SeCURE
Saltwater intrusion and climate change: monitoring, countermeasures and informed governance

Deliverable 3.1.2 – Technical report on the investigation on climate change, its effect to low laying coastal agricultural areas in Italian site and potential for the implementation to other vulnerable areas within the Adriatic basin

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Contributing partners:
LP – UNIPD , PP1 – CNR-IGG

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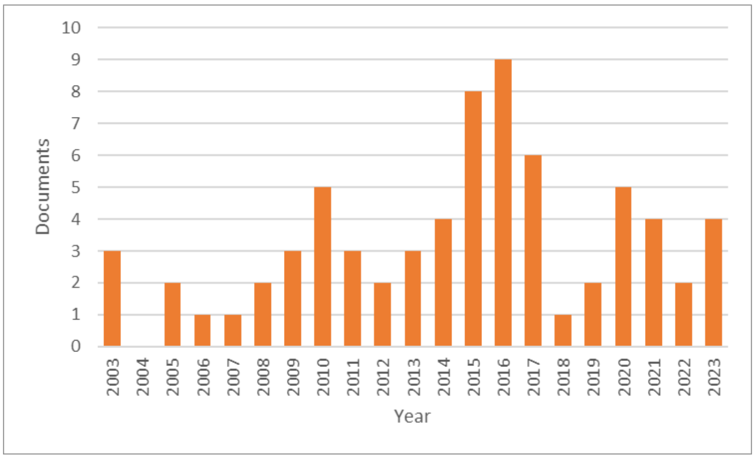
1. Introduction

Coastal agriculture holds significant importance as a vital component of global food production and socio-economic dynamics. This significance is underscored by the fact that millions of people around the world reside in coastal regions.

The main requirement of agricultural practice is the availability of fresh water for irrigation purpose. However, many coastal regions in the world experience an intensive salt water intrusion in aquifers due to natural and anthropogenic causes. Sea level rise, land subsidence, drought, and overexploitation of groundwater are increasing salinization of aquifers and soils in lowlying coastal regions. This results in a decrease of crop production, which negatively impacts sustainable agricultural, social, and economic development, especially in low-lying coastal plains.

In Italy, the number of studies on salinization of water resources published in indexed scientific journals has increased significantly since the early 2000s (Fig. 1a). The distribution of papers is uneven and appears to increase approximately after the driest years and during water emergencies (i.e., 2003, 2012, 2017, 2019, 2022). There is also a very irregular spatial distribution, with Emilia-Romagna and Veneto being the most studied regions (Fig. 1b). This is because these are the regions where the problem of saltwater intrusion in low-lying agricultural areas is most critical. Other coastal areas have probably not yet received enough attention or, most likely, the process of saltwater intrusion is not yet so advanced or particularly noticeable in the agricultural areas of the coastal plains in central and southern Italy because of the smaller areal extent. A final consideration must be highlighted on the "gray literature" published before the 2000s that has not yet been considered in this analysis.



a)

b)

Fig. 1 – a) Number of papers regarding saltwater intrusion on agricultural areas of the Italian Adriatic coasts found in Scopus (last accessed 10 July 2023). b) Location of the investigated sites/areas reported in the papers.

The coastal area of Venice (Italy) is an example of a heterogeneous transitional environment that includes farmlands, lagoons, estuaries, deltas, and littorals (Fig. 2). This area has been used for agriculture and livestock since the early 1900s, after the pre-existing wetlands and lagoons were (mechanically) drained.

Today, most of the agricultural land is below mean sea level, with a minimum elevation of - 4 m a.s.l., due to the combined effect of the inherited ancient morphology and high land subsidence rates. The area is crossed by the Brenta, Bacchiglione, and Adige rivers and includes a dense network of artificial channels and drainage ditches that are currently used to control water flow and depth to the groundwater level in low-lying agricultural areas.

Unconfined and locally confined aquifers consist of sandy littoral deposits that spread with continuity in the coastal zone, and small aquifers in channelized morphosedimentary bodies related to former lagoons and fluvio-deltaic bodies and remnants of coastal ridges. Both types of aquifers are usually salinized, with serious consequences for agricultural productivity. Indeed, soil salinity is considered a strong stressor for plants, limiting their growth and affecting crop yields.

In the following, the term 'farmland' is use to refer to the subsurface layer that includes the agricultural zone and the underlying shallow subsoil, where saltwater intrusion can threaten agricultural productivity.

Fig. 2 – Location of the Italian study area (green polygon) and the Pilot Site (white polygon). The backgrounds are satellite images.

2. Saltwater intrusion in the low-lying coastal agricultural area (Italian Site)

Saltwater intrusion into the aquifer system and the contamination of agricultural soils progressively affected the study area, especially during the last two decades. The saline plume intrudes irregularly up to 20 km inland from the nearby sea and lagoon (Fig. 3). Its top varies from 0 to 10 m below msl, whereas its bottom ranges between 15 and 70 m below msl, and it locally deepens to 100 m. Where the freshwater-saltwater interface rises near agricultural soils, salinity stress inhibits plant growth.

