groundwater table.
A summary is then provided of the first study conducted by the Geological, Seismic and Soil Survey (SGSS) of the Emilia-Romagna Region, which in 2009 planned and established a dedicated monitoring network specifically aimed at the observation of the coastal phreatic aquifer.
Finally, the section presents the contribution developed within the framework of the current European project, consisting of a variable-density flow and transport numerical model, designed to identify the areas most affected by salinization during the 2011–2021 period.

4.1. The Coastal Aquifer of the Emilia-Romagna Region

The coastal aquifer of the Emilia-Romagna Region extends along the Adriatic shoreline for approximately 130 km, from the Po di Goro estuary (Province of Ferrara) to the Municipality of Cattolica (Province of Rimini), continuing southward up to the Gabicce promontory, at the border with the Marche Region.
In the northern sector, particularly within the Ferrara and Ravenna provinces, the aquifer extends inland for about 20 km, reaching an average thickness of 30 metres.

Proceeding southward, the lateral extent of the aquifer progressively decreases: in the coastal zone between Cesenatico and the regional border, its width is limited to about 1 km, while its thickness thins out to 5–6 metres.
The coastal area of Ferrara and Ravenna preserves the geomorphological evidence of the main sea-level fluctuations that occurred during the last glacial and post-glacial cycles.
These eustatic oscillations profoundly influenced sedimentation processes and coastal morphology, leading to the formation of complex deltaic, littoral, and lagoonal systems.
During the Last Glacial Maximum (around 18,000 years ago), sea level was up to 120 metres lower than at present, and the coastline was located up to 250 km further east.
With the subsequent marine transgression, between approximately 16,000 and 5,500 years ago, the Adriatic platform was submerged, resulting in the deposition of sandy and silty sediments of marine and coastal origin.

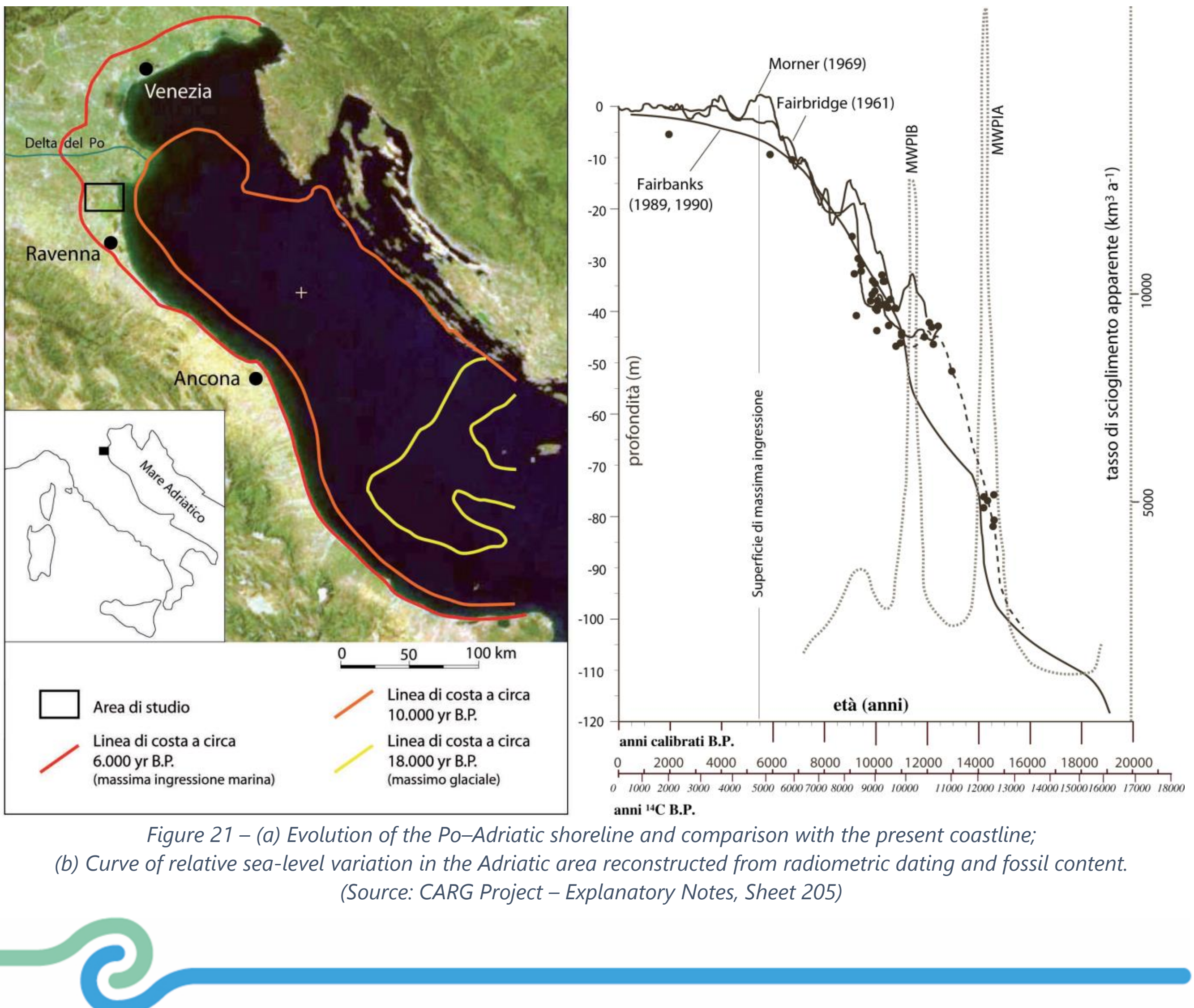


Figure 21 – (a) Evolution of the Po–Adriatic shoreline and comparison with the present coastline;
(b) Curve of relative sea-level variation in the Adriatic area reconstructed from radiometric dating and fossil content.
(Source: CARG Project – Explanatory Notes, Sheet 205)

The analysis of sediments and fossil content, together with radiometric dating, has made it possible to reconstruct a curve of relative sea-level variation for the Adriatic area (Figure 21b).
This curve shows a rapid sea-level rise corresponding to the melting phases of the ice sheets (MWP-1A and MWP-1B), followed by a slowing trend and then a stabilization phase around 6,000 years ago, which corresponds to the maximum marine transgression. During this stage, the sea reached its innermost position, approximately 25 km westward of the present coastline.
Subsequently, the increased sediment supply from the Po and Reno rivers led to a depositional regression (progradation), resulting in coastal advancement and the formation of the modern deltaic and littoral systems.
Within this depositional framework, the Holocene sedimentary environments visible in the Comacchio area (Figure 22) developed, characterized by coastal ridges, lagoonal basins, interdistributary plains, and submerged beaches. These sedimentary units now form part of the coastal aquifer, whose composition and spatial distribution are directly derived from the Holocene transgressive–regressive dynamics.

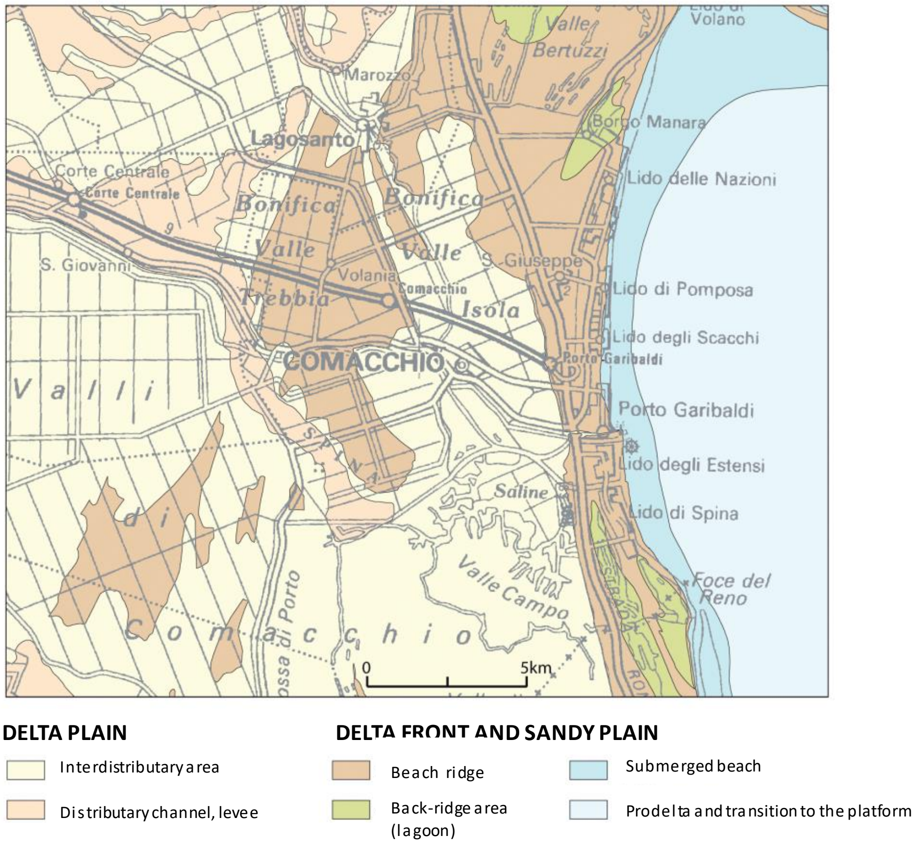


Figure 22 – Distribution of Depositional Environments Distinguished Within the Outcropping Deposits (Source: Progetto CARG – Explanatory Notes, Sheet 205)

The main aquifer of the area consists of sandy sediments deposited in marine, coastal, and deltaic environments during the Holocene transgressive–regressive cycle.
The successive phases of marine advance and retreat resulted in the superposition of sedimentary sequences with variable grain size and permeability, which control the hydrogeological behaviour of the system.
At the base of the complex lie Pleistocene alluvial-plain deposits, composed of low-permeability silts and clays, which act as an aquitard, separating the shallow aquifer from the deeper confined aquifers.
During the Holocene regressive phase, the coastline progressively advanced, leading—particularly in the northern sector—to the progradation of Po and Apennine river deltas, while farther south, a continuous sandy coastal plain (strand plain) developed.
Inland, the aquifer is laterally and vertically bounded by recent alluvial and deltaic deposits (silts, peats, lagoonal sediments), which reduce the hydraulic connectivity with the more permeable layers.
This heterogeneous structure gives rise to a multilayered system, with aquifers of variable extent and continuity.
The morphology and stratigraphy of the aquifer directly influence its storage and transmissivity capacity, as well as its vulnerability to saltwater intrusion, which is particularly high in the low-lying, sandy coastal zones.
Sea-level variations and recent subsidence further accentuate this fragility, making it essential to maintain continuous monitoring of the hydrogeological evolution of the Po–Adriatic coastal system.

Given the stratigraphic complexity and lateral discontinuity of the sedimentary bodies, the Geology, Soils and Seismic Survey Unit (SGSS) of the Emilia-Romagna Region has developed a detailed three-dimensional geological model of the regional coastal aquifer, illustrated by **Bonzi et al., 2010**.
This model is referenced here for its usefulness in delineating the geometry of the aquifer and understanding the spatial distribution of the sedimentary facies that characterize it.
Prior to the development of this geological model, SGSS carried out an in-depth analysis and GIS-based integration of the data produced by the **CARG Project**.
Drawing inspiration from international geological mapping experiences in lowland areas - such as the Netherlands and Denmark - and following the completion in 1976 of the Geological Map of Italy at a 1:100,000 scale, a new national geological mapping programme was launched in 1988 at a 1:50,000 scale: the CARG Project (Carta Geologica d'Italia).

Its objective was to provide comprehensive geological and physical knowledge of the Italian territory and subsurface through the use of rigorous data-surveying techniques and methodologies.

The cartographic data production is supported by a strategic information system, the CARG Database, which allows for the preservation of field data, their integration and updating, the production of new geological maps, and the generation of derivative products for specific applications.
One of the most significant aspects of the project lies in the national technical standards specifically designed to ensure uniformity and coordination in the compilation of each map sheet. Each operational team is required to follow the same set of guidelines, published in the Quaderni del Servizio Geologico d'Italia, Series III.
The geological sheets have been, and continue to be, produced under agreements between ISPRA, regional authorities, autonomous provinces, universities, and CNR institutes.
The state funding provided over time enabled the completion of a first phase (1989–2004), producing 281 geological sheets, covering approximately 44 % of the national territory.
The second phase, launched in 2020, is still ongoing and foresees the preparation of an additional 79 geological sheets, bringing the overall coverage to nearly 58 % of the national territory.
Within the CARG Project, Emilia-Romagna stands out nationally as the only region to have almost fully completed the programme, activating 55 out of 58 sheets, thereby achieving geological coverage of approximately 95 % of the regional territory.

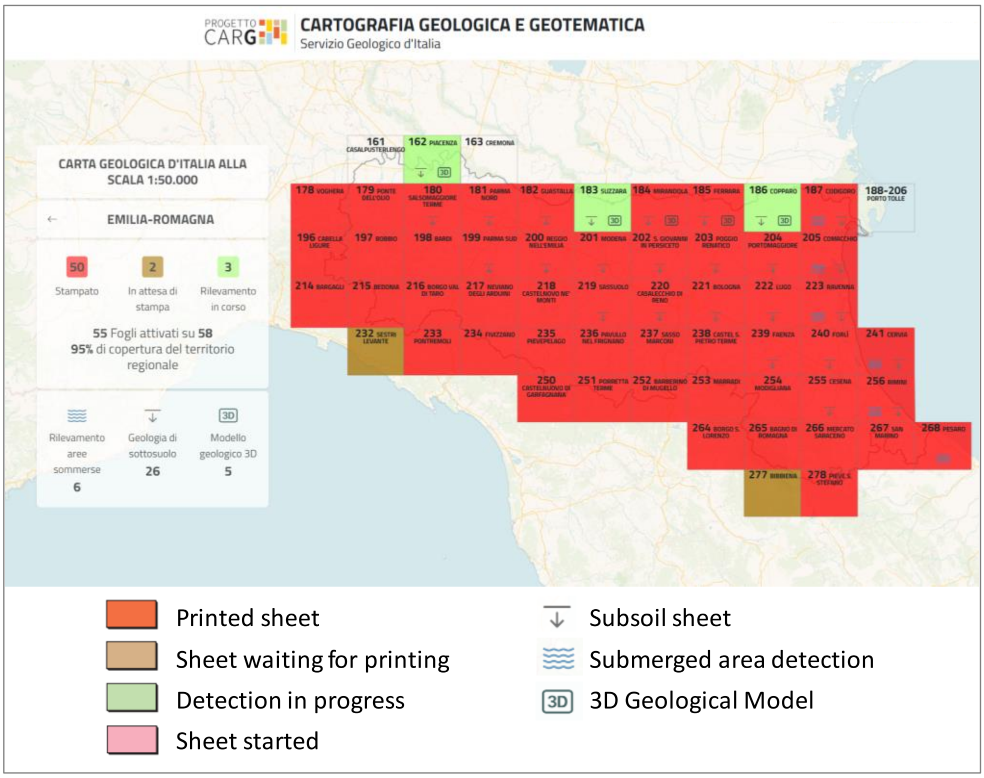


Figure 23 - State of the Art of Geological Mapping at 1:50,000 Scale in the Emilia-Romagna Region (https://progetto-carg.isprambiente.it/cartografiaCARG/index.php?source=cartageologica&regione=Emilia-Romagna)

Bonzi et al. (2010) gathered information concerning both the mapping of sandy body outcrops and the contours of the top isobaths of coastal sands from the geological sheets covering the coastal aquifer area (specifically Sheets 187, 205, 204, 223, 240–241, 256, and 268, shown in Figure 23).

These datasets were cross-referenced with information from 5,726 geognostic investigations—in particular cone penetration tests with piezocone (CPTU) and continuous-core boreholes—available for the study area within the SGSS Geognostic Database.

This integration made it possible to elaborate three detailed maps of the coastal aquifer, shown in Figure 24, which represent the geometry of its bounding surfaces and the thickness of the aquifer itself.

The **map of the aquifer top surface** (Figure 24a) shows a clear deepening trend toward the west, consistent with the structural setting of the area.

In the southern sector, the aquifer behaves as unconfined (phreatic), being directly connected to the piezometric surface.

In the central and northern sectors, however, unconfined conditions are limited to coastal zones; moving inland, the aquifer becomes progressively buried beneath low-permeability horizons, thus acquiring a semi-confined or confined configuration.

This hydrogeological framework suggests a spatial variation in groundwater flow and aquifer vulnerability along the coast–inland transect.

The interpretation of the **map of the aquifer bottom surface** (Figure 24b) reveals a pattern similar to that observed for the top surface, characterized by a progressive deepening westward and by shallower depths in the southern sector and coastal areas, particularly in the central and northern zones.

The morphology of the basal surface, like that of the top surface, reflects the influence of two main geological processes that shape the architecture of the aquifer:

a more pronounced subsidence in the central and northern areas, and the presence of structural surfaces (top and base) controlled by lithological conditions, related to the progressive seaward progradation of the coastal plain.

The integration of all available data and the GIS-based processing performed by Bonzi et al. (2010) enabled the development of a three-dimensional geological model of the aquifer.

This model not only provides a more realistic representation of the subsurface, but also allows for the estimation of aquifer thickness and spatial lithofacies variations, derived from the combination of the top and bottom bounding surfaces.