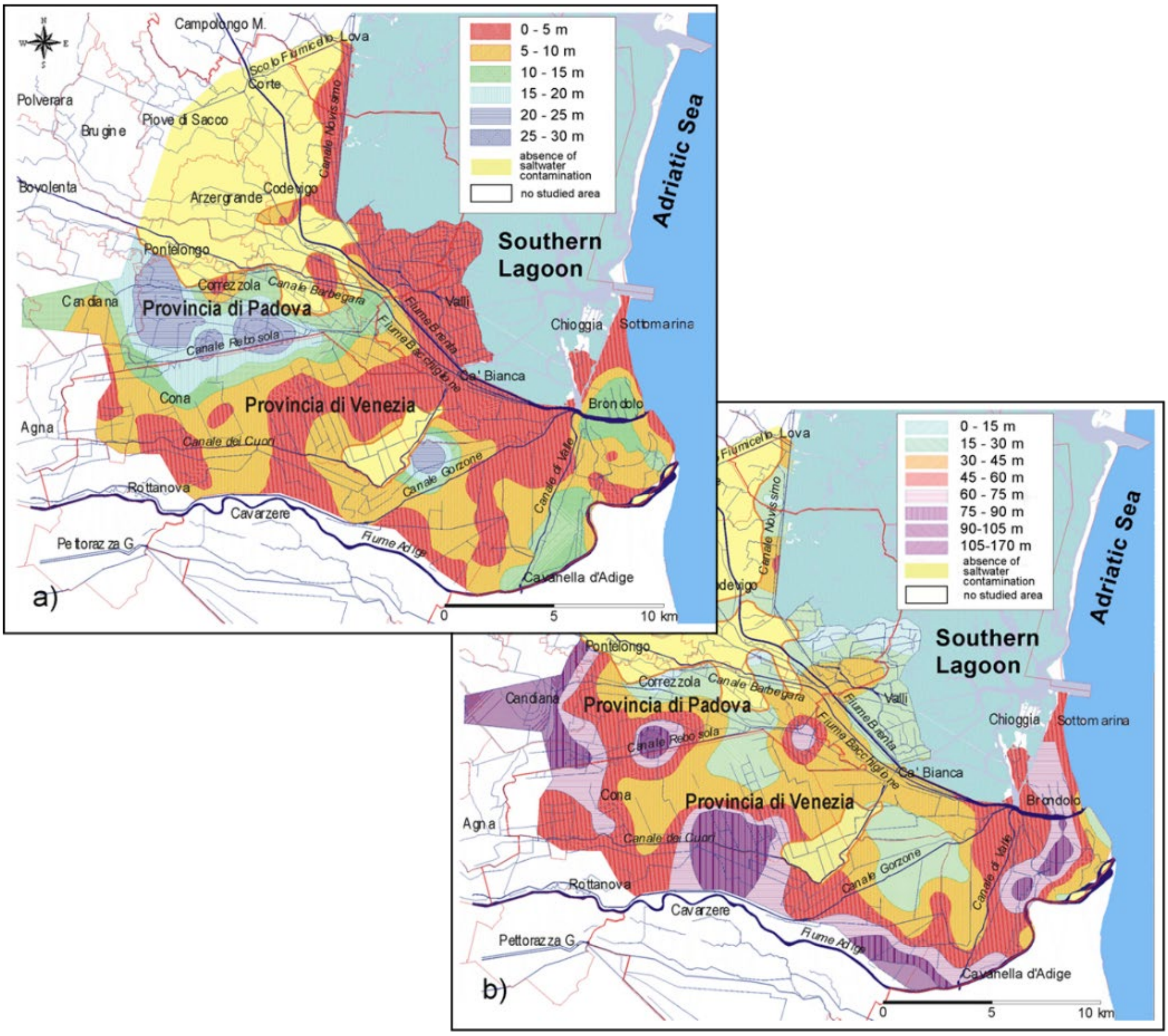


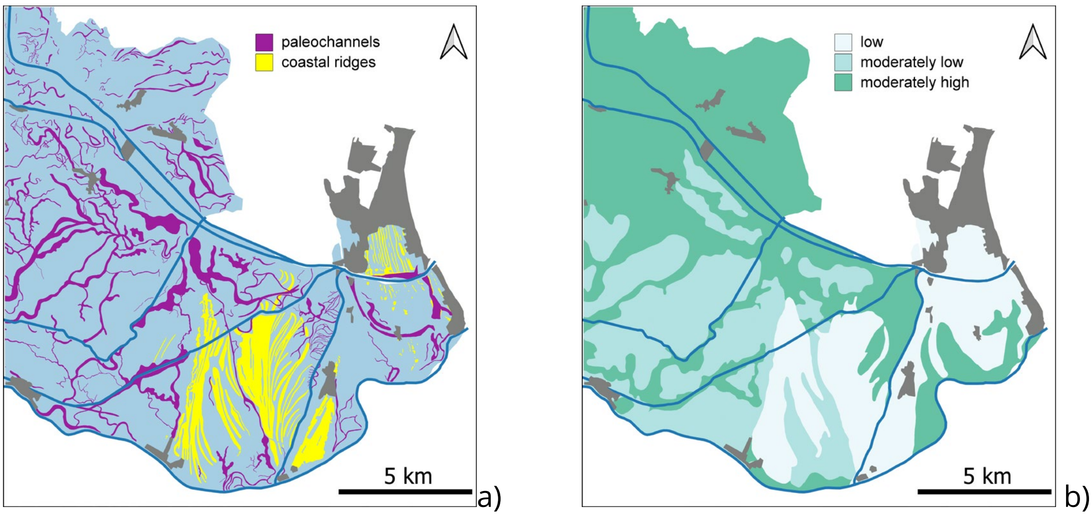
Fig. 3 – Maps of a) top and b) bottom of the saltwater plume.

Saltwater intrusion is enhanced by several factors, including the low elevation of the area, the drainage network associated with dozens of pumping stations, and processes related to climate change such as sea level rise and prolonged droughts. In addition, the presence of several buried paleochannels that act as preferential pathways for groundwater flow and solute transport, along with seawater encroachment from the river mouths into the final part of watercorses, exacerbate salinization of agricultural fields.

The presence of saline groundwater in the sectors farthest from the sea and the lagoon and in the deeper parts of the aquifer system is associated to paleo-marine waters trapped in the subsurface due to the geological evolution of the coastal area.

3. Farmland sensitivity

The sensitivity of farmland system to salinization is closely related to the characteristics of the physical indicators that can enhance or mitigate the effects of saltwater intrusion, such as geomorphological setting, potential runoff, shallow subsoil permeability, ground elevation, distance from saline and freshwater sources (Fig. 4).