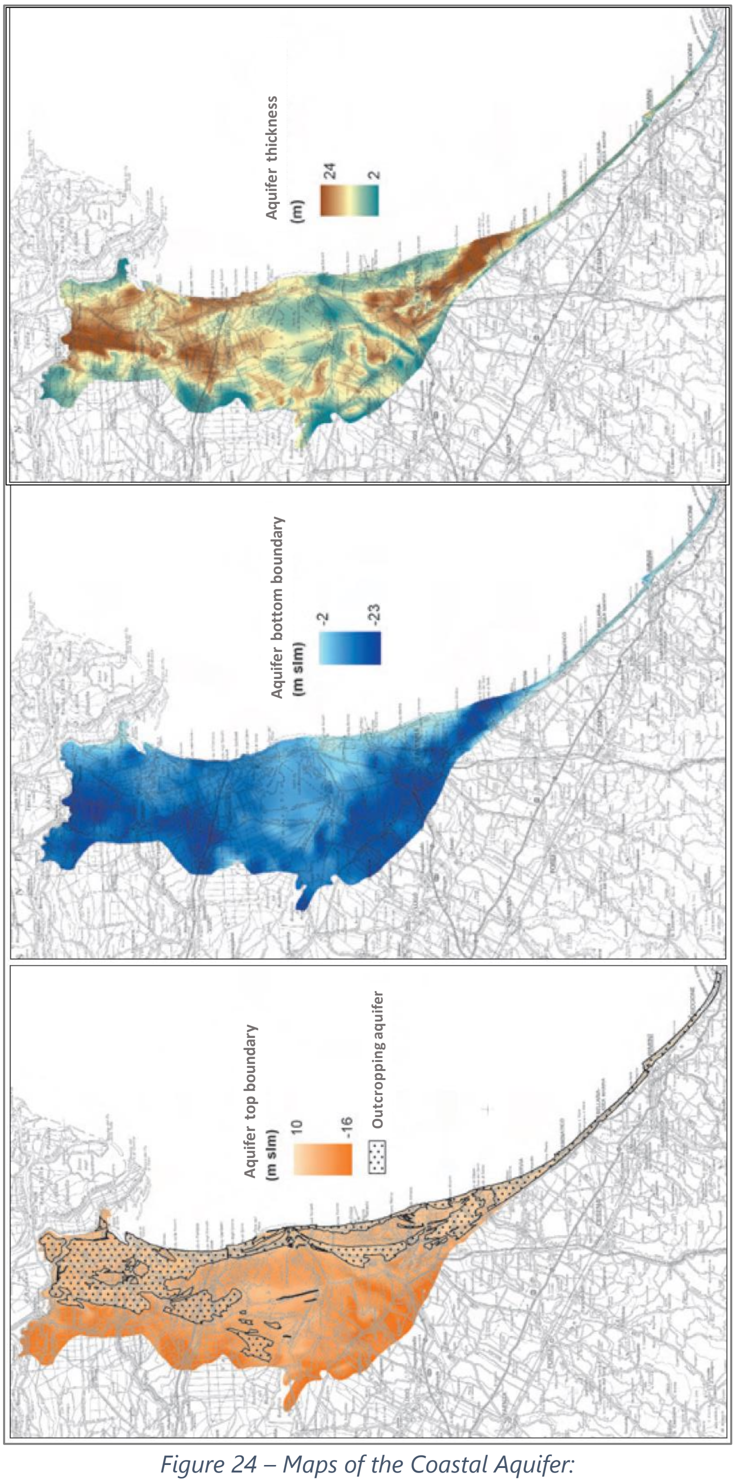


Figure 24 – Maps of the Coastal Aquifer:
(a) Top surface, (b) Bottom surface, (c) Thickness.
(Source: Bonzi et al., 2010, modified)

The **distribution of aquifer thicknesses** shown in Figure 24c highlights a high degree of lateral heterogeneity, indicative of significant depositional variability.
This heterogeneity is closely linked to the complexity of hydrogeological parameters, with direct implications for transmissivity.
The greatest thicknesses are concentrated along the central belt, following a predominantly north–south trend.
These thicker zones correspond to the superposition and amalgamation of sandy bodies generated during deep transgressive depositional phases, followed by more recent regressive episodes.
The maximum values are observed particularly between the Po River and Comacchio, and between Ravenna and Cervia.
These peaks are likely associated with substantial sandy inputs originating respectively from the Po River (northern sector) and from the Romagna rivers (southern sector).
Additional significant thicknesses are observed along the eastern coastal belt, corresponding to littoral ridge systems developed between the Reno River mouth and the Bosco della Mesola, as well as near the delta cusp of the Savio River.
Conversely, the minimum thicknesses occur in the westernmost portion, near the termination of the Holocene sedimentary wedge, where the aquifer thickness drops below 2 metres.
Similar conditions are also found in some sectors of the eastern margin, where the discontinuity between transgressive and regressive sandy deposits, combined with the interbedding of fine-grained levels (often derived from distal submerged beaches), limits sandy accumulation and favours the occurrence of aquitard deposits.

4.2. Geological Cross-Sections of the Shallow Coastal Aquifer Between the Po di Goro and the Reno Rivers

For the geological and hydrostratigraphic characterization of the coastal aquifer sector between the Po di Goro and the Reno River—the area targeted for flow and transport modelling within this European project - three shallow geological cross-sections were analysed, each oriented perpendicular to the coastline: one in the northern sector (Goro–Bosco Mesola area), one in the central sector (Comacchio area), and one in the southern sector (Lido di Spina–Reno River mouth area).
These sections effectively illustrate the lateral and vertical variability of the Holocene and Late Pleistocene deposits forming the Po–Adriatic coastal aquifer system.

Northern Section: Goro – Bosco Mesola Area
(CARG Project, Sheet 187, Section D–D′)
In this sector, deltaic and littoral sandy deposits prevail, with well-developed distributary channels and coastal ridges.
The medium- to coarse-grained sands exhibit good lateral continuity and high permeability.
Clay layers are thinner and more discontinuous than in the other sections, favouring greater hydraulic connectivity.
The base of the sandy unit (AES_7) lies at depths between –20 and –30 m a.s.l., resting on marine silts and clays belonging to the lower subsystem (AES_6).

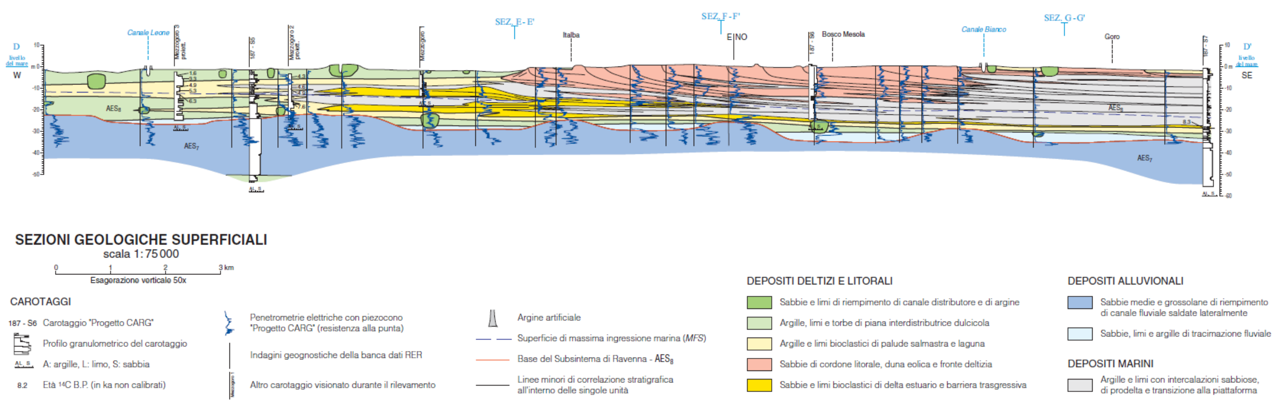
Central Section: Comacchio Area
(CARG Project, Sheet 205, Section C–C′)
This section shows the most complex succession, representing the transition between deltaic and lagoonal environments.
Littoral-ridge and distributary-channel sands are interbedded with clayey–silty lenses of back-ridge and brackish-marsh deposits, giving the system a multilayered character.
The surface of maximum marine transgression and the subsequent progradational phase are clearly identifiable, with a gradual upward transition from marine to deltaic facies.
Permeability is therefore more heterogeneous and variable compared to the northern section.

Southern Section: Lido di Spina – Reno River Mouth Area
(CARG Project, Sheet 223, Section A–A′)
In this sector, marine and prodelta deposits are thicker, while the littoral and deltaic sandy bodies are thinner.
The distributary-channel sands are less laterally continuous and more isolated, embedded within a silty or clayey matrix.
The greater abundance of fine sediments and the gradual southward decrease in grain size indicate a reduction in depositional energy and a lower overall permeability of the coastal aquifer compared to the northern sectors.

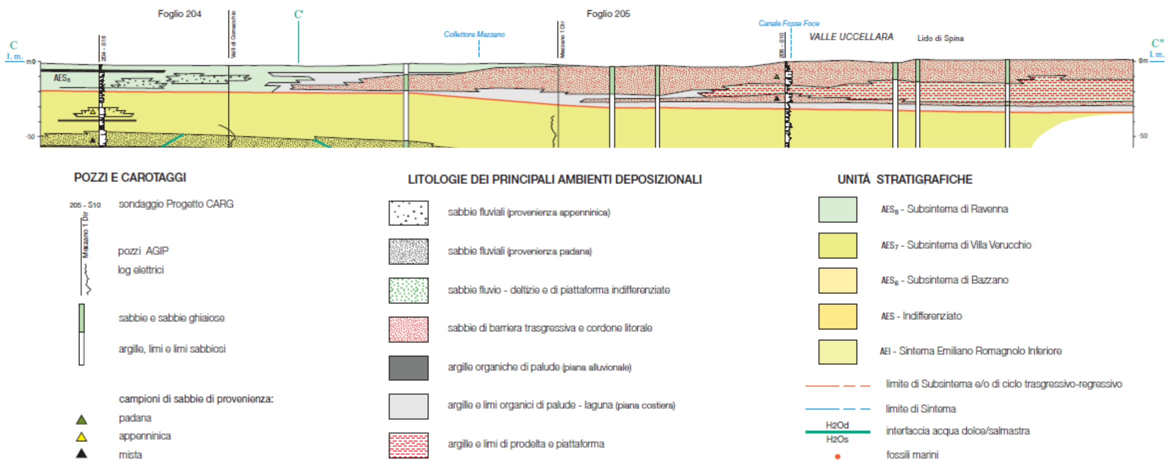
Overall, the three cross-sections highlight a composite aquifer system controlled by paleogeographic variations and by the Holocene transgressive–regressive dynamics.
The northern sectors exhibit greater hydraulic continuity and thicker sandy layers, whereas toward the south, the system becomes more confined and compartmentalized due to the presence of thicker and more extensive clay layers.

These stratigraphic and depositional differences directly influence groundwater circulation, aquifer recharge, and the vulnerability to saltwater intrusion along the coastal zone.

Foglio 187 - Sezione D-D'



Foglio 205 - Sezione C-C'



Foglio 223 - Sezione A-A''

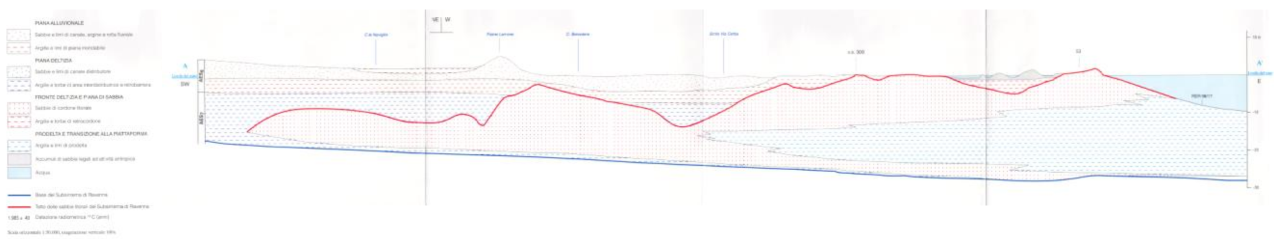


Figure 25 – Shallow Geological Cross-Sections of the Coastal Aquifer Between the Po di Goro and the Reno River, Extracted from the CARG Project

4.3. Groundwater Monitoring

Environmental Monitoring Network of Groundwater Bodies in Emilia-Romagna

Groundwater monitoring in Emilia-Romagna represents one of the most structured and long-standing environmental programmes implemented by the Region.
Established in 1976 for the quantitative component and in 1987 for the qualitative component, the system has been progressively updated and enhanced in accordance with EU Directives 2000/60/EC and 2006/118/EC, transposed into Italian law through Legislative Decree No. 30/2009.
The main objective is to achieve and maintain the “good status” of groundwater bodies, both in terms of chemical and quantitative conditions, thereby ensuring the sustainable management of a vital resource for the region.
The monitoring activity covers both the quantity and the quality of groundwater and is conducted through an extensive regional network comprising 733 observation stations distributed across plain, hilly, and mountainous areas. Among these, 600 stations are dedicated to quality monitoring, while over 633 stations measure groundwater levels. In many locations, the two components are integrated, providing a comprehensive and coherent assessment of the overall state of the groundwater resource.
The **quantitative monitoring** is based on the periodic measurement of static groundwater levels (or spring discharge, where applicable), expressed relative to mean sea level, from which the depth to water table (soggiacenza) is derived.
Measurements are carried out twice a year, during the maximum level period (spring) and the minimum level period (autumn).
This activity is supported by a network of approximately 40 automatic monitoring stations, which record hourly data on water level and temperature, allowing for a more detailed analysis of seasonal trends and fluctuations related to groundwater abstraction or climatic variability.

In parallel, chemical monitoring allows the assessment of groundwater quality through a comprehensive analytical framework.
Each sample is subjected to a basic analytical profile, which includes key physico-chemical parameters (pH, electrical conductivity, nitrates, metals, etc.).
Depending on the risk level and vulnerability of the aquifer, additional analytical profiles may be applied, dedicated for example to the detection of pesticides, hazardous substances, perfluoroalkyl compounds (PFAS), and, in the case of drinking-water aquifers, microbiological indicators.

Every six years, a complete baseline analytical profile is also performed, enabling the update and verification of the overall chemical status of the groundwater bodies.

The monitoring system, structured in this way, is operational throughout the entire regional territory and ensures homogeneous coverage of 135 groundwater bodies of different types: shallow phreatic aquifers, deep confined aquifers, mountain aquifers, and valley-floor aquifers.

Sampling frequencies vary according to the degree of vulnerability and environmental risk—they are higher for shallow phreatic aquifers, which are more exposed to anthropogenic pressures, and less frequent for deep aquifers, where conditions tend to be more stable.

In Figure 26, the monitoring points of the coastal phreatic aquifer in the lowland area are shown in yellow, with the depth to the bottom of each piezometer indicated, while green points correspond to the fluvial phreatic aquifer of the plain.

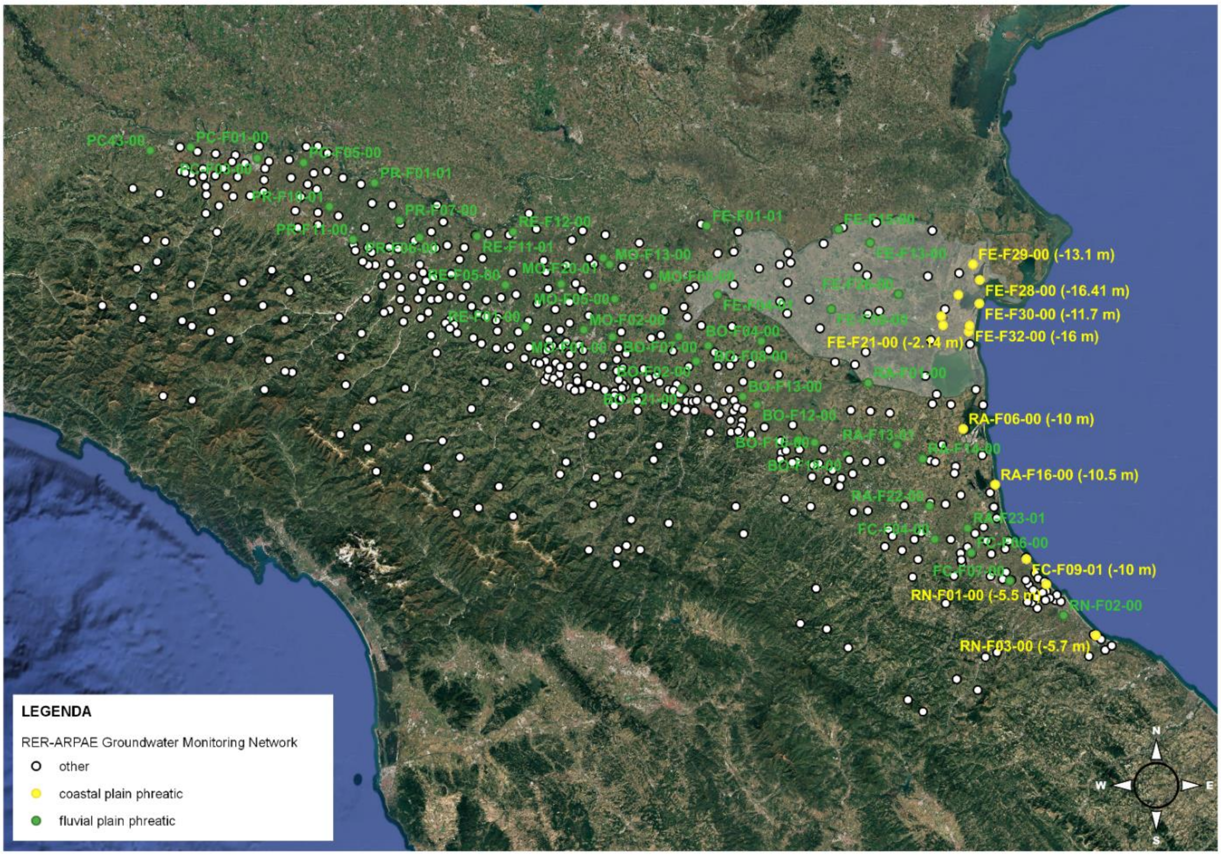


Figure 26 - Groundwater Monitoring Network of Emilia-Romagna

The systematic groundwater monitoring programme, in its current form, has been operational since 2002 and is periodically updated.