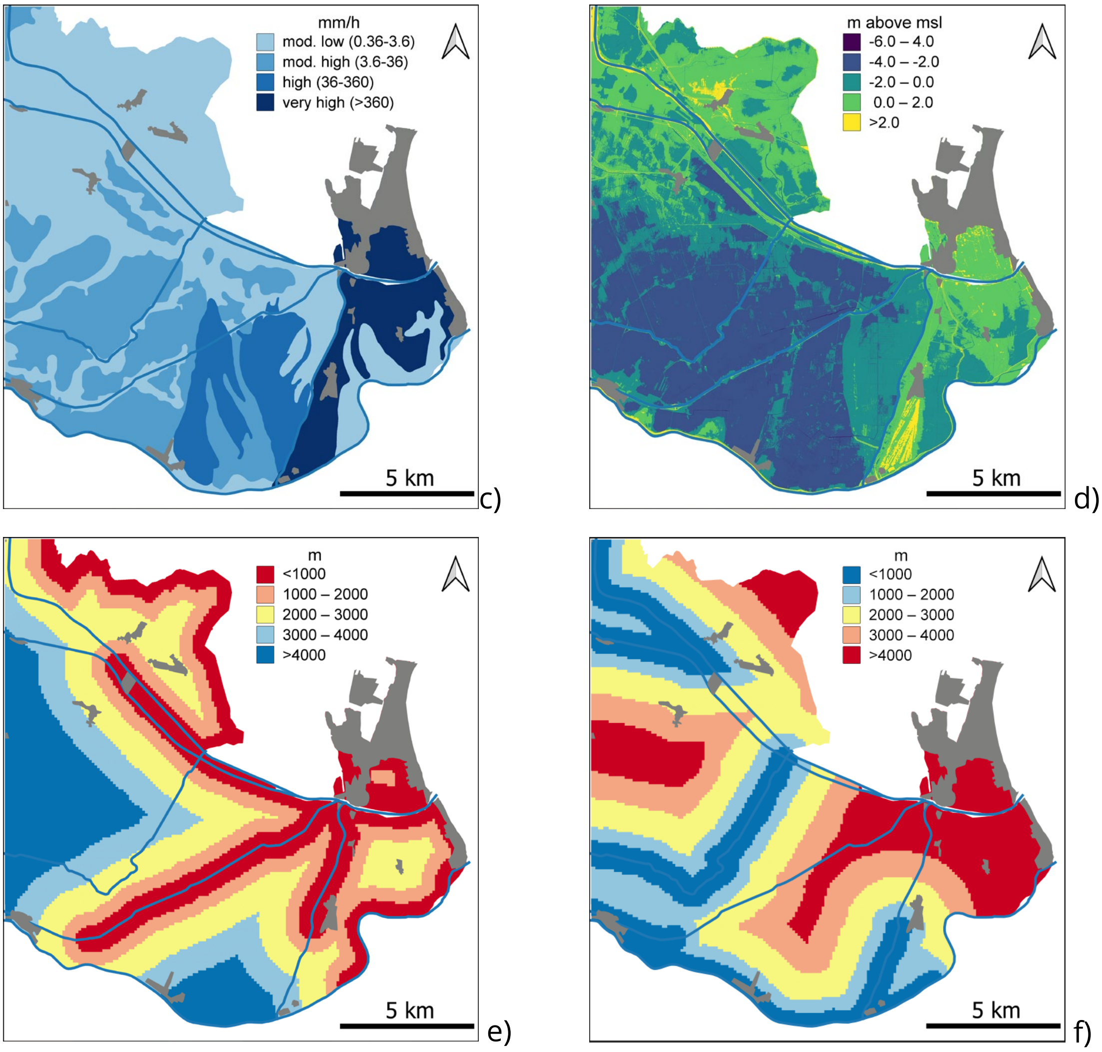


Fig. 4 – Sensitivity indicators: a) geomorphological setting, b) potential runoff, c) shallow subsoil permeability, d) ground elevation, e) saline and f) freshwater source distance.

4. Climate forcings

Drought and sea-level rise are the main climate forcing leading to a deterioration of groundwater resources and increase in saltwater intrusion.

The effects of drought in the coastal zone are most evident along the rivers, as the reduced water flow due to the lack of rainfall is unable to counteract tidal intrusion, which encroaches inland for several kilometers. This process is taken into account in the sensitivity indicators referred to the distances from salt- and fresh- water sources.

It should be noted that relative sea level rise is given by a climatic component (eustasy) and a geological one (land subsidence). Presently, sea-level rise of the Northern Adriatic sea (without the subsidence component) is quantified in 3 mm/year as derived from a linear regression of the last 30 years of tide gauge records. Concerning the next decades, sea-level rise projection for 2050 is given by IPCC SSP2-4.5 and reaches 5.8 mm/year in the period 2040-2050 (Fox-Kemper et al., 2021) (Fig. 5). Relative sea-level rise is considered a sensitivity indicator.

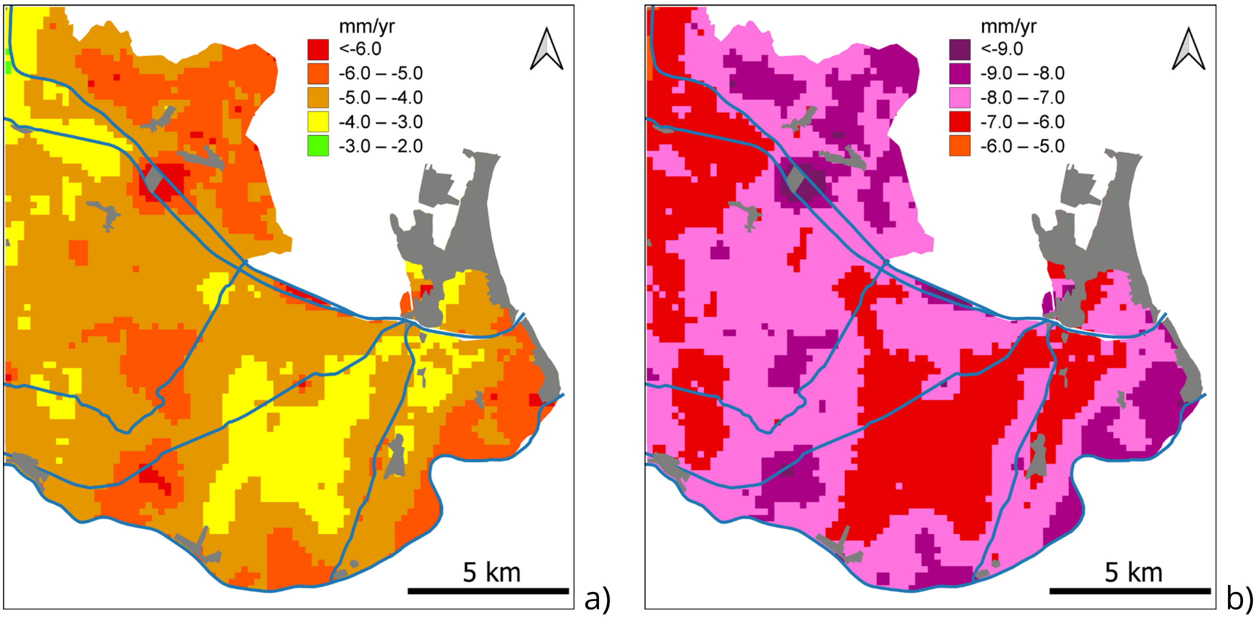


Fig. 5 – Relative sea level rise a) in the present day and b) in 2050 senarios.

5. Sensitivity maps

The sensitivity map derives from an appropriate aggregation of the sensitivity indicators considered, including climate forcings. Considering the two relative sea level rise scenarios, i.e., the current scenario and the scenario by 2050, two sensitivity maps are produced (Fig. 6). These maps provides an initial classification of areas potentially subject to saltwater intrusion impacts.

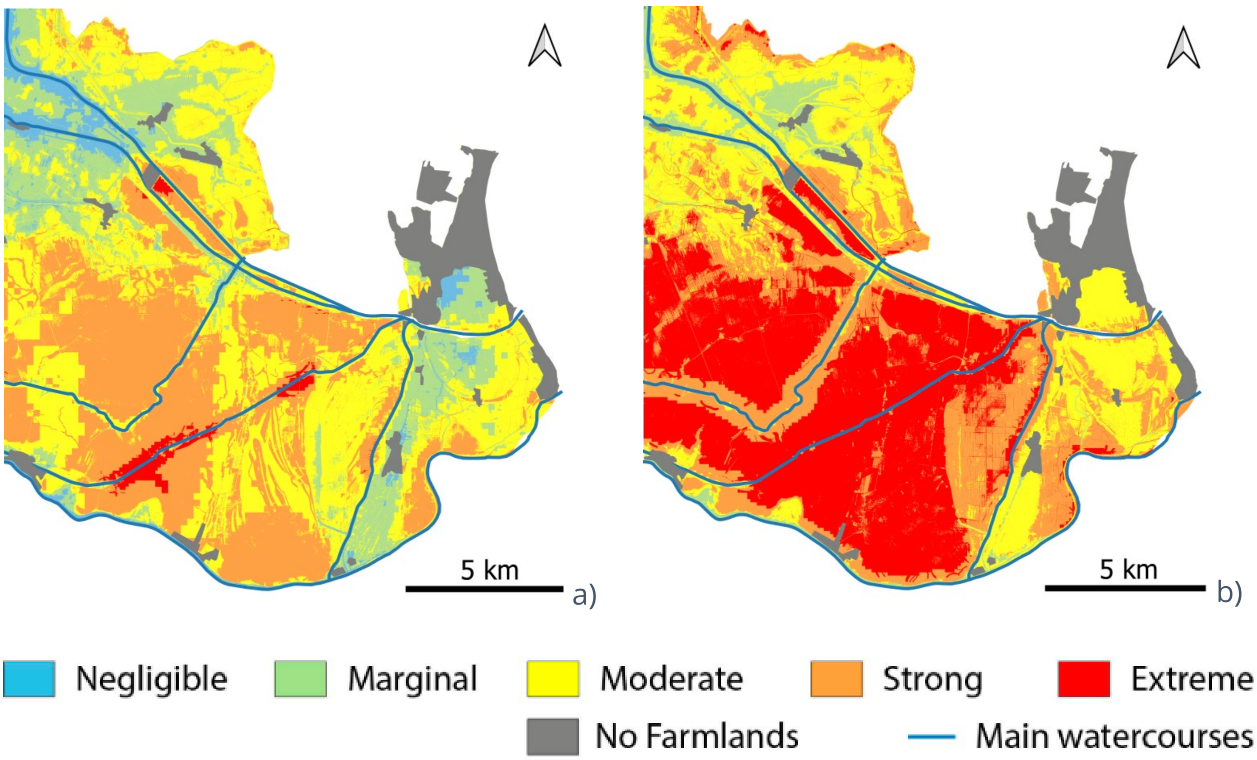


Fig. 6 – Maps of the sensitivity classification: a) present-day and b) in 2050.

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6. Hazard status

The Hazard status of the farmland system can be described by the depth of the freshwater - saltwater interface and the salinity degree in the shallowest subsoil (Fig. 7). These two indicators are important to capture the significance of the actual extent of saltwater intrusion.

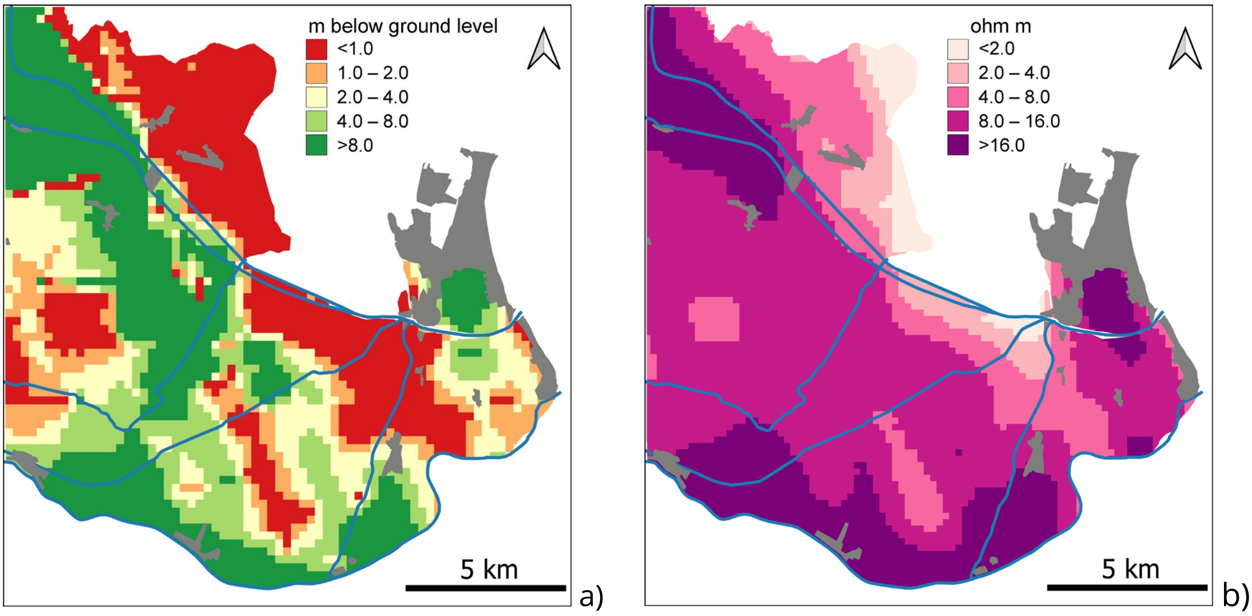


Fig. 7 - Maps of hazard indicators: a) depth to the fresh-saltwater interface and b) salinity degree in the shallowest subsoil.

7. Vulnerability

Vulnerability assessments represent a fundamental starting point for providing information to guide mitigation strategies and water management plans that will become increasingly critical in view of the predicted rise in the mean sea level over the next century.

Vulnerability refers to the propensity of the farmland system to be adversely affected by groundwater salinization from the nearby Adriatic Sea and Venice lagoon when different triggers modify the current hazard status. Specifically, this study assumes that the vulnerable farmland system to the saltwater intrusion is the subsoil that includes the agricultural zone and the underneath layers up to 3-4 m depth.

Vulnerability was assessed by combining the sensitivity maps (i.e., present-day and by 2050) with the hazard status (Fig. 8).