The first major revision took place in 2010, with the launch of the first River Basin Management Plan, while in 2015 the monitoring network and observation criteria were further refined in preparation for the second management cycle (2015–2021).
After each monitoring cycle, the Regional Authority processes and synthesizes the results obtained, updating the overall knowledge framework on the status of groundwater resources.
All data and analyses are compiled into an official report, which is published and made available on the institutional website of the Emilia-Romagna Region, ensuring maximum transparency and public accessibility of environmental information.
(https://www.arpae.it/it/temi-ambientali/acqua/report-bollettini/acque-sotterranee)

The coastal phreatic aquifer extending along the littoral zone of Emilia-Romagna, composed mainly of coastal sands and outcropping dune deposits, is naturally exposed to the risk of saltwater intrusion.
This phenomenon represents one of the main factors of concern and a key focus of the regional groundwater monitoring programme.

Report 2010–2013
The depth-to-water (soggiacenza) measurements indicated average values below 4 metres, with only a few localized exceptions—up to 8 metres—in areas such as the provinces of Ravenna and Ferrara (Figure 27a).
Most coastal monitoring stations showed depth-to-water values between 1 and 2 metres (green points) and between 0 and 1 metre (blue points) in areas closest to the coastline, particularly in the Ravenna and Rimini sectors, indicating a shallow, well-recharged water table.
Higher values, ranging from 2 to 4 metres (yellow) and 4–8 metres (brown), were observed locally in inland areas, especially in the Forlì sector, where the water table lies deeper, consistent with the reduced marine influence and slightly higher topography.
Overall, the situation reflected a stable hydrogeological balance, with phreatic waters generally shallow or near the surface along the coastal belt—a condition that ensures good recharge potential, but also greater vulnerability to salinization processes.
Seasonal fluctuations were mainly related to precipitation patterns and to interactions with surface water bodies.
As for electrical conductivity, data confirmed generally favourable values across most monitoring stations, though with a gradual increase toward the coast, where localized signs of salinization were observed—linked to proximity to the sea and to the high permeability of coastal sands.
Nevertheless, during this monitoring period, no widespread evidence of anthropogenic saltwater intrusion was detected; the observed variations were consistent with natural factors.

Report 2014–2019

In the subsequent monitoring cycle, the coastal phreatic aquifer maintained a "good" quantitative status, confirming the overall hydrogeological stability already observed in the previous period (Figure 27b–c).

The analysis of groundwater levels and depth-to-water data showed a generally stable trend, with no evidence of significant drawdown.

In particular, the average water-table depth in 2019 was comparable to the mean values recorded during 2010–2018, indicating a balanced condition between natural recharge and abstraction (Figure 27d).

No saltwater wedge intrusion effects related to groundwater pumping were detected.

The fluctuations of the saline wedge—measured over the years through seasonal depth profiles of electrical conductivity—were instead attributed to natural, climate-driven variations, including extreme events.

From the standpoint of electrical conductivity, the values remained within the range typical of fresh to slightly mineralized waters, with localized increases only in areas closest to the coastline, where marine influence is naturally expected.

No deteriorating trends or systematic increases in chlorides or other salinization indicators were observed.

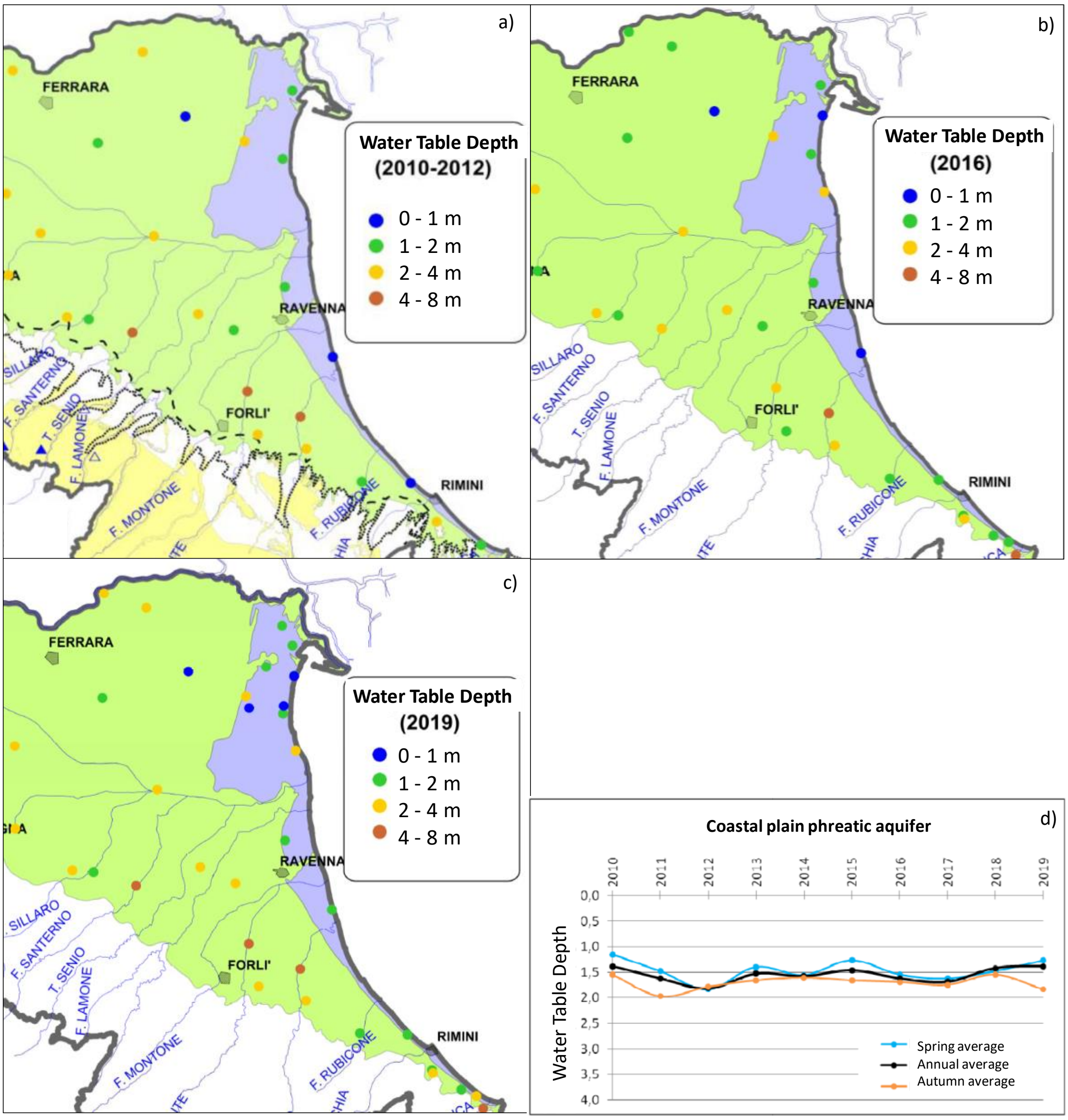


Figure 27 - Average Annual Depth to Water in the Phreatic Groundwater Bodies of the Emilia-Romagna Plain: (a) 2010–2013, (b) 2016, (c) 2019, (d) 2010–2019

Monitoring Network of the Shallow (Hypodermic) Groundwater Table

In 1995, based on previous studies carried out by the Second-Level Land Reclamation and Irrigation Consortium for the Emiliano-Romagnolo Canal (CER) on the relationship between groundwater levels and irrigation requirements of crops, the Emilia-Romagna Region funded and commissioned the same consortium to develop a monitoring network of the phreatic groundwater table (both coastal and fluvial) for the creation of a dynamic water-table map of the Emilia-Romagna plain.

The project was launched by the Region in 1997 and is currently managed by CER.

The location of the monitoring stations was determined through a detailed study of territorial characteristics, including geomorphology, soil types, recurrence of waterlogging phenomena, importance of irrigated crops, activities of land reclamation consortia, and the distribution of irrigated areas.

Particular attention was given to the 1:50,000-scale Soil Map of the Plain, which enabled the identification of the most widespread soil types, highlighting those with morphological evidence of water stagnation, and thus areas with a likely presence of a shallow water table.

A total of 203 monitoring stations were installed starting in 1997, of which 121 are currently operational (Figure 28).

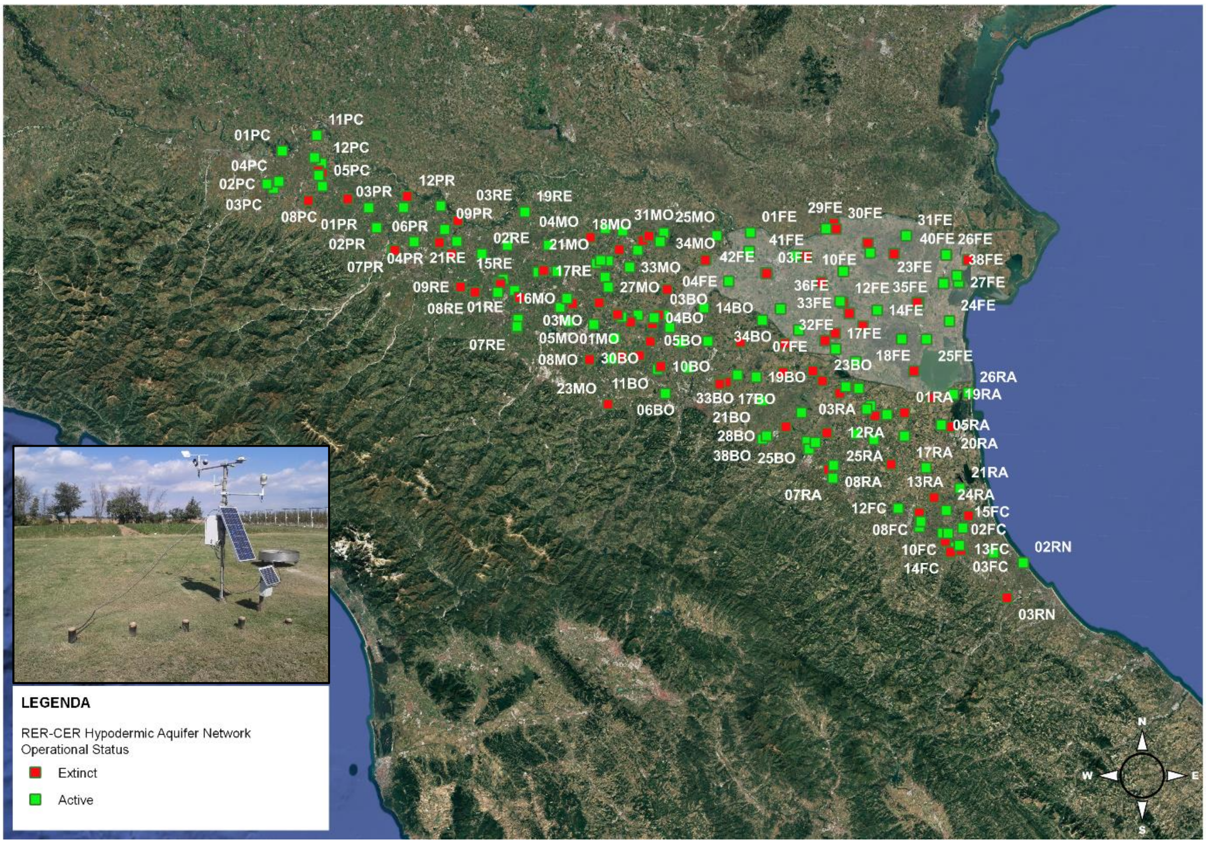


Figure 28 - Monitoring Network of the Shallow (Phreatic) Groundwater Table of Emilia-Romagna

Each monitoring station is equipped with piezometer nests, reaching a maximum depth of 300 cm, where the presence of the shallow groundwater table is measured at a variable frequency

depending on the season: every ten days from March to October (24 measurements) and monthly during the remaining months (4 measurements), for a total of 28 measurements per year.
The data are made available to users through the web application FaldaNET-ER (https://faldanet.consorziocer.it/Faldanet/retefalda/index), which allows the visualization of the groundwater level extension map (based on the 1:50,000-scale Soil Map), the location of active monitoring stations, and the extraction of depth-to-water data from the shallow groundwater table.

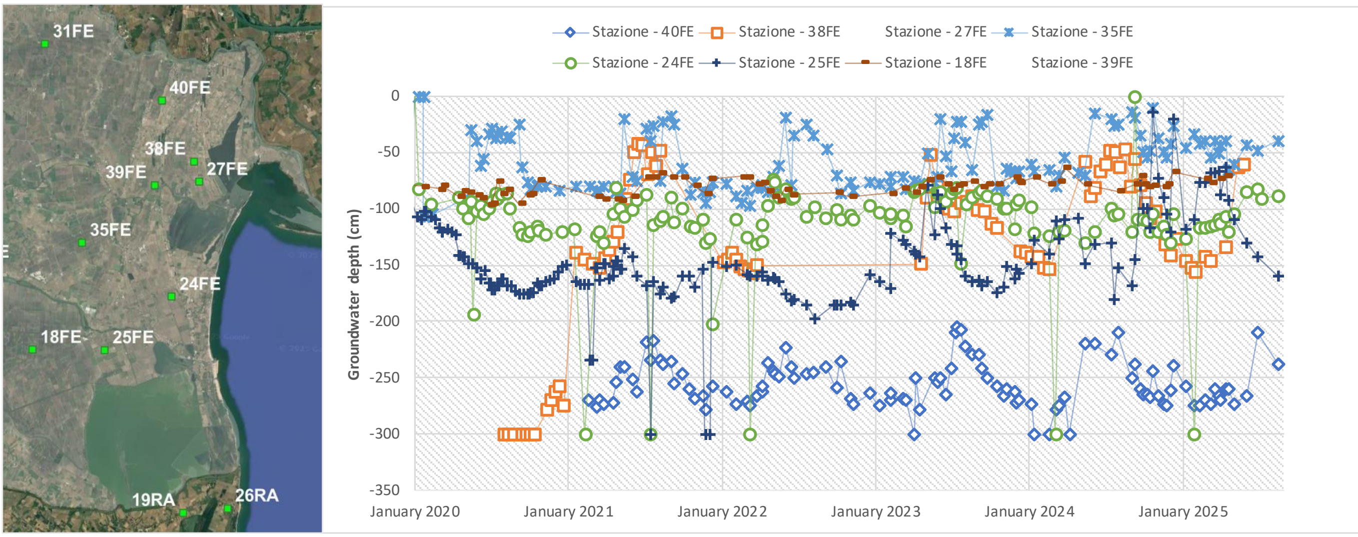


Figure 29 – Trend of the Shallow Groundwater Table Depth along the Northern Coastal Sector of Emilia-Romagna

Figure 29 shows the distribution of the shallow groundwater monitoring stations along the northern coastal sector of Emilia-Romagna under investigation, between Lido di Spina and the mouth of the Reno River.
The stations are numbered from 18FE to 40FE (Ferrara) and are arranged along a sea–inland gradient, allowing the analysis of piezometric evolution and the potential influence of the saline wedge.
The coastal stations (e.g., 24FE, 25FE, 27FE) are located close to the shoreline or near the lagoons and wetlands of Comacchio, while the inland stations (e.g., 18FE, 35FE, 38FE, 39FE, 40FE) are situated in agricultural areas of the backplain.
On the right, the trend of the shallow groundwater table depth for the period 2020–2025 is shown for the eight active stations representative of the Ferrara coastal area.
The vertical axis represents the groundwater depth (cm), while the horizontal axis shows the time scale (2020–2025).

Analysis of the historical data series shows that average groundwater depths are generally shallower in the coastal piezometers (e.g., 24FE), while they progressively increase inland (as in stations 38FE, 25FE, and 40FE).
This distribution reflects the antropogenic coastal–inland piezometric gradient, induced by the drainage network which governs the groundwater flow direction from the sea toward inland.
Seasonal oscillations are evident in all the datasets, but inverted respect ot the natural ones, with an increase in groundwater depth (i.e., a lowering of the water table) during the winter months, and a reduction in late spring and summer, due to irrigation channels leakage.
In fact, in piezometers located in permeable areas (paleochannels and paleodunes), fluctuations are more subdued and regular, indicating a greater stability of the phreatic level, likely due to good hydraulic connection amng surface water water bodies and the shallow aquifer.
Conversely, the piezometers located in less permeable zones (back-barrier or interbasins) exhibit larger amplitude variations and higher average depths, suggesting a behavior more strongly influenced by local recharge dynamics and seasonal rainfall patterns.
Overall, the analysis confirms a spatial correlation between average groundwater depth and the depositional environments, with shallower levels in permeable zones and deeper levels low permeability zones, consistent with the morphological and hydrogeological setting of the system.

Monitoring Network of the Coastal Phreatic Aquifer

As described in Section 4.1, the Emilia-Romagna Region launched a dedicated study project on the coastal phreatic aquifer to develop an updated knowledge framework highlighting its physical characteristics, hydrodynamic behavior, and potential vulnerabilities.
The project began in 2009, with two main objectives:
on one hand, the definition of the geological model of the aquifer body; on the other, the design and installation—through drilling—of a dedicated piezometric monitoring network in areas where the aquifer occurs under phreatic conditions, i.e. composed of outcropping sandy deposits near the coastline, as shown in Figure 24.
The network extends along the entire coastline and includes 30 piezometers, of which 11 are located in the province of Ferrara, 12 in Ravenna, 2 in Forlì-Cesena, and 5 in Rimini (Figure 30).
The locations of the instruments were selected to ensure a homogeneous spatial distribution of data and to effectively represent the inland progression of the saline wedge within the phreatic portion of the aquifer.
Whenever possible, transects were designed perpendicular to the shoreline, enabling the correlation of field data with the geological cross-sections.

The drilling depths range between 6.9 and 21.0 meters, and the precise elevation of the piezometer heads was determined using GPS surveying.

The number of monitoring points in the network has changed over time: from the initial approximately 30 piezometers, the network was progressively expanded to a maximum of 37 measurement sites, and then reduced to 24 active points in 2018, for which historical data series are generally available from 2009 to the present.
In each piezometer, groundwater depth (depth to water) is measured together with the vertical profiles of electrical conductivity (EC, in mS/cm), temperature (°C), and total dissolved solids (TDS, in g/L).
Measurements are taken using a portable multiparameter probe equipped with a graduated cable, recording values at one-meter intervals along the water column.
This approach allows for the construction of vertical profiles of the measured parameters for each piezometer and the comparison of profiles under different seasonal conditions.

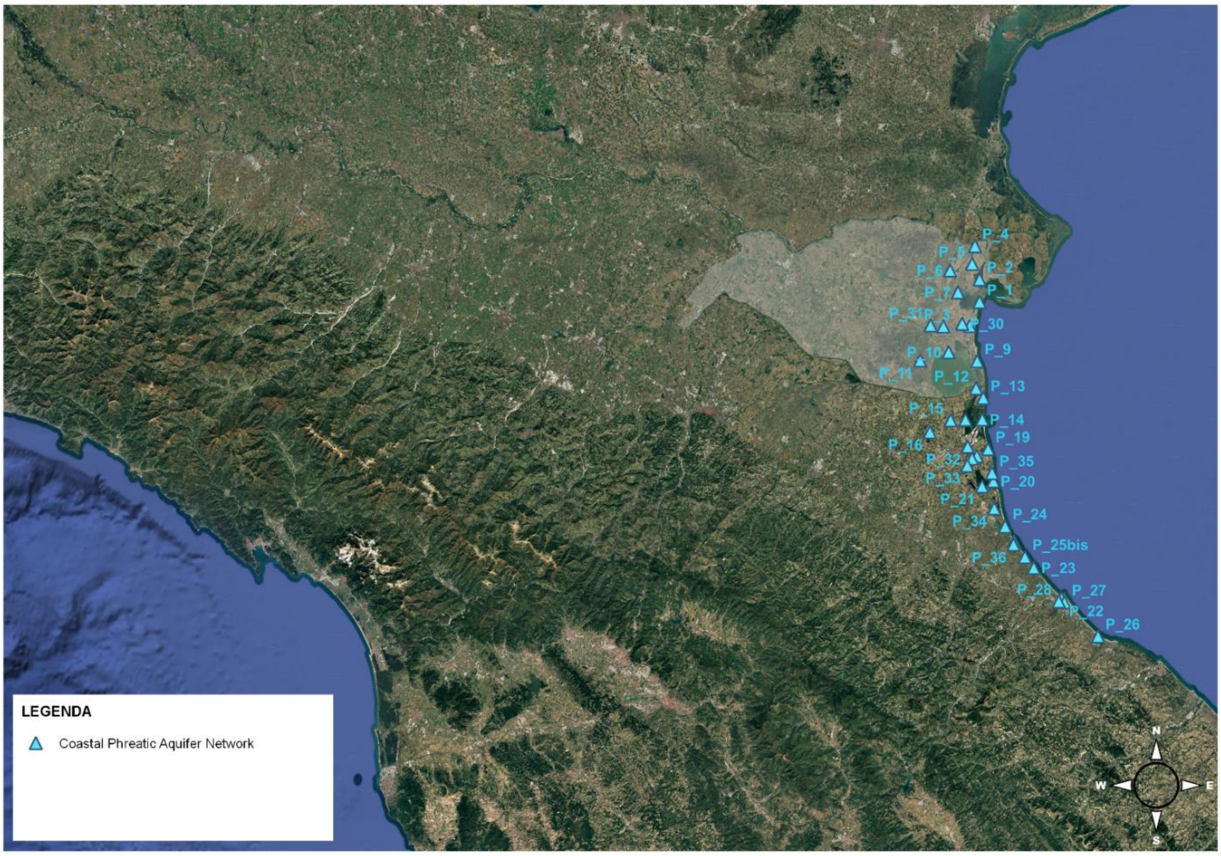
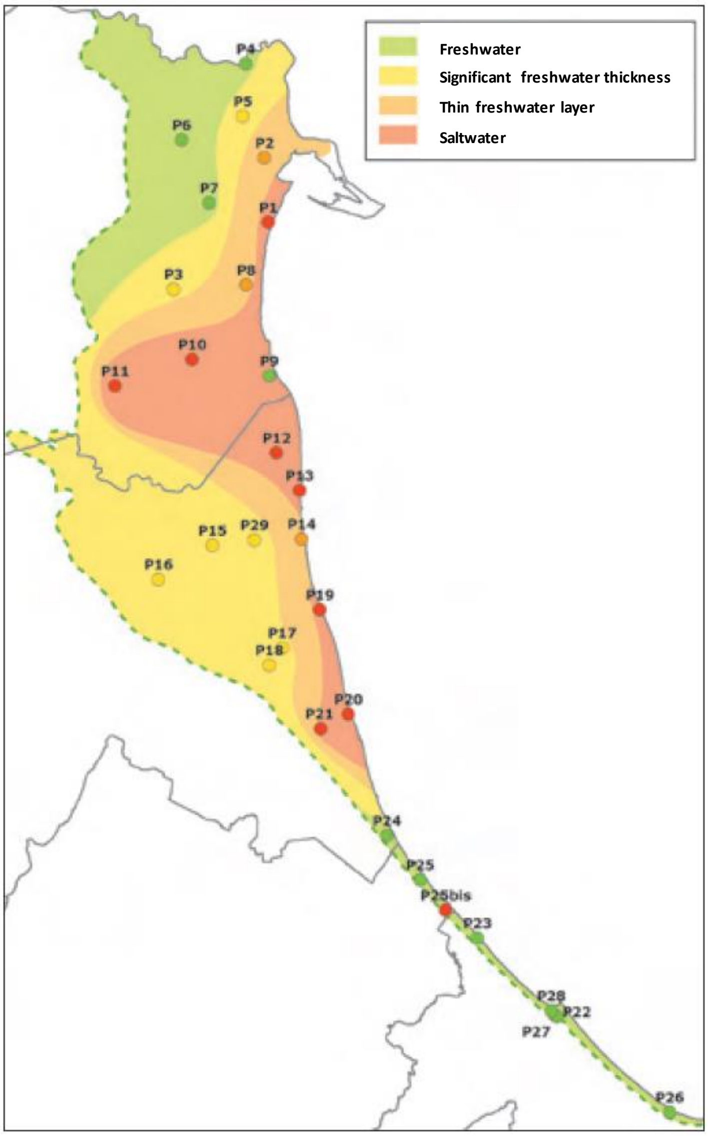


Figure 30 - Monitoring Network of the Phreatic Aquifer of Emilia-Romagna



Based on the electrical conductivity profiles reconstructed for all piezometers during the monitoring campaigns carried out between June 2009 and May 2010, Bonzi et al. (2010) produced a first regional-scale synthesis of the groundwater quality distribution within the coastal phreatic aquifer, as shown in Figure 31.

In the analyses carried out, the following reference values were considered: 2.5 mS/cm (threshold value indicated by Legislative Decree No. 31/2001 for drinking water), 10 mS/cm (transition value between brackish and saline water), and 56 mS/cm (indicative value of seawater salinity).

The red zone includes the points where the entire water column was found to be brackish or saline.

The orange zone identifies areas with a thin layer of fresh water overlying the transition zone.

The yellow zone represents points characterized by a thicker layer of fresh water, while the green zone includes sites where the water column was entirely and consistently fresh.

Figure 31 – Regional synthesis of the first year of salinity monitoring in the coastal phreatic aquifer (Source: Bonzi et al, 2010)

From a spatial perspective, the northern and southern sectors of the coastal plain appear predominantly green, a condition attributable respectively to the influence of the Po River and to the contributions from the Apennine watercourses, which promote a greater presence of freshwater in the shallow aquifer.

This confirms the importance and effectiveness of freshwater inflows in counteracting the inland progression of the saline wedge, and also the presence of paleo saline groundwater that

characterize the inland zones of the Ferrara Province (Caschetto et al., 2017; Colombani et al., 2017).
Within the different areas, piezometers exhibit significantly different electrical conductivity profiles and absolute values.
The authors highlight that the shape of the conductivity profile, which is closely related to the salinity distribution, is influenced by local hydrodynamic conditions, the configuration of piezometric heads, and the overall water balance of the aquifer system.
Particular attention is given to the piezometric profiles analyzed in the referenced study, which concern the coastal portion of the aquifer investigated in the present work.

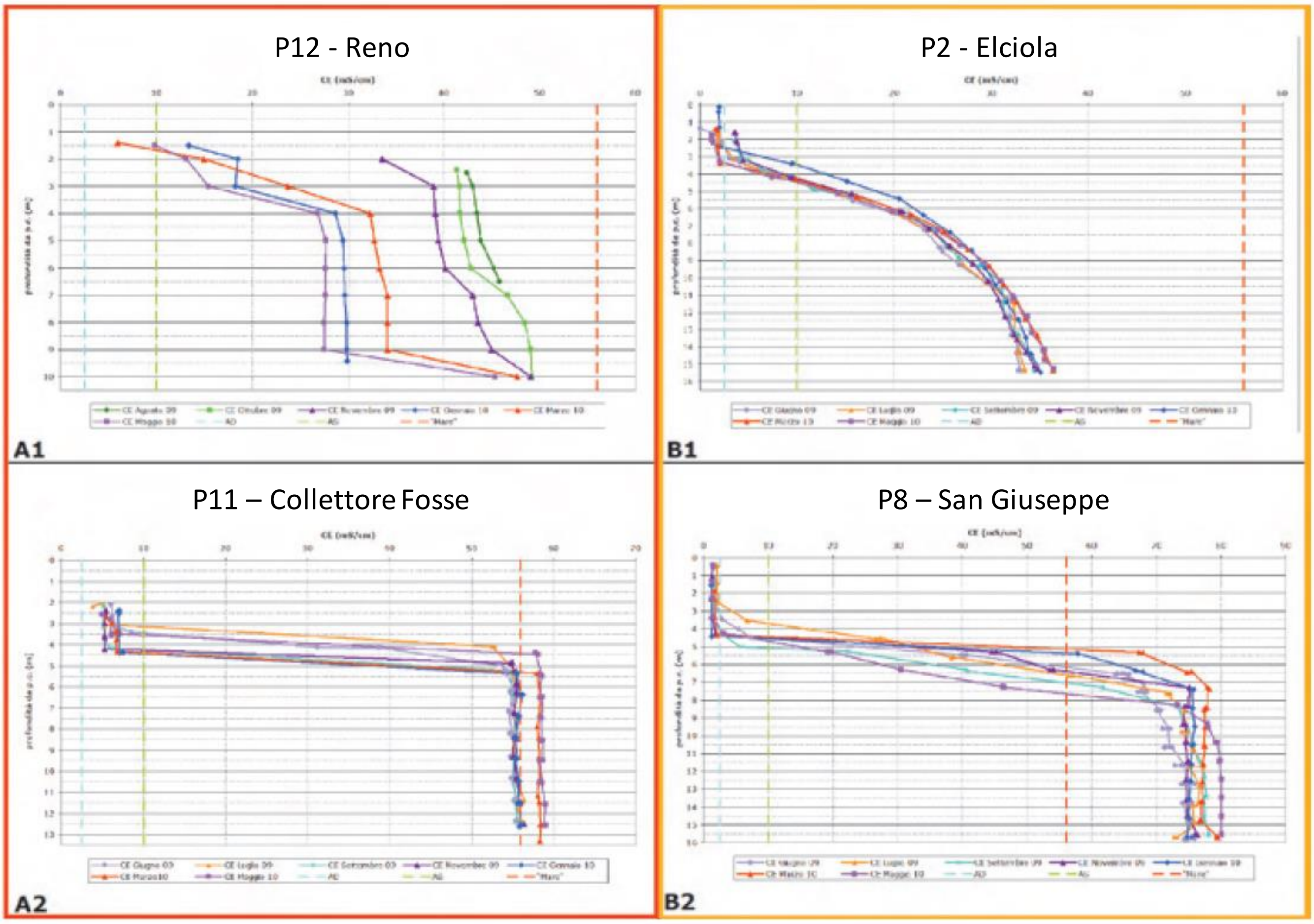


Figure 32 – Electrical conductivity profiles of piezometers located in the red zone (P12 – P11) and in the orange zone (P2 – P8) (Source: Bonzi et al, 2010)

The P12 – Reno piezometer (Figure 32 – A1) shows a marked seasonal variability in electrical conductivity values, attributable to the local hydrodynamic characteristics.

The highest values were recorded during the August 2009 monitoring campaign, followed by a progressive decrease after the abundant winter precipitation, which caused an increase in hydraulic head and consequently limited the inland intrusion of the saline wedge.
In the case of the P11 – Collettore Fosse piezometer (Figure 32 – A2), located within the Valli del Mezzano area, a remarkable consistency among the different profiles is observed, along with a sharp electrical conductivity gradient, where values shift from less than 10 mS/cm to levels comparable to those of seawater.
This variation identifies a distinct interface between freshwater and saltwater, which is subject only to minor seasonal fluctuations in depth.
Winter precipitation appears to have little influence on the advancement of the saline wedge, except for a slight deepening of the transition zone, whose depth shifted from approximately 3 m below ground level in July 2009 to about 4.5 m between January and March 2010.
This salinization condition cannot be explained solely by the classical model of marine intrusion, but is instead attributable to the geological origin of the subsurface, formed as a result of the drainage of ancient lagoons or valleys that were once occupied by brackish or saline waters.

In the P2 – Elciola piezometer (Figure 32 – B1), the electrical conductivity profiles show consistent trends across the different monitoring campaigns, with nearly stable conductivity values.
The freshwater layer, ranging between 2 and 3 meters, tends to increase during the winter months due to meteoric water infiltration, while a partial increase in salinity is observed in late summer.
The transition between freshwater and saltwater appears gradual and diffuse, lacking a distinct interface.
The P8 – San Giuseppe piezometer (Figure 32 – B2), located in a recently reclaimed area within former brackish lagoons, shows a freshwater layer varying between 2 and 4 meters, with a sharp interface separating it from the underlying saline waters.
The deeper water exhibits electrical conductivity values even higher than the average seawater, due to the presence of high-salinity water trapped in the lower portion of the aquifer.
The seasonal fluctuation of the transition zone is limited, with a slight upward movement during winter, likely influenced by precipitation and by the local irrigation regime.

The authors focused their analysis on the data collected during the first two years of monitoring, deriving important insights into the hydrodynamic behavior and the salinity distribution of the system.
These results provide a baseline knowledge framework and represent a useful starting point for the present work, which aims to deepen the understanding of the system's evolution over the

subsequent period (2011–2021) by extending the analysis to the temporal and spatial variations of the coastal shallow groundwater (hypodermic aquifer).
The following figure shows the locations of the monitoring points belonging to the various networks described above, within the portion of the coastal aquifer between the Po di Goro and the Reno rivers.
This area defines the modeling domain used for the variable-density flow and transport simulations developed under the framework of this European project, as further detailed in Section 4.4.