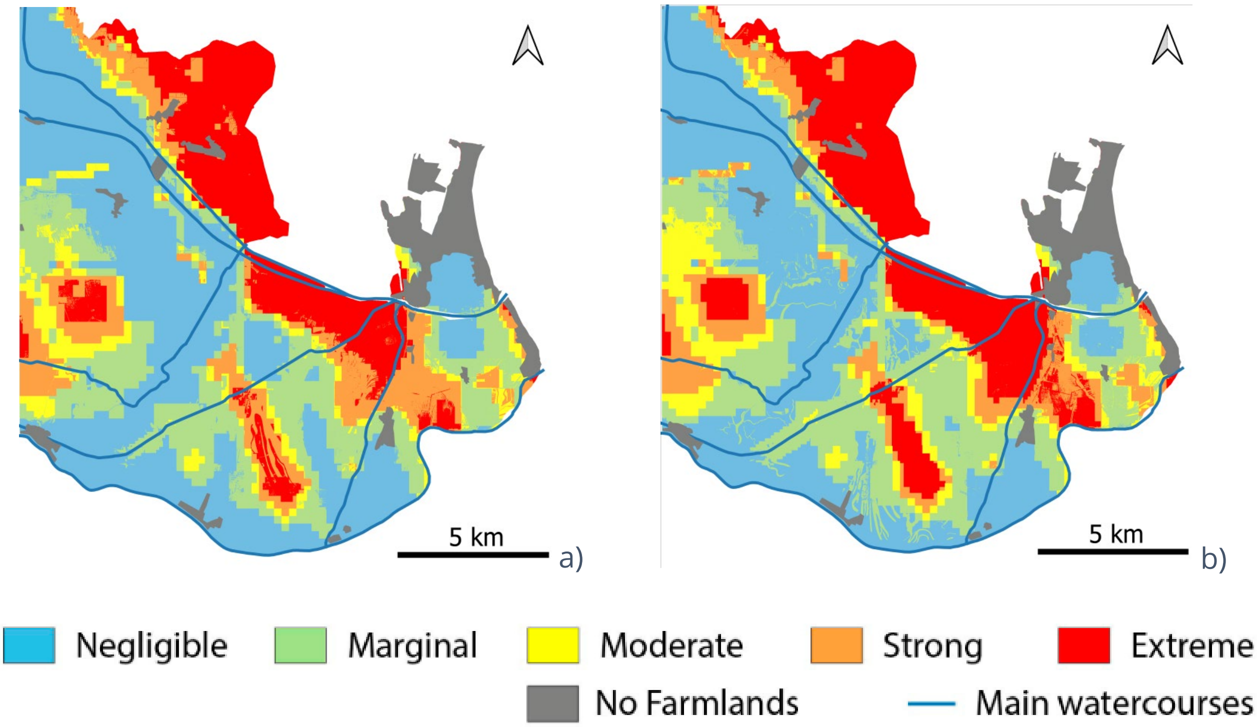


Fig. 8 - Maps of vulnerability: a) present-day and b) in 2050.

The areal coverage of the different hazard classes for the two scenarios is compared in Fig. 9.

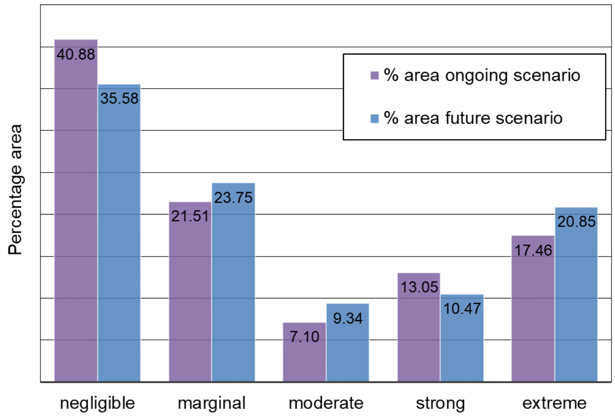


Fig. 9 – Comparison between present-day and 2050 vulnerability status.

8. Impact of climatic conditions on crop productivity

The detailed monitoring activities carried out in the pilot site at the Venice coast has allowed to highlight how climatic condition strongly affect the farmland productivity. The maximum and minimum daily temperature (°C), ETc and rain recorded in 2020 and 2022 by the meteorological station located in the pilot site are shown in Fig. 10. Yield data was recorded using yield monitoring system mounted on a Claas Lexion combine harvester. The records were used to produce the yield maps for the years 2020 and 2022 (Fig. 11). An estimate of the difference is shown in Fig. 11, highlighting how the dry conditions characterizing the climate during the 2002 crop season dramatically reduced the maize production.

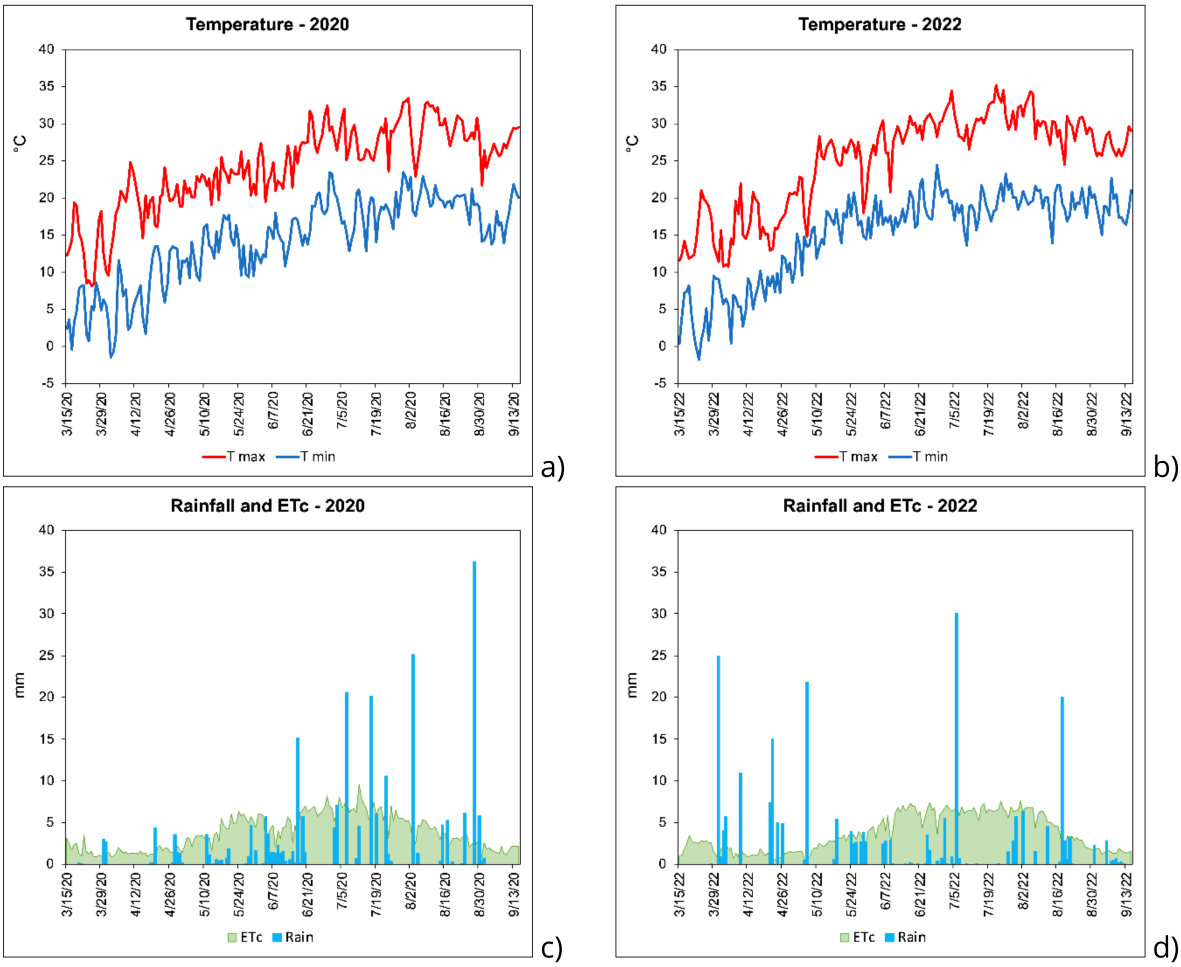


Fig. 10 - Meteorological data recorded by the weather station located in the pilot site: Max and Min Temperature in a) 2020 and b) 2022 (b); ETc and Rain in c) 2020 and d) 2022.