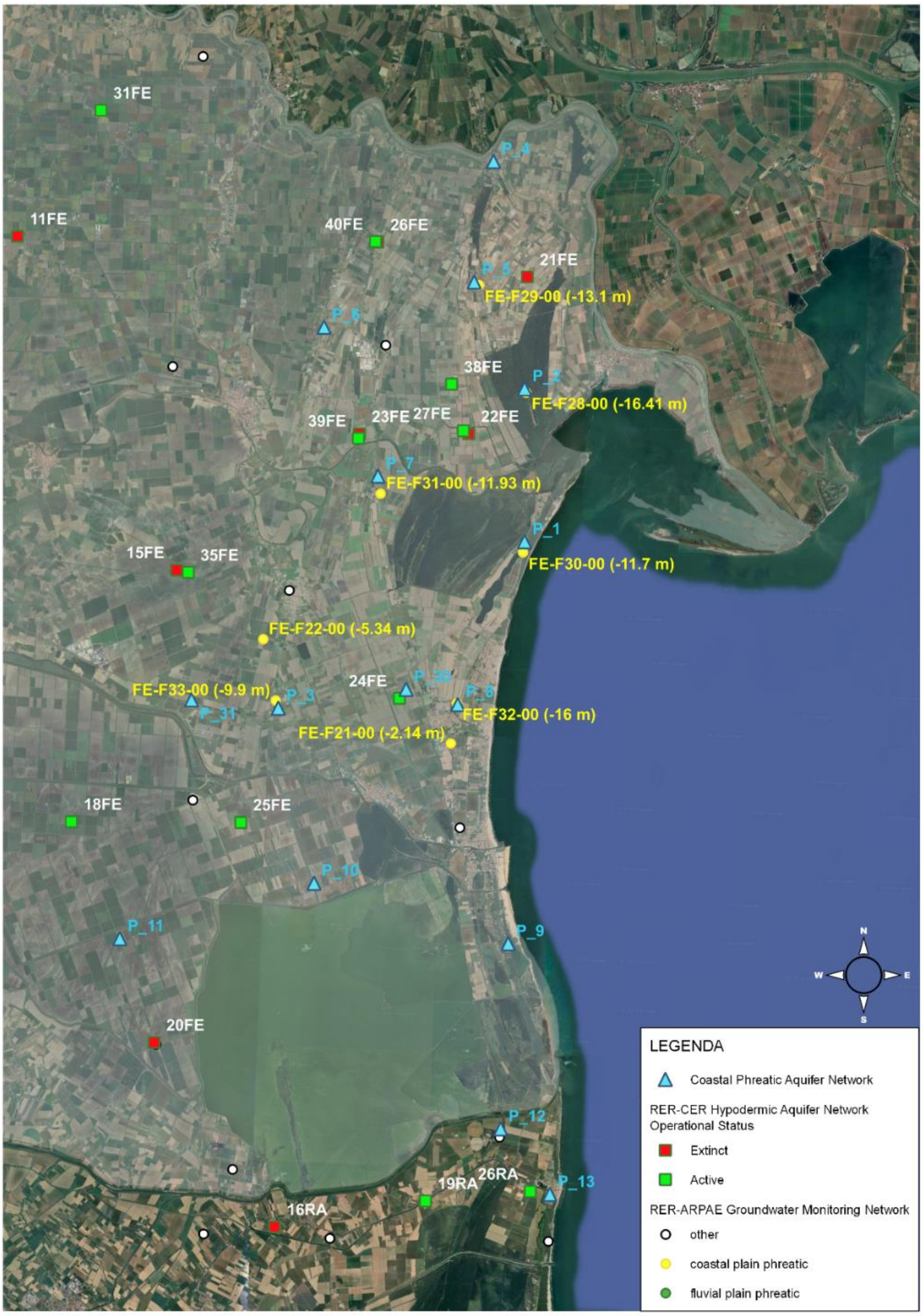


Figure 33 – Monitoring points within the coastal aquifer between the Po di Goro and the Reno River

4.4. Flow and Transport Modelling of the Ferrara Coastal Phreatic Aquifer

The work of **Colombani et al. (2016a)** represents the first development of a three-dimensional numerical flow and salt transport model of the Ferrara coastal phreatic aquifer, aimed at assessing the potential impacts of climate change on groundwater salinization.
The model was implemented using the numerical code SEAWAT 4.0, developed by the U.S. Geological Survey (USGS), and was automatically calibrated through PEST. It reproduced the current hydrogeological conditions and simulated future scenarios up to 2050, accounting for sea level rise and changes in meteoric recharge.
The climate change boundary conditions were based on the IPCC A1B scenario, downscaled over the Po River basin using the Prometeus regional model (Dell'Aquila, 2011) and the CIRCE model (Gualdi et al., 2013), with a relative sea level rise projection from Scarascia and Lionello (2013) — a condition that is now considered outdated.
Model calibration — the automatic optimization process of numerical parameters such as hydraulic conductivity, recharge rate, and porosity, aimed at minimizing the difference between simulated and observed values — was carried out using piezometric and salinity data (specifically Total Dissolved Solids, TDS) collected between 2010 and 2013 at a network of 54 monitoring points, including multi-level wells, piezometers, and quarry lakes distributed across the entire coastal plain.
Additional support for model development was provided by hydrostratigraphic data from borehole logs and drilling reports, as well as meteorological and water balance data supplied by ARPA Emilia-Romagna and the Ferrara Plain Reclamation Consortium.

The study by Colombani et al. (2016a) represents the reference framework for the development and update of the numerical model of the Ferrara coastal phreatic aquifer carried out within the present European project, with the support of CFR (Consorzio Ferrara Ricerche).
This model was developed with the aim of identifying areas with higher or lower salinization levels within the simulated flow domain for the 2011–2021 reference period, while also locating potential salinization "hot spots" within the aquifer that may interact with the reclamation canal network, increasing its salinity content.
Specifically, the activities carried out included:

- the collection, processing, and analysis of historical and recent data related to hydraulic and hydrological forcings affecting the model flow domain;
- the acquisition and processing of piezometric data and chemical characteristics of groundwater and reclamation canal waters;
- the conversion of the original model, developed using the now outdated PMWIN 8.0 software, to the updated PMWIN 11.0 interface, and verification of its full operability;

- the update of the model through the integration of spatially distributed monthly data for the 2011–2021 period, aimed at analyzing the temporal evolution of both groundwater levels and salinity;
- the recalibration of the updated model, using the most recent piezometric and salinity data available.

Model Setup

The flow and solute transport model of the Ferrara coastal phreatic aquifer was implemented using the most updated version of the numerical code **SEAWAT 4.2** (Langevin, 2009), integrated within the new graphical platform PMWIN 11.0 (Chiang, 2022).
The update was carried out starting from the original large-scale calibrated model, by importing **the geometry and hydraulic conductivity values into the PMWIN 11.0 environment**.
Subsequently, the **number of layers** was reduced from 10 to 7 in order to optimize computation time while maintaining an adequate level of hydrogeological accuracy. The **model grid** was refined to reproduce in greater detail the main geomorphological features of the study area, particularly the fluvial meanders and the geometry of the Vene di Bellocchio and the Valli di Comacchio.
As described in Section 4.2, the **conceptual model** consists of a complex phreatic aquifer mainly composed of sandy deposits, which downward alternate with clayey–silty lenses, forming a sequence of semi-confined aquifers. These layers tend to merge into a single unconfined aquifer in correspondence with major paleochannels, dune ridges, and paleodunes, located in the central portion of the flow domain and along the coastal belt.
The lower boundary of the aquifer system is represented by prodelta clays and Pliocene clayey sediments, generally found at elevations below –20 m a.s.l. The thickness of permeable deposits is significant along paleochannels and dune ridges, while it gradually decreases toward the inland areas.
The **surface hydrographic network** is densely developed across the entire study area, with the main watercourses (Po di Goro, Po di Volano, Navigable Canal, and Reno River) flowing west–east and strongly influencing the hydraulic regime of the underlying aquifer.
For the purpose of assessing the impact of groundwater on the progressive salinization of reclamation canals, the entire hydrostructure of the Ferrara phreatic aquifer was considered, with the goal of analyzing the influence exerted by the dense drainage network (canals and pumping stations) on the aquifer behavior throughout the simulated years.

The estimation of the recharge rate represents one of the most influential input parameters in the implementation and calibration of flow and transport models, although effective infiltration is difficult to assess at a local scale.
In the Ferrara plain, the surface deposits are generally poorly permeable; however, due to the high irrigation supply and the very low field slope, which minimizes surface runoff, soils can in some cases allow significant infiltration.
Several studies in the literature have estimated the upper limit of infiltration at approximately 455 mm/year (Mollema et al., 2012).
For the updated flow model, the effective infiltration over the Ferrara coastal aquifer was estimated using the spatially distributed BigBang method, which was then refined during the model calibration phase.
Overall, the recharge rate shows marked seasonal variability and has not decreased in recent years, despite declining rainfall and rising average temperatures—thanks to the substantial summer irrigation inputs supplied by the Reclamation Consortium (Consorzio di Bonifica).
The analysis was carried out both from a hydrodynamic perspective, by studying piezometric levels and groundwater–surface water interactions, and from a hydrochemical perspective, through the assessment of groundwater and surface water salinity variations.
The conceptual model was progressively refined into a numerical model through successive stages of improvement, evolving from an initially simplified representation of the hydrogeological setting toward a detailed definition of the main stress factors controlling the piezometric distribution and the groundwater flow regime.
Subsequently, **time-varying boundary conditions were defined**, enabling the implementation of a transient model for the 2011–2021 period.
Thanks to the availability of extensive field data, a high degree of geological detail was achieved in model reconstruction, including the characterization of hydrogeological parameters (such as hydraulic conductivity and storage coefficient) and the definition of boundary conditions, which encompass surface water bodies, impermeable limits, effective rainfall, and evapotranspiration processes from the water table.

Data Collection for Model Update

The data collection activity was carried out with the aim of defining the main input parameters required for the numerical modelling of variable-density groundwater flow and solute transport within the Ferrara phreatic aquifer.
To achieve this goal, **data from the ISPRA open-access database on the national hydrological balance (BigBang)** (Braca et al., 2019) were analyzed. The dataset is available for download from the official website:

https://www.isprambiente.gov.it/pre_meteo/idro/BIGBANG_ISPRA.html
The ISPRA database provides data on groundwater recharge and actual evapotranspiration, which were recalibrated using information on crop types and agricultural practices supplied by the Reclamation Consortium, following the procedure developed by Gaiolini et al. (2022) and successfully applied and validated in the coastal aquifer of the Campania region.
For model calibration, **data from the regional hypodermic water table monitoring network of Emilia-Romagna**, described in Section 4.3, were used. These data are publicly available on the official website:
http://faldanet.consorziocer.it/Faldanet/retefalda/index
Finally, to assess whether the variable-density transport model was properly calibrated, its results were compared with salinity monitoring data of the regional phreatic aquifer, as published by Giambastiani et al. (2021).

Input Data for Numerical Modelling

The data used for the development of both the conceptual and the numerical model include:

- Digital cartographic base at a 1:5,000 scale and numerical topographic base;
- Thematic geological and hydrogeological maps in vector format;
- Meteoclimatic data;
- Discharge tests, geophysical surveys, and well tracer tests;
- Salinity analyses performed over the simulated period.

The **model domain** covers an area of approximately 860 km^2, extending about 25 km in the East–West direction and 48 km in the North–South direction (Figure 34a).

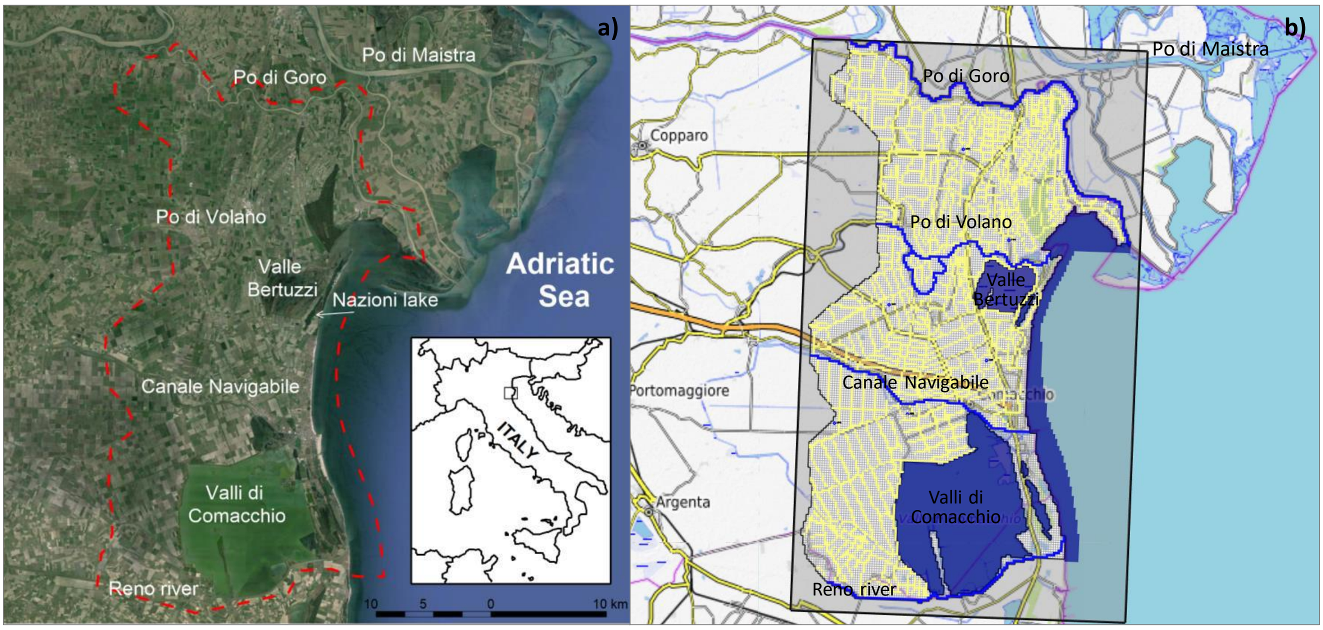


Figure 34 a) Location of the study area and main water bodies; b) Cells of the simulated flow domain showing major surface water bodies (dark blue), rivers (light blue), and the reclamation canal network (yellow).

The **simulation grid** consists of 125 columns and 243 rows, with 7 layers of variable thickness for the vertical discretization (Figure 34b).
The upper boundary of the grid corresponds to the topographic surface, ranging between −8 and +9 m a.s.l., obtained from the Digital Terrain Model (DTM) provided by the Emilia-Romagna Region.
The lower boundary, representing the top of the underlying aquitard, lies between −12 and −20 m a.s.l., as derived from stratigraphic logs available in the Geological Survey Database of the Emilia-Romagna Region.
The **hydraulic conductivity** values (Figure 35) were kept unchanged from the original model by Colombani et al. (2016a), since it provided an accurate representation of the distribution of permeable and impermeable horizons. This choice was further supported by literature data and well discharge test results reported by Giambastiani et al. (2013) and Colombani et al. (2016b).
These datasets allowed for a highly detailed representation of the vertical variability in hydraulic conductivity, consistent with the findings of tracer tests conducted using environmental tracers.

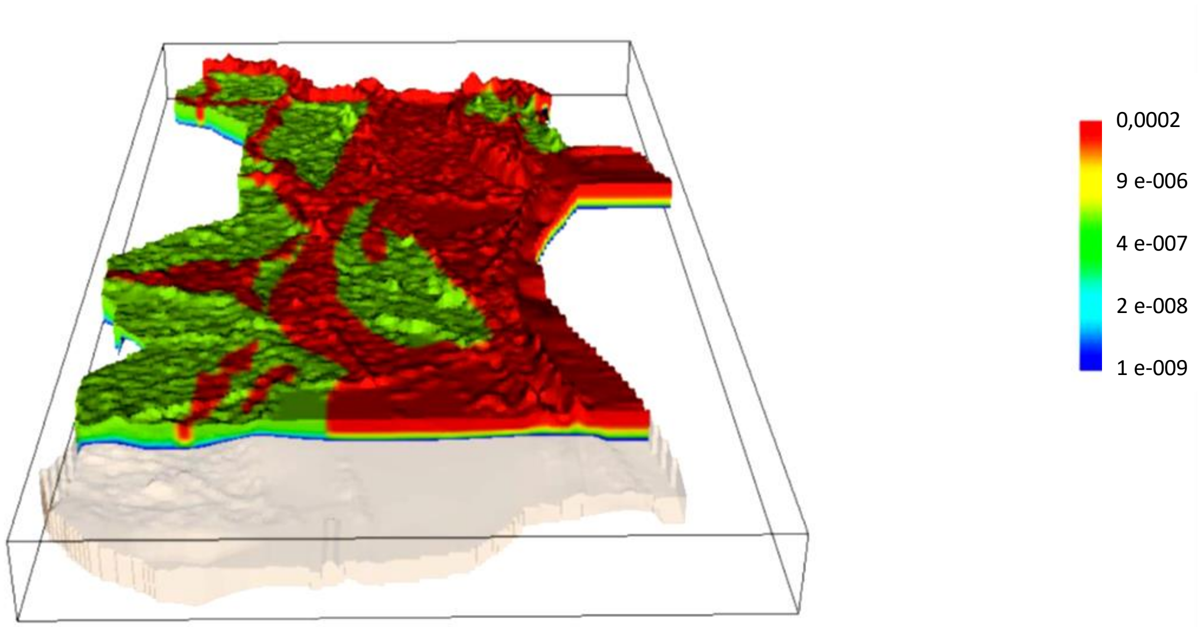
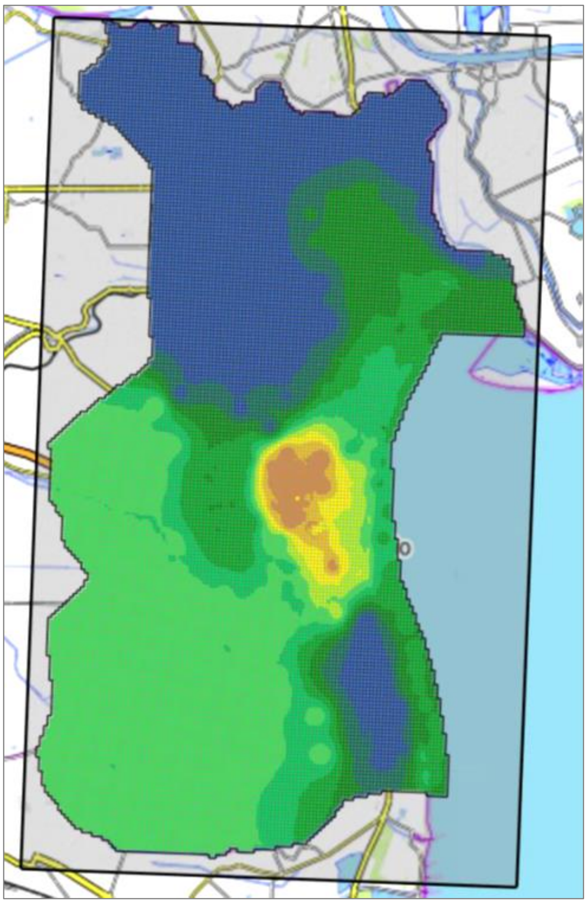


Figure 35 – 3D map of hydraulic conductivity (m/s) of the hydrogeological units represented within the numerical model domain, along a cross-section (vertical exaggeration 1:100) extending between Volania and S. Giuseppe di Comacchio.