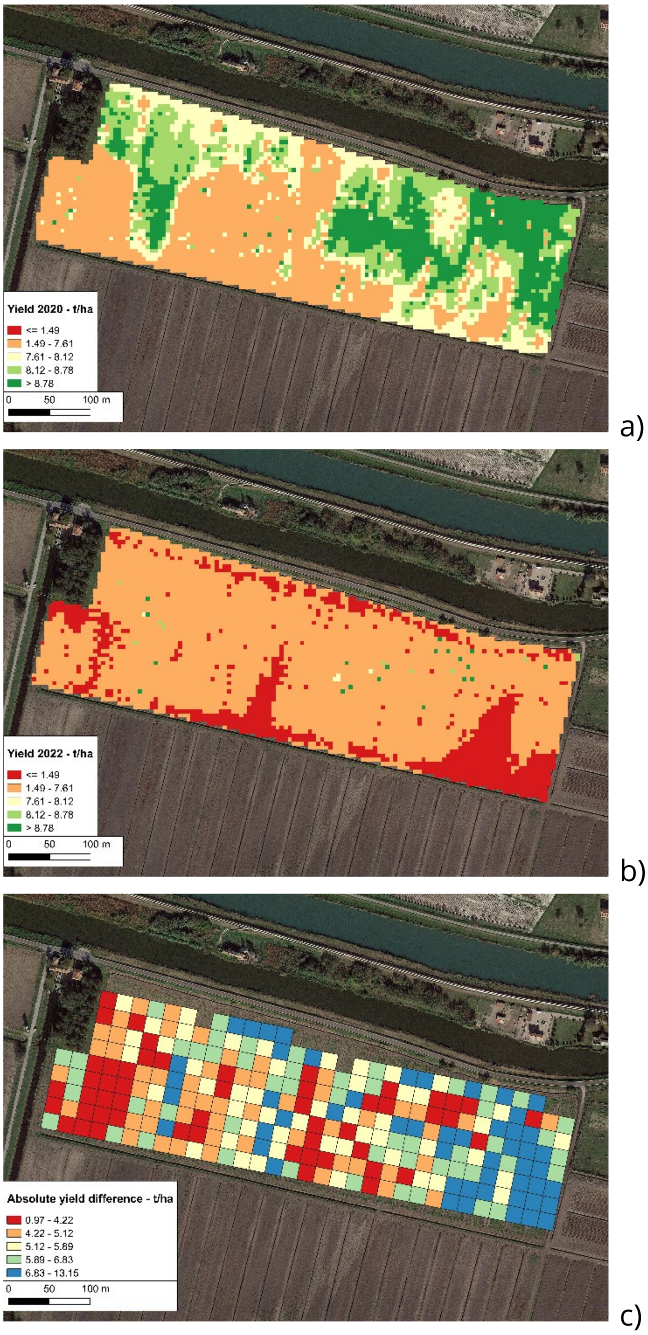


Fig. 11 – Maps of the crop productivity in a) 2020 and b) 2022. The difference between the two year is shown in c).

9. Potential for the implementation to other Adriatic vulnerable areas

A general picture of the extent of the agricultural areas on the Italian Adriatic coastal plains potentially affected by salt intrusion can be obtained from an elevation map that highlights the land below mean sea level to an elevation of 1-2 m above it (Fig. 12).

In general, the land elevation alone may not be sufficient to define coastal areas where agriculture is threatened by salt intrusion. Therefore, other factors, such as distance from saline water sources, water table elevation, and geologic features, are also critical. However, due to the hydro-geomorphological characteristics of the low-lying coastal areas of the Adriatic, the other factors that contribute to the identification of areas of potential salt intrusion are indirectly included. Indeed, the pumping stations artificially control the water table of low-lying farmlands to ensure drainage and thus agricultural activities in large areas that would otherwise be inundated by sea water. Distance from saline sources is certainly important, but even so, there are many areas far from these sources that are affected by paleosaline waters trapped during the maximum transgression of the coastline, which was farther inland than it is today. Since these are plains formed during Holocene marine transgression, their geo-morphologic setting is quite similar, with a high degree of variability in lithology and depositional units. With these assumptions and due caution, it is reasonable to suppose that agricultural areas with elevations below 1-2 m above msl are seriously threatened by salt intrusion.

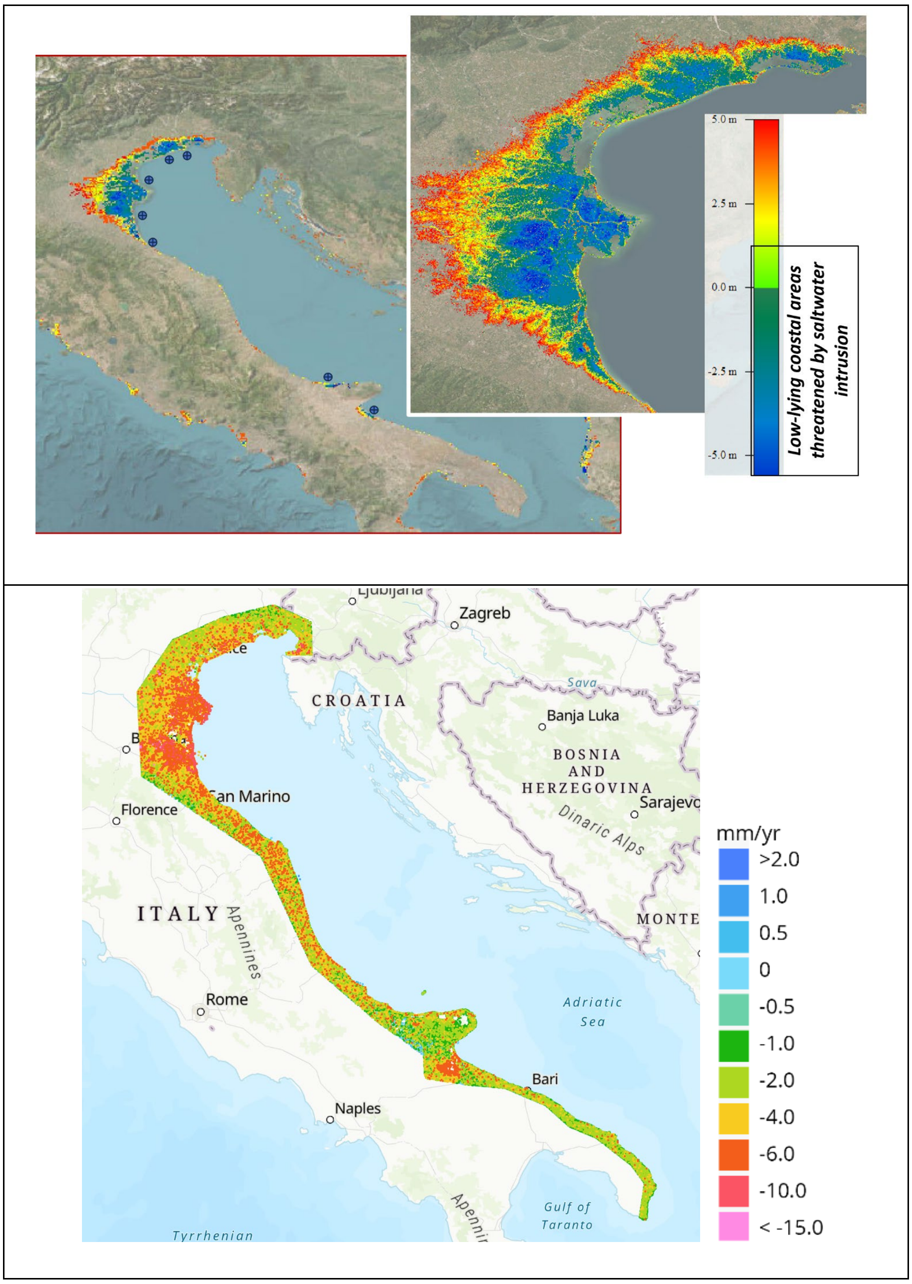


Fig. 12 – a) Low-lying areas along the Adriatic coast where agricultural production is threatened by saltwater intrusion. b) Vertical ground velocities. Negative values mean land subsidence.

The inspection of Fig. 12a shows that a large part of the coastal area of the Emilia-Romagna, Veneto and Friuli-Venezia Giulia regions is potentially threatened by saltwater intrusion, whereas Manfredonia, Lesina and other small plains are affected only to a minor areal extent.

Land subsidence reduces the elevation of coastal plains at highly variable rates, exceeding 5 mm/year in some areas and reaching 1-centimeter values locally (Fig. 12b). Land subsidence increases the tendency of aquifers and soils in coastal agricultural areas to become saline. The more the land subsides, the more water must be drained by pumping stations to maintain groundwater levels below the ground surface. In many cases, this increases the inflow of saline water from the deeper part of the aquifer due to spreading from hanging river beds combined with the greater advance of the seawater wedge through river mouths.

10. Mitigation Measures

Salinization from saltwater intrusion is one of the main causes of groundwater contamination worldwide and is expected to increase with increasing seawater levels due to climate change. According to the Intergovernmental Panel on Climate Change, in the year 2100, about 95% of the coastal areas in the world will be considerably affected by sea-level rise, hence increasing the risk of inundation and saltwater intrusion in coastal aquifers (Siarkos et al., 2017). Therefore, it is essential to identify appropriate mitigation measures.

There are several approaches to counteract seawater intrusion into coastal aquifers, using individual or combined hydraulic engineering methods. Selection criteria depend mainly on site characteristics and freshwater availability.

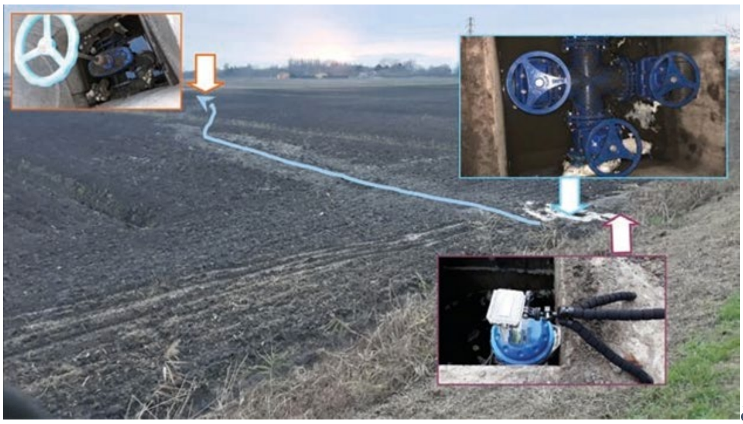
Many authors have discussed the countermeasures used in various parts of the world to prevent or at least reduce saltwater intrusion into coastal aquifers (Abd-Elhamid et al. 2018; Abd-Elhamid et al. 2020; Khadra et al. 2017; Kallioras et al., 2017; Jain, H., 2023; Oude Essink, 2001; Shi et al., 2014; Stein et al. 2023; Todd and Mays, 2005). For a summary, see Tab. 1.

Measure	**Short description**
Injection Barriers	Use of injection well fields to raise the water table and push back saltwater.
Underground Barriers	Build underground dams to prevent seawater intrusion.
Biological Barriers	Re-establish forest and freshwater wetlands to deepen saltwater intrusion and allow freshwater storage.
Artificial Recharge	Increases water storage by infiltration into the subsurface of fresh water from artificial basins and other sources.
Barrier at river estuaries	Prevent seawater encroachment and upstream freshwater storage by physical barriers.
Managment of groundwater abstraction	Re-plan the well fields by optimizing their withdrawal rates and/or distributing them landward. Monitoring of pumping through a proper monitoring network. Use numerical model for quantifying sustainable pumping.
Desalination	Use of brackish or salty groundwater after appropriate treatment.

Tab. 1 – Examples of countermeasures used in various parts of the world to prevent or at least reduce saltwater intrusion into coastal aquifers.

Focusing on the Italian study area and the nearby coastland, the measures taken to reduce saltwater intrusion into agricultural soils are reported in the following.

As part of the MoST projects, a sub-irrigation pipe was installed at a depth of about 1.5 m in a sandy morphological structure (paleochannel). The pipe draws fresh water from a reclamation canal whose bottom is about 2 m higher than that of the nearby farmland (Fig. 13).


a)


b)


c)

Fig. 13 – Photos of a) the MoST site with the trace of the buried drainpipe and detail of the manholes with valves and flowmeter; b) the realized intake structure; and c) the pipe drain during the installation works.

In the coastal region of the study area, mitigation measures have been taken since the 1980s, including the construction of seawater barriers adjacent to river mouths.

The purpose of the barriers is to separate the fresh water of the river from the seawater that encroaches along the mouths and to create a sort of freshwater reservoir for irrigation purposes in the upstream watercourse section.

The first saltwater intrusion barrier was built on the Po di Gnocca in 1987 with funding from the Ministry of Agriculture as a pilot project to test its operation, effectiveness and consequences. It was necessary to ensure the following: the regular flow of water and the balance of the river bottom; the navigation; the migratory movements of fish species; the complete mobility of the structure, which could only occupy part of the river bed.

For the above reasons, a structure with a fixed sill was ruled out. The chosen solution consisted of a structure composed of modular, mobile sluices that adapt to the morphological configuration of the riverbed (Fig. 14).