To simulate the main surface water bodies within the modeled domain, **Constant Head Boundary (CHB) conditions** were applied. Specifically, the following hydraulic heads were assigned: 0 m a.s.l. for the Adriatic Sea, −0.5 m a.s.l. for Valle Bertuzzi and Lago delle Nazioni, and −0.3 m a.s.l. for Valli di Comacchio and Vene di Bellocchio (Figure 2).

An additional CHB condition was applied at the base of the seventh layer to reproduce the upward groundwater flux observed from multi-level piezometric measurements.
The **RIVER package** was used to simulate the main river courses, while the weak hydraulic coupling between rivers and the aquifer was modeled by assigning a streambed hydraulic conductivity of 1×10^{-7} m/s.
The drainage network was represented using the **DRAIN package**, assuming an average canal depth of −0.8 m below ground level and a drain conductance of 3×10^{-2} m^2/s.



The initial solute concentration for the transport simulation was set to 1 g/L across the entire modeled domain, except for the main surface water bodies, for which the following values were assigned: 35 g/L for the Adriatic Sea, 20 g/L for the Sacca di Goro, 30 g/L for the Lago delle Nazioni, and 25 g/L for the Valli di Comacchio, Valle Bertuzzi, and Vene di Bellocchio.
The initial concentration assigned to layer 7 was defined based on salinity data obtained from multi-level samplers installed at the base of the phreatic aquifer.
Low salinity values were assigned to modern dunes and paleo-dunes, consistent with their higher recharge rates, while in the northern portion of the domain, influenced by the Po River, the aquifer was characterized by fresher groundwater due to fluvial recharge inputs.
Conversely, in back-dune paleo-environments, where evapoconcentration processes occurred in the past, significantly higher salinity values were imposed.

Figure 36 - Initial dissolved salt concentrations used in the variable-density transport model, assigned at the base of Layer 7.

The input data for the transport model were derived from a historical analysis of salinity, which revealed an almost constant concentration over time, attributable to the presence of low-permeability lenses containing very high saline contents — in some cases up to twice the current salinity of the Adriatic Sea.
These lenses act as localized saline sources, from which solutes slowly diffuse toward the surrounding, more permeable zones.
Accordingly, the initial total dissolved solids (TDS) concentration was defined with values ranging from 1 to 70 g/L, depending on depth (Figure 36).
The assumption of a temporally stable average salinity was further supported by regional monitoring data, which show unchanged values since 2010 in the piezometers of the Emilia-Romagna Region.
For the **dispersion coefficients**, the following values were adopted:

- Longitudinal dispersivity: 2.0 m

- Horizontal dispersivity: 0.2 m
- Vertical dispersivity: 0.01 m

The **molecular diffusion coefficient**, set to 1×10^{-9} m^2/s, was derived from literature values reported in Zheng et al. (2012).

Climatic data on precipitation (annual average of 676 mm/year for the period 2001–2012), mean monthly air temperature (14.8 °C), and other meteorological variables required for applying the Penman–Monteith equation were obtained from the DEXTER Climate Database of the Emilia-Romagna Region and from the online system of the Land Reclamation Consortium.
The annual average precipitation was corrected by including an **average irrigation contribution** of 320 mm/year (Ventura et al., 2008), in order to provide a more realistic representation of the overall water balance.
Based on these data, **the average groundwater recharge rate** was estimated at approximately 155 mm/year.
The **maximum evapotranspiration rate** was set to 95 mm/year, assuming an extinction depth of 1.5 m.
The main flow and transport parameters used in the simulations are summarized in Table 3.

Parameter name	N° of parameter	Value (units)
Horizontal hydraulic conductivit	9	2×10^{-4a} – 1×10^{-9a} (m/s)
Vertical anisotropy	1	0.1^{b} (-)
Effective porosity	1	0.25^{b} (-)
Specific yield	2	0.25^{b} – 0.1^{b} (-)
Specific storage	2	1×10^{-4b} – 1×10^{-5b} (m^{-1})
Horizontal dispersivity	1	0.1^{b} (m)
Vertical dispersivity	1	8.16×10^{-3c} (m)
Longitudinal dispersivity	1	1.02^{c} (m)
Molecular diffusion coefficient	1	1×10^{-9b} (m^2/s)

a Parameter values optimized by PEST
b Parameter values from Zheng et al. 2012
c Parameter values from Colombani et al. 2014

Table 3 - Flow and transport parameters used in the simulations

The **simulation period** was set to 10 years, divided into approximately 1,000 time steps of equal duration, in order to allow a direct comparison with the original model, in which density-dependent transport had been simulated under quasi-steady-state conditions.
From this simulation, the computed piezometric heads were extracted and subsequently used as initial conditions for the transient model, covering the period 2011–2021.

For the groundwater flow simulation, the **Geometric Multigrid (GMG) numerical solver** was employed, with a convergence criterion of 1×10^{-3} m between successive iterations and a mass balance closure criterion of 1×10^{-3} m^3/s, in order to minimize balance errors.
For solving the advection–dispersion term of the solute transport equation, the third-order TVD-ULTIMATE numerical scheme was adopted, ensuring a conservative solution free from numerical dispersion and artificial oscillations.
The Courant number was set to 0.1, further reducing numerical dispersion effects and ensuring computational stability.

For the transient simulation, covering a total duration of approximately 11 years corresponding to the period in which the main hydrological forcings could be continuously monitored or estimated (January 2011 – December 2021), 132 monthly stress periods were defined, each subdivided into three time steps.

For each stress period, **variable values of aquifer recharge and actual evapotranspiration were assigned**, derived from the national BigBang database.
As an example, Figure 37 illustrates the monthly trend of these hydrological variables at the regional scale for Emilia-Romagna. The analysis reveals a progressive reduction in the recharge rate due to effective rainfall, along with an increase in evapotranspiration during the winter season, mainly attributable to surface evaporation processes.
These variations provide clear evidence of ongoing climate change, which has resulted in a regional mean temperature increase of about 1.1 °C over the analyzed period.
The raw data from the BigBang database were subsequently integrated with **irrigation rate estimates calculated on a crop-type basis**, together with transpiration values and the corresponding extinction depths.

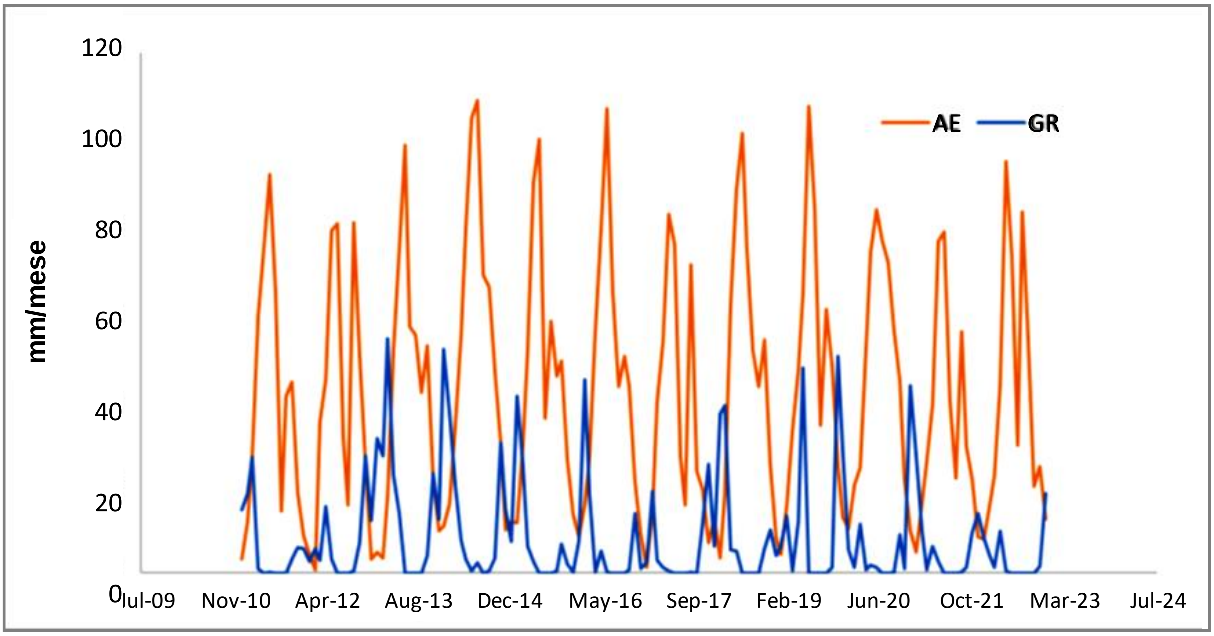


Figure 37 – Monthly precipitation recharge rate (blue) and actual evapotranspiration rate (orange) for the Emilia-Romagna region, derived from the ISPRA BigBang database.

Numerical Modelling Output

The distribution of groundwater depth reflects the altimetric variations of the terrain — deeper beneath topographic highs and shallower or even surfacing within the depressed coastal plains.

Among the most effective tools for analyzing the hydrodynamic behavior of an aquifer is the piezometric map, which depicts the spatial distribution of groundwater levels relative to mean sea level using isopiezometric lines (isopieze).

This representation allows identification of the direction of groundwater flow, since flow lines are perpendicular to the isopieze: groundwater moves from higher to lower hydraulic potentials — that is, from higher to lower piezometric levels. This makes it possible to distinguish recharge zones (where flow is downward and infiltration replenishes the aquifer) from discharge zones (where flow is upward or horizontal toward surface water bodies, and groundwater emerges or is drained).

Furthermore, analyzing the spacing between isopieze provides an estimate of the hydraulic gradient, a parameter directly related to groundwater flow velocity and residence time: a small gradient indicates slower flow and longer residence times, whereas a steeper gradient reflects more active circulation.

Therefore, the piezometric map represents a fundamental tool for interpreting groundwater flow dynamics and assessing aquifer vulnerability to saltwater intrusion, particularly in low-gradient coastal systems, where even minor variations in piezometric levels can significantly alter the direction and intensity of subsurface flow.

Figure 38 shows the piezometric map obtained from the transient simulation for December 2021, together with the corresponding hydraulic profile (cross-section) traced along the transect from Lido delle Nazioni (eastern sector) to Ostellato (western sector).
To better highlight the main groundwater flow directions, the drain cells associated with rivers and surface water bodies - such as Lago delle Nazioni, Valle Bertuzzi, Vene di Bellocchio, and the Valli di Comacchio - have been hidden from view.

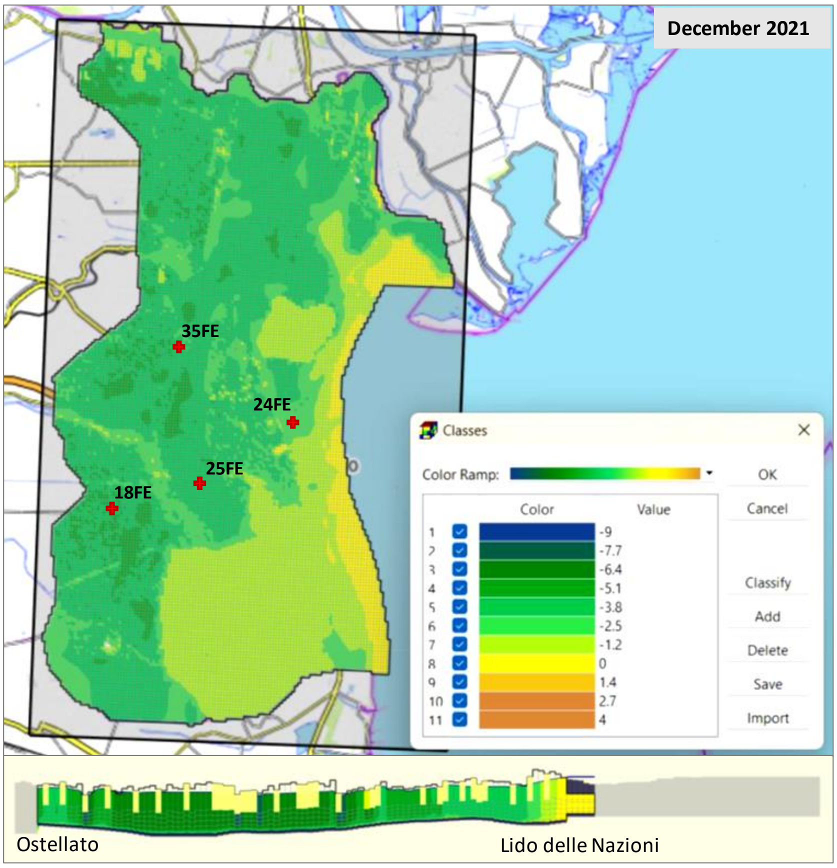


Figure 38 – Piezometric map from the transient simulation (December 2021) and hydraulic cross-section along the transect Lido delle Nazioni (right) – Ostellato (left).

The isopiezometric pattern is predominantly oriented east–west, from the sea toward the inland, and is locally influenced by variations in hydraulic conductivity and by the presence of surface

water bodies, which—being located at slightly higher elevations—contribute to the recharge of the coastal phreatic aquifer.
More specifically, the vertical transect highlights how the groundwater flow is characterized by the formation of convective cells developing between the various drainage canals (shown in yellow). As a result, no continuous horizontal flow from the sea toward the inland is observed; instead, the aquifer exhibits a system of localized circulation patterns, where groundwater flow is confined within hydraulically distinct but interconnected sub-basins.

The groundwater table is characterized by very low hydraulic gradients, generally below 1‰. These gradients are slightly higher in the northern sector of the flow domain, south of the Po di Goro and the Boscone della Mesola, which forms an arched structural high oriented predominantly NW–SE, with a maximum elevation of about 7 meters. This feature corresponds to a broad paleo-dune ridge, marking the late medieval–Renaissance shoreline.
The average hydraulic gradient is approximately 0.5‰, leading to long groundwater residence times depending on the hydraulic conductivities of the individual sedimentary lenses.
Groundwater residence time is estimated to be on the order of several decades within the upper 3–4 meters of the saturated zone (Caschetto et al., 2016), while in the deeper portions of the aquifer, residence times are significantly longer, potentially reaching several hundred years (Colombani et al., 2019).

The comparison between the piezometric maps for August 2016 (Figure 39) and December 2021 (Figure 38) reveals an overall variation in groundwater levels, showing a general tendency toward lower values in 2016 compared to 2021.
Specifically, during August 2016—a period characterized by maximum evapotranspiration and minimal recharge—the piezometric levels were notably lower across most of the model domain, particularly in the central and southern sectors, where values dropped below −5 m a.s.l.. This condition indicates hydric deficit and a greater depression of the water table, potentially linked to enhanced inland movement of brackish water from the coastal areas.
It follows that the simulated groundwater levels fluctuate seasonally according to the recharge and evapotranspiration patterns, with higher levels during the wet season and lower levels during the dry season.

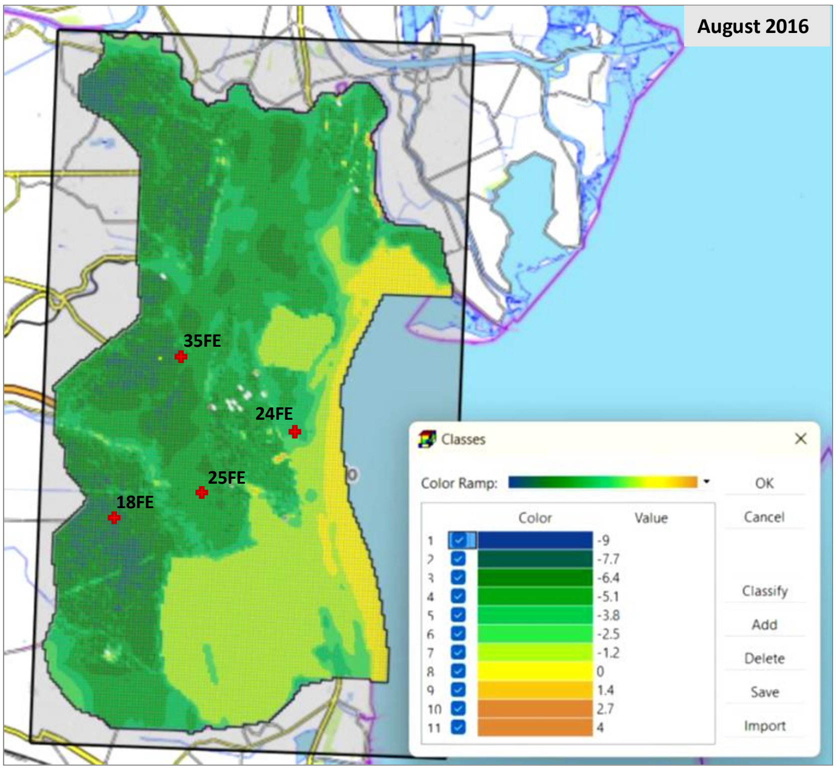


Figure 39 – Output piezometric map for the transient simulation – August 2016

During the simulation period, relatively stable trends were observed in each monitoring well, reflecting the strong hydraulic control exerted by the dense drainage canal network (blue symbols in Figure 40).

Groundwater levels recorded in the shallow phreatic monitoring network of the Emilia-Romagna region have shown a slight decline in recent years, due to reduced precipitation and higher temperatures, which have led to increased evapotranspiration.

The comparison between observed and simulated levels (orange lines in Figure 40) should be considered indicative only, as the modelled cell values corresponding to the monitoring wells do not capture local hydraulic head variations influenced by small-scale factors that cannot be accurately represented at this temporal and spatial resolution.

Nevertheless, the model successfully reproduced the magnitude and variability of groundwater levels measured by the regional monitoring network, achieving very high performance indicators: R^2 = 0.969, MAE = 0.17 m, and NSE = 0.968 - according to the criteria of Moriasi et al. (2015).

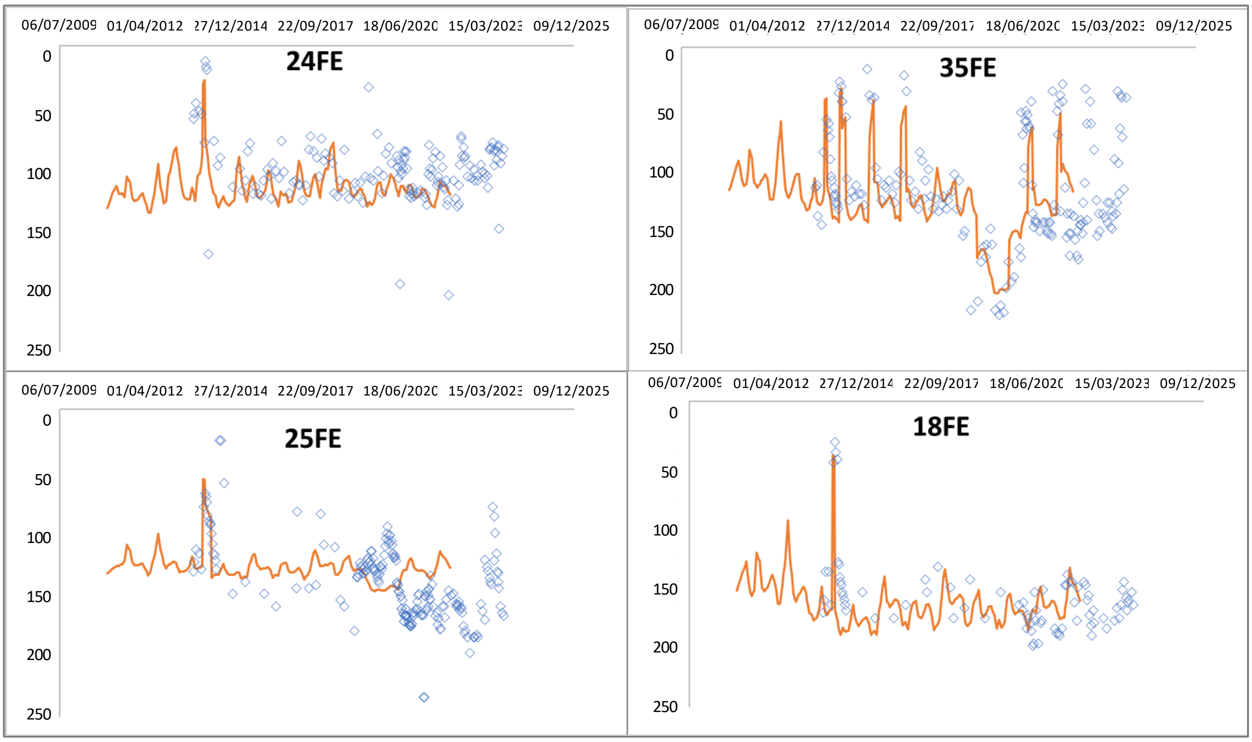


Figure 40 – Comparison between simulated piezometric level (orange lines) and observed level in the shallow groundwater monitoring wells of the Emilia-Romagna network (blue symbols)

The model provided a reliable estimation of the temporal evolution of groundwater salinity over the simulated decade.

Figure 41 illustrates the final salinity map at the end of the transient simulation, together with the salinity concentration trends recorded in selected piezometers.

The concentration values, as well as the observed increasing or decreasing trends, depend on each piezometer's location relative to the spatial patterns of recharge and evapotranspiration within the model domain.

Some zones—particularly near Lido di Pomposa and in the Mezzano area—display highly saline groundwater, with concentrations reaching up to 75 g/L, nearly twice the average salinity of the Adriatic Sea, as also confirmed by field measurements (Colombani et al., 2016).

These conditions are attributed to the presence of residual paleo-marine waters, trapped within peaty and silty-clayey sediments, leading to the formation of salinity hot spots.

Such areas require careful management strategies to ensure the sustainability of agricultural productivity and to mitigate further salinization.

The horizontal section taken approximately at the level of Lido di Pomposa reveals that the groundwater becomes saline immediately below the water table, with concentrations significantly exceeding the average salinity of the Adriatic Sea.

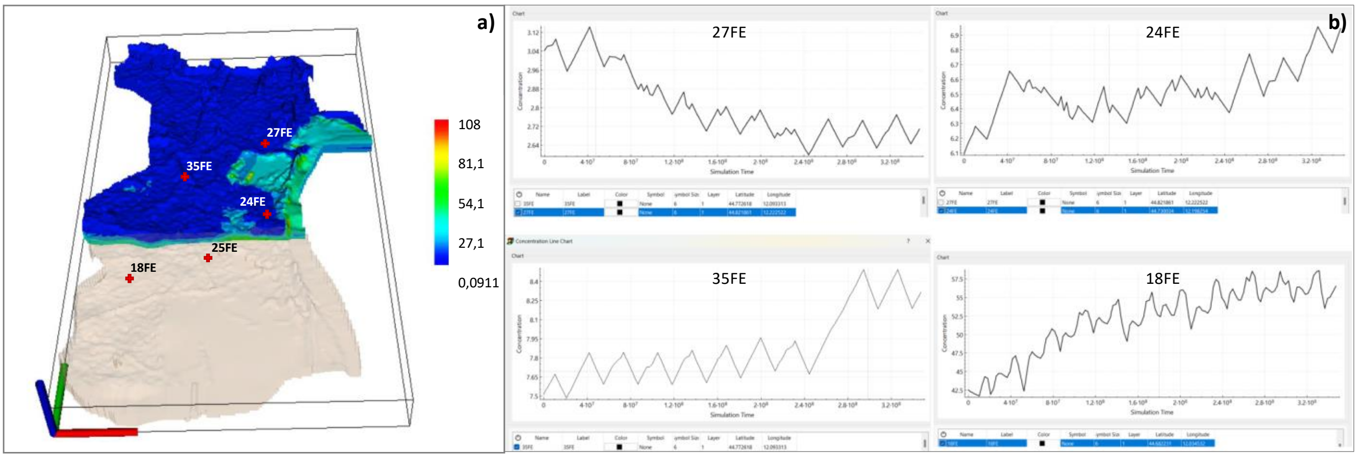


Figure 41 a) 3D map of salinity isoconcentration calculated for December 2021;
b) Simulated dissolved salt concentrations (g/L) in wells 27FE, 24FE, 35FE, and 18FE.

The 27FE piezometer shows a decreasing trend in salinity concentrations, indicating a strong dependence on recharge inputs (rainfall and irrigation surplus) to the aquifer.
In contrast, the other piezometers display a clear increasing trend in salinity, particularly 18FE, which reaches values up to 60 g/L.
This pronounced increase is attributed to the proximity of the Comacchio Lagoons, which in the model are represented as boundary conditions with constant piezometric level and salinity values.

Hydrogeological and Salinity Balance

The ZoneBudget routine, integrated within the post-processing package of the MODFLOW software, was employed to evaluate the volumetric water balance within the modeled domain.
This procedure made it possible to quantify the inflow and outflow contributions of the hydrogeological system, distinguishing among:

- Recharge fluxes,
- Evapotranspiration losses,
- Anthropogenic withdrawals, and
- Surface–subsurface exchange flows.

In addition, it allowed for the verification of the overall mass-balance closure of the simulated groundwater system, ensuring the internal consistency and reliability of the model's hydrodynamic representation.

Figure 42 illustrates the temporal trend of recharge (blue) and evapotranspiration (orange) of the aquifer over the modeled simulation period.
The data reveal a marked seasonal variability in recharge, with higher values occurring during wet seasons and intense rainfall events. Peaks reaching ~8 m^3/s indicate phases of substantial groundwater replenishment. Conversely, evapotranspiration increases during dry seasons, coinciding with higher temperatures and reduced surface water availability, reaching maximum values of about 6 m^3/s.
Overall, the time series highlights a progressive decline in recharge rates accompanied by a gradual increase in evapotranspiration, signaling a developing imbalance in the aquifer's water budget. The reduction in recharge limits groundwater replenishment and increases soil water stress, while the enhanced evapotranspiration reflects drier climatic conditions and greater water consumption by vegetation.
This divergence represents an early warning sign from an agro-environmental perspective: the reduced percolation toward deeper layers decreases the soil's ability to dilute and leach salts from the root zone. Consequently, salt accumulation may occur within the soil profile, potentially leading to decreased agricultural productivity and reduced sustainability of water-demanding crops over the medium to long term (Ondrasek et al., 2011; Sairam & Tyagi, 2004).

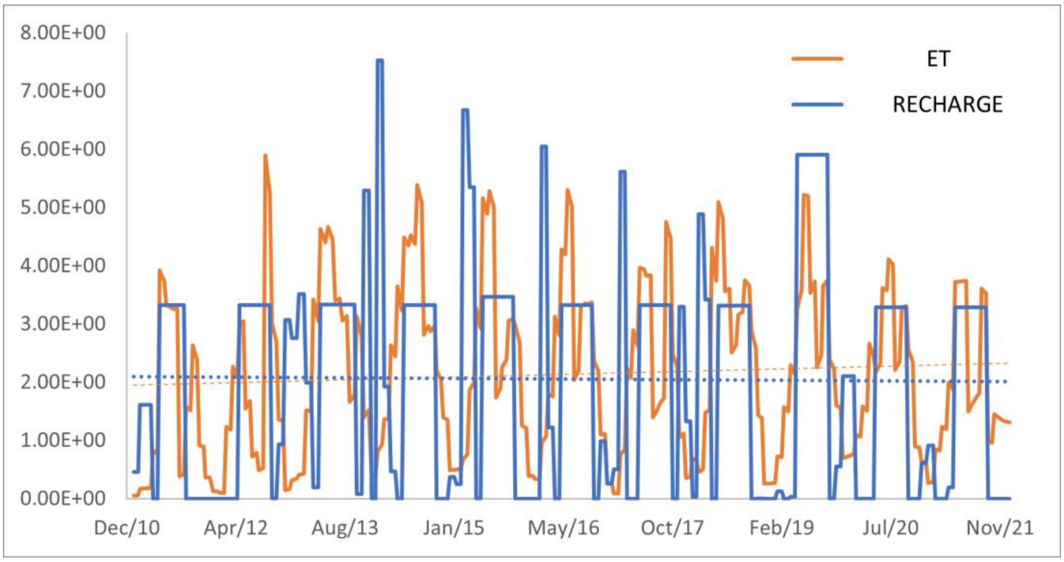


Figure 42 – Comparison between aquifer recharge inflow (blue line) and evapotranspiration outflow (orange line) expressed in m^3/s, with corresponding linear trend lines.

The drainage flow conveyed by the canal network shown in Figure 43 varies significantly throughout the seasons and exhibits a growing trend over the simulated decade.
This progressive increase may enhance the salinization of surface water bodies and soils, particularly in areas where the drainage canals intersect the most saline portions of the coastal aquifer, facilitating upward saline fluxes and the transfer of dissolved salts from groundwater to surface systems.

The water exchanges between the aquifer and the fluvial network are overall limited within the study area (Figure 44).
The inflow from rivers into the aquifer, ranging between 0.13 and 0.16 m^3/s, is predominant compared to the outflow from the aquifer toward the rivers, which is almost negligible—generally below 0.01 m^3/s.
Both flow components display relatively stable trends over time, with minor oscillations reflecting variations in local hydraulic gradients and meteorological conditions—particularly flood and low-flow events—that directly influence river discharge and stage levels.
It is noteworthy that the magnitude of these interactions is approximately one order of magnitude lower than the exchanges between the aquifer and the artificial drainage network (Figure 43).
Given its dense spatial distribution across the modeled domain, the drainage system exerts a more significant control on the overall groundwater balance, playing a dominant role in regulating the hydrodynamics and salinity balance of the coastal phreatic aquifer.

The water inflow from brackish and saline surface bodies into the aquifer averages approximately 1 m^3/s, whereas the outflow from the aquifer toward these areas is significantly smaller, generally below 0.1 m^3/s (Figure 45).
Over the simulation period, a slight increase in inflow toward the aquifer is observed, suggesting a progressive trend of system salinization. This evolution indicates a shift in the hydrodynamic equilibrium between groundwater and brackish/saline surface waters, increasingly favoring the intrusion of saline waters into the aquifer.
This behavior can be interpreted as the consequence of a reduced hydraulic gradient seaward or of negative water balance conditions—namely, decreased recharge and increased withdrawals—which together promote the landward migration of more mineralized waters into the fresh groundwater domain.

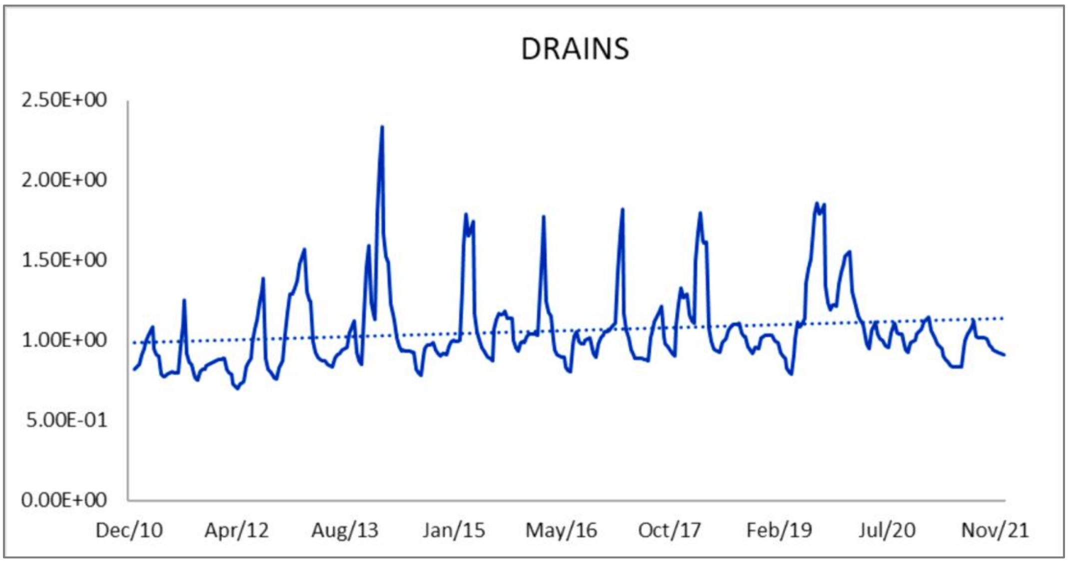


Figure 43 – Outflow from the aquifer toward the drainage canal network, expressed in m³/s, along with the corresponding linear trend line.