The functionality of the salt barrier was verified by on-site measurements and with the help of permanently installed conductivity loggers upstream and downstream of the dam. Based on the positive experience with this structure, two more salt barriers were subsequently funded and built at the mouth of the Po di Tolle and at the mouth of the Adige. The management phase of the "mobile" anti-salt barriers has shown that: (i) the salt wedge is effective at a river flow not lower than 450 m^3/s at Pontelagoscuro for the Po and 90 m^3/s at Boara Pisani for the Adige. However, experience has shown that the effectiveness of the barriers on the Po is guaranteed if the flow is larger than 330 m^3/s

in the Pontelagoscuro section; (ii) maintenance costs are by no means negligible and cannot be borne exclusively by the farmer operators and the reclamation authority, since the function of the barrier is not only irrigation but also serves other purposes (aqueducts) and has a general environmental benefit; (iii) uncontrolled navigation (especially on the Adige river) can cause significant damages to the barrier structures.

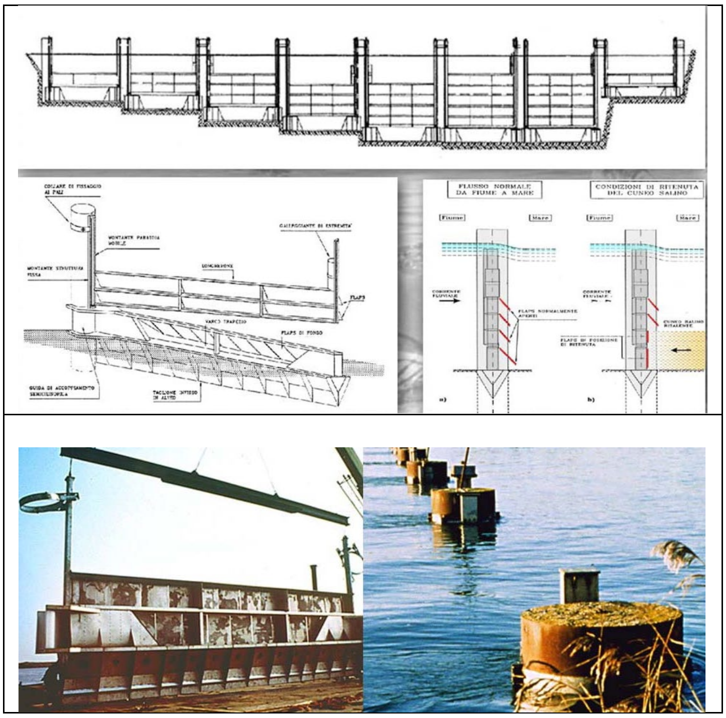


Fig. 14 - Saltwater intrusion barrier built at the Po di Gnocca mouth in 1987.

Thus, during exceptionally low water levels, as in 2003, 2005, 2006 and 2007, with values in the Po below 330 m^3/s and in the Adige in the range of 30 to 40 m^3/s, and in combination with particularly dry seasons, the effectiveness of the barriers (in the flood phase) was greatly reduced, since the exceptionally low discharges are not able to

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counteract the encroaching seawater edge.

In the late 1980s, the Magistrato alle Acque del Po created a water basin of about 50 hectares (Fig. 15) to provide more fresh water for irrigation. The basin water was realizing by straightening a major meander of the Po River (locality of Volta Vaccari) and building two dams. This work made available a volume of about 1,000,000 m^3 of fresh water.

Fig. 15 – Artificial fresh water basin for irrigation realized in a meander of the Po river.

In 2006, the Adige Bacchiglione Reclamation Authority proposed a project to build a mobile sluice gate at the mouth of the Brenta River to stop tidal water encroachment (Fig. 16). This work would generate a freshwater volume of more than $3{\times}10^6$ m^3 in the upper reaches of the Brenta, Bacchiglione, Gorzone and the Canale di Valle, otherwise occupied by seawater. The preliminary project was approved and funded by the Ministero delle Politiche Agricole e Forestali. However, due to a number of problems unrelated to seawater intrusion barrier, this work has not realized to date.

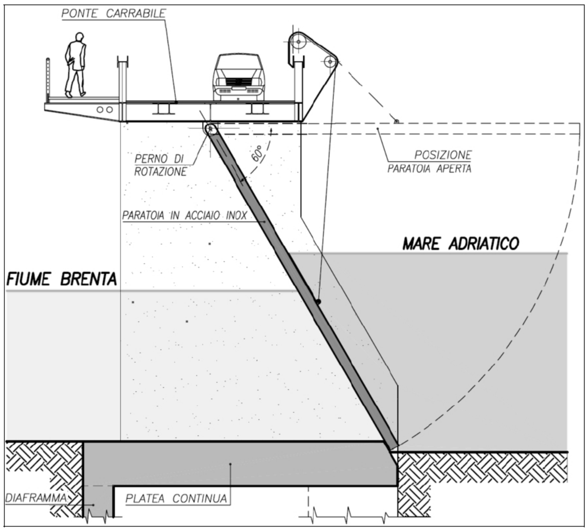

Fig. 16 - Sluce gate against sea water encroachment at the Brenta river mouth.

This section concludes with some suggestions and remarks for further measures to reduce saltwater intrusion that should be studied for the Italian Adriatic coastal plains. In addition to the mitigation measures already taken and outlined above, it is important to raise awareness in all levels of society about the importance of saving water to cope with its scarcity and ensure land use sustainability. In particular, it is very important to make farmers and landowners aware of the growing problem of salt intrusion and the fact that, in the face of climate change, annual productivity losses are becoming more frequent. They should be informed of the potential value-added income opportunities that can result from alternative crops. This could lead landowners to find other crops that are much more salt tolerant or require less water to sustain the local economy.

Creating dynamic maps of the vulnerability of various agricultural crops to salt intrusion in response to changes in salinity in groundwater, surface water and climatic conditions will help highlighting areas where it is most cost-effective to adopt certain adaptation measures, such as growing salt-tolerant crops. The same maps will also help to better understand the economic impacts of potential crop losses and adaptation strategies.

Water demand for irrigation should be significatively reduced using drip irrigation, which is the most efficient way as it uses only a fraction of the water compared to sprinkler irrigation. Because the water is applied slowly, this system is ideal for irrigating silty-clayye soils because they can absorb the water instead of losing it through runoff. Irrigation system need to be "smart" and equipped with controllers that measure weather and soil moisture conditions and automatically adjust watering schedules according to landscape conditions. This should be combined with the use of unmanned aerial vehicles (UAVs) to track crop fields with remote sensing in high spatial and temporal resolution to improve water stress management in irrigation.

Thought should be given to how to re-establish the conditions of freshwater wetlands and forests in some areas because of their ability to store surface water and deepen the freshwater-saltwater boundary.

Barriers against seawater wedge intrusion should be build along river mouths as they allows accumulation of freshwater in the upstream.

In the event of a water crisis, brackish groundwater could be extracted and desalinated by plants or mixed with freshwater from rivers. The reuse of water could be also an important source for irrigation. Some of the water from pumping stations that would flow to the sea could be used for irrigation and the reuse of wastewater after appropriate treatment should also be explored.

The measures just described are just a few examples on how to mitigate the salinization of agricultural land on the Italian coastal plains of the Adriatic. It is clear that their feasibility must be adequately verified, since their effectiveness depends on site-specific conditions, as mentioned above.

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