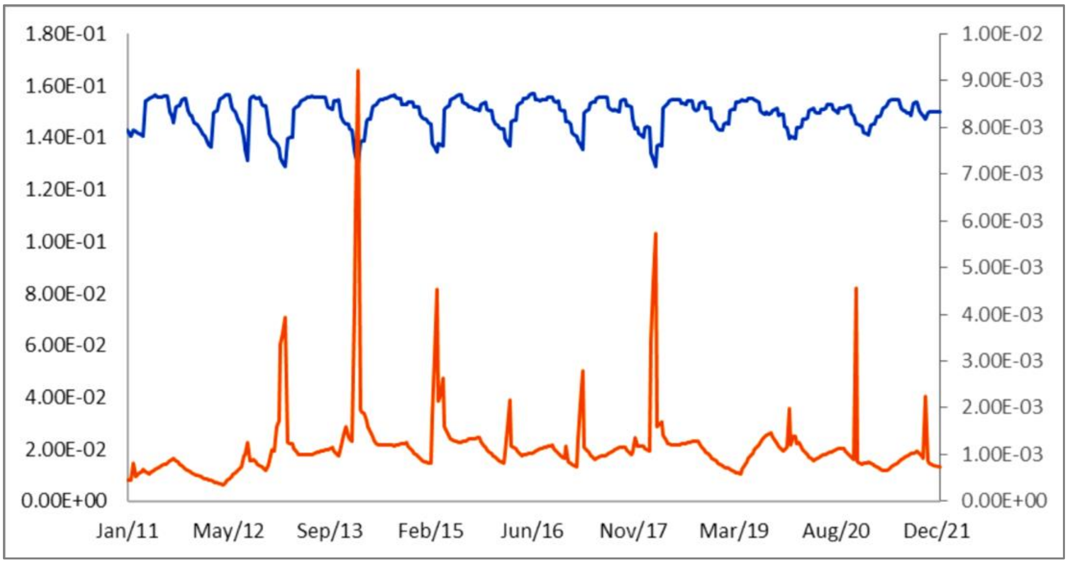


Figure 44 – Comparison between inflows into the aquifer from rivers (blue line, left Y-axis) and outflows from the aquifer toward the rivers (orange line, right Y-axis), expressed in m³/s.

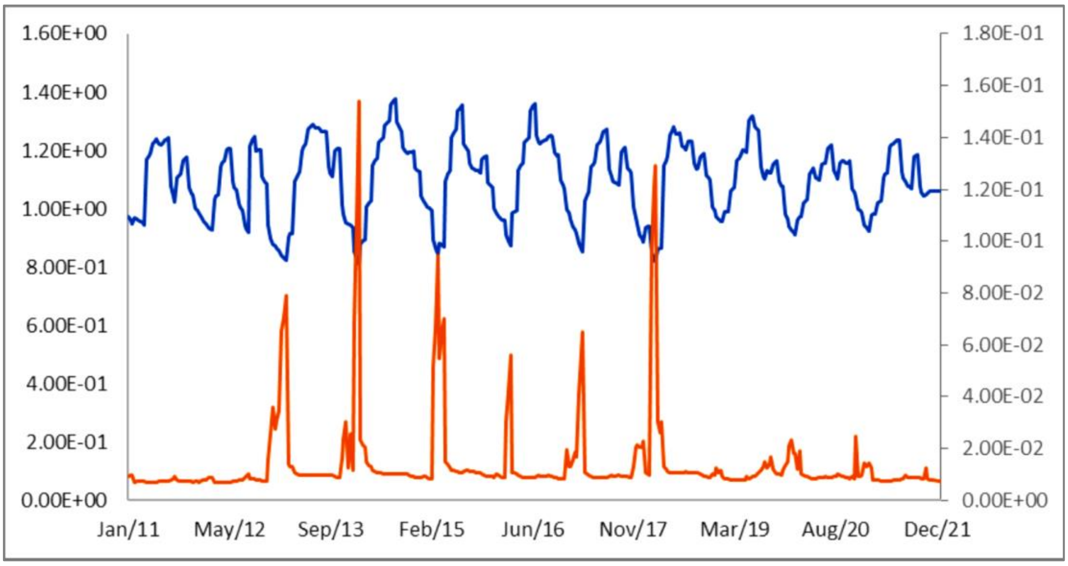
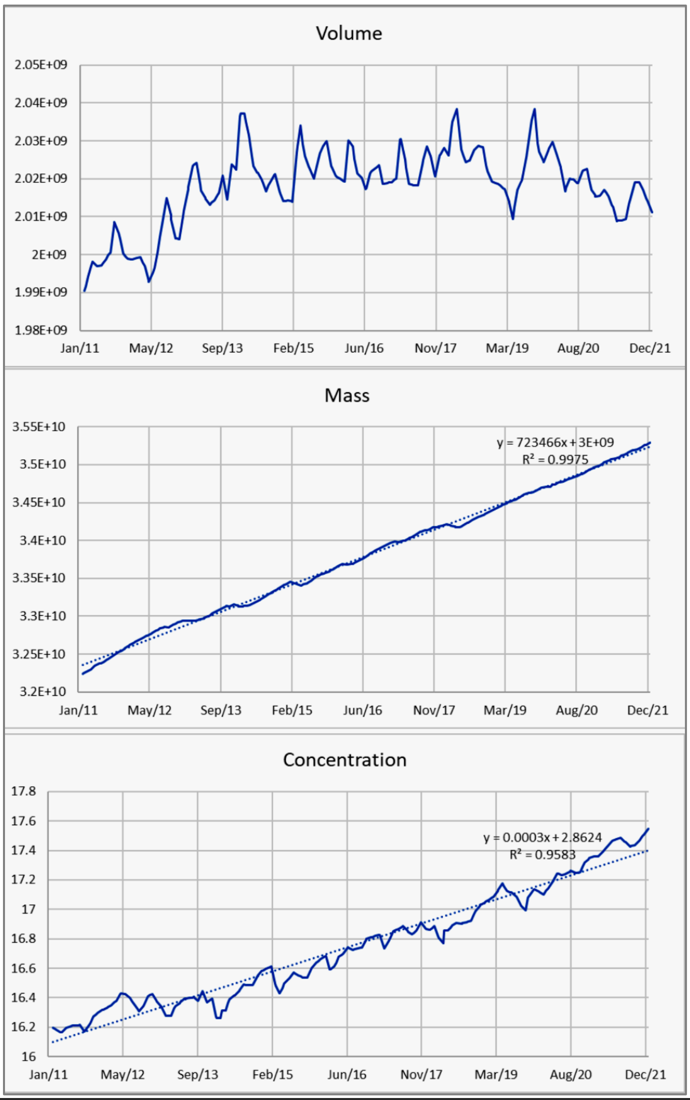


Figure 45 – Comparison between inflows into the aquifer from brackish and saline surface water bodies (blue line, left Y-axis) and outflows from the aquifer toward these surface water bodies (orange line, right Y-axis), expressed in m^3/s.

The analysis of the cumulative mass balance, derived from the results of the flow and transport model, shows good overall consistency between the volumes and masses entering and leaving the aquifer, indicating the correct hydraulic balance and the numerical stability of the model (Figure 46). In particular, in the numerical summary, the total contributions are nearly equivalent: IN = 0.1737390E+11 OUT = 0.1737366E+11.
The difference between them is minimal, equal to 0.0014%, confirming the closure of the mass balance and thus the accuracy of the simulations for both flow and solute transport. From a physical point of view, the main contributions to the system are related to the brackish or saline surface water bodies and the saline aquitard at the base of the aquifer (11,455 tons), natural recharge (498 tons), and river inflows (230 tons), while the main losses derive from salt released by aquifer drainage (2,795 tons + 4,743 tons from the solid matrix), drainage and flows toward rivers (5,487 tons), and evapotranspiration (4,131 tons).

The temporal evolution shown in the figure highlights that while the water volume remains overall stable over time, with limited seasonal fluctuations, the solute mass exhibits a linear increasing trend ($R^2 \approx 0.99$), indicating a progressive accumulation of salts within the aquifer. Consequently, the average concentration rises over time ($R^2 \approx 0.96$), reflecting a tendency for solute buildup, consistent with a gradual salinization process due to the predominance of more concentrated inflows or the reduced dilution capacity of the system.

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   CUMULATIVE MASS BUDGETS AT END OF TRANSPORT STEP    2, TIME STEP    3, STRESS PERIOD  132
   -----------------------------------------------------------------------------------------

                                    IN                           OUT
                             ----------------             ----------------
            CONSTANT CONCENTRATION:   0.1145494E+11             -0.2158917E+09
                     CONSTANT HEAD:    0.000000                   0.000000
                            DRAINS:    0.000000                 -0.5486673E+10
                            RIVERS:   0.2306817E+09              -1624322.
                          RECHARGE:   0.4983318E+09               0.000000
                EVAPOTRANSPIRATION:    0.000000                 -0.4131524E+10
            1ST/0TH ORDER REACTION:    0.000000                   0.000000
            MASS STOR (FLOW MODEL):   0.2644339E+10             -0.2794718E+10
             MASS STORAGE (SOLUTE):   0.2545609E+10             -0.4743224E+10
          ---------------------------------------------------------------------------
                           [TOTAL]:   0.1737390E+11    M        -0.1737366E+11    M

                                          NET (IN - OUT):    246470.0
                                     DISCREPANCY (PERCENT):  0.1418632E-02
```

Figure 46 – Trend of water volume (m³), solute mass (kg), and average salinity concentration (g/L) in the aquifer.

The implemented numerical model successfully reproduced the spatiotemporal evolution of salinity in the phreatic aquifer, showing excellent calibration and consistency with observed data. The piezometric levels remain stable thanks to the control exerted by the drainage canal network. Transport simulations highlighted a progressive increase in salinity in the deeper aquifer layers, mainly due to low-permeability hypersaline lenses, interpreted as remnants of ancient marine intrusions (paleo-seawater). Local salinization trends, both increasing and decreasing, were also observed, influenced by the spatial and temporal distribution of recharge and evapotranspiration, as well as the proximity to brackish water bodies and drainage canals. Finally, the modeling confirmed the presence of a current marine salt wedge, whose extent is very limited, generally confined within the first two kilometers from the coastline (actual-seawater).

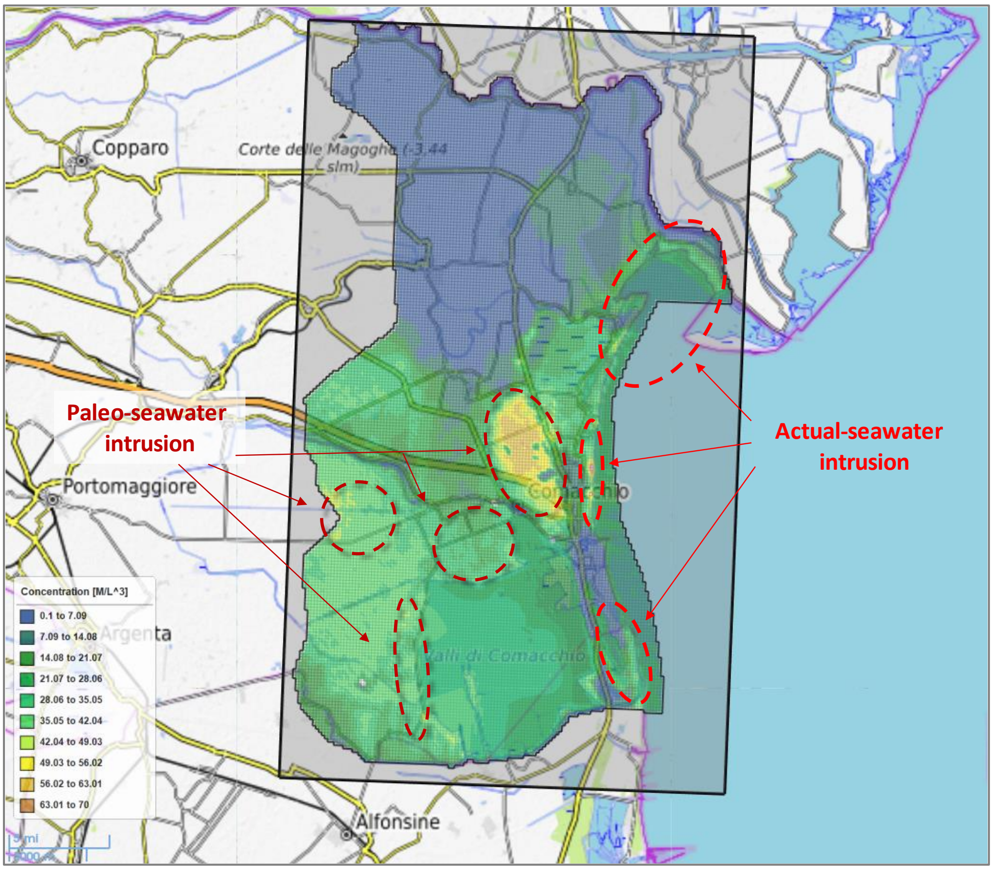

Figure 47 – Areas most affected by paleo-seawater intrusion and actual-seawater intrusion.

It can therefore be inferred that the main cause of salinization is not direct marine intrusion, but rather the upward movement of deep, trapped brackish waters within the sediments, driven by the drainage network and the reversed vertical hydraulic gradient.

The analysis of the mass balances for the various basins in the study area highlighted particularly critical conditions in the Bonello, Circondariale Gramigne, Golena Vene di Bellocchio, Mezzano Nord Ovest basins, as well as in the wetlands including the Valli di Comacchio, Bertuzzi, and Lago delle Nazioni (Table 4). In these systems, both the total mass of dissolved salts (kg/day) — considering maximum and median values — and the specific mass of dissolved salts per unit area (kg/day/ha) are high, indicating a strong concentration of salinity in both surface and subsurface flows.

	Kg/day (massimo)	Kg/day (mediana)	Kg/d/ha (massimo)	Kg/d/ha (mediana)
Bonello	2012	80.1	0.922	0.037
Campello	3.4	0.2	0.005	0.001
Circondariale Gramigne	**1478**	**224.6**	**0.356**	**0.054**
Giralda	1114	61.8	0.176	0.010
Golena Vene di Bellocchio	**4334**	**155.8**	**1.514**	**0.054**
Leone Collettore acque basse	122	13.0	0.003	0.001
Marozzo	550	29.5	0.055	0.003
Mezzano Sud Est	1631	28.3	0.167	0.003
Mezzano Nord Ovest	**1199**	**57.0**	**1.786**	**0.088**
Pomposa	54	2.9	0.050	0.003
Salghea	23	1.6	0.021	0.001
Valle Lepri	117	3.0	0.004	0.001
Valle Isola	**5119**	**332.4**	**0.705**	**0.046**
Valle Pega	555	124.5	0.199	0.045
Vidara Nord	103	5.3	0.059	0.003
Valli e zone umide	**5955**	**768.0**	**0.512**	**0.056**

Table 4 - Dissolved salt mass (kg/day) – maximum and median – and dissolved salt mass per hectare (kg/day/ha) for the various zones of the domain between 2011 and 2021.

Between 2011 and 2021, the trend of dissolved salt mass generally shows an increasing pattern across most of the analyzed basins, with particular intensity in the valley and wetland areas such as the Golena Vene di Bellocchio and the complex of Valli and wetlands, where rising average temperatures have promoted evapoconcentration in surface water bodies.
A marked increase in salinity is also observed in the Mezzano Nord Ovest, Mezzano Sud Est, Circondariale Gramigne, and Valle Pega basins, located upstream of the Valli di Comacchio, which are influenced by significant contributions of relict salinity of paleo-marine origin.

In contrast, the Valle Isola basin represents an exception, showing a decreasing trend in the mass of dissolved salts, likely due to historical leaching of salts resulting from the presence of rice fields, which have promoted desalination processes. In this area, however, isolated peaks of high salinity (up to 80 g/L; Mastrocicco et al., 2012) are recorded in localized back-dune environments near S. Giuseppe di Comacchio, while most of the basin exhibits groundwater ranging from fresh to brackish.
In conclusion, the results indicate that the most critical and worsening conditions are found in the Mezzano Nord Ovest, Mezzano Sud Est, Circondariale Gramigne, and Valle Pega basins, as well as in the main valley and coastal wetland areas, where evapoconcentration processes and the release of relict salinity are the dominant factors driving increasing salinization

5. Conclusions

The three-dimensional numerical modeling of flow and variable-density transport, conducted under transient conditions, has allowed a highly detailed reconstruction of the temporal and spatial evolution of salinity in the phreatic aquifer of the delta plain. The results show that variations in dissolved salt concentrations in the aquifer are strongly influenced by the inflow of highly mineralized waters from the southeastern sector of the study area, where low-permeability, high-salinity lenses are present, with values significantly higher than those of the current brackish surface water bodies.
The hydraulic connection between the phreatic aquifer and the network of drainage canals has caused a progressive enrichment of dissolved salts within the canals themselves, particularly in the southern portion of the domain, south of Valle Bertuzzi, and in the Mezzano basins, which are among the most affected by salinization processes.
The increase in mean temperature, together with the decrease in precipitation and the consequent rise in evapotranspiration, has promoted higher salinity concentrations in the shallow portions of the coastal aquifer over the simulated period. The model satisfactorily reproduced these trends, showing good agreement with the salinity data measured in the monitoring wells of the Emilia-Romagna Region, thus confirming its reliability and predictive capability.
In light of these results, there is a clear need to deepen the analysis through the definition of future forecast scenarios that take into account the main climatic and hydrological drivers (temperature, precipitation, water levels, and irrigation practices). These scenarios, aimed at quantifying the temporal evolution of salinity in the most environmentally critical areas, will be addressed in the next deliverable of the project.

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