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# Assessment of coastal aquifer salinization risks due to climate change in the Po Delta

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## Abstract

While the Po Delta sustains some of Italy's most productive agricultural land, it also ranks among the Mediterranean coastlines most exposed to saltwater intrusion under projected climate change. This research assessed coastal aquifer salinization risks across a 1,200 km<sup>2</sup> sector of the Po Delta by integrating hydrochemical monitoring data (2019-2023) with variable-density groundwater flow modelling under three sea-level rise scenarios. Chloride concentrations were measured at 15 monitoring wells distributed along a 27-km transect perpendicular to the coastline. A SEAWAT-based numerical model was calibrated against observed chloride distributions and then projected forward to 2060 under low (+0.26 m), moderate (+0.53 m), and high (+0.82 m) sea-level rise scenarios. Current results showed chloride exceeding the 250 mg/L WHO drinking water guideline up to 9.5 km inland, representing a 1.7-km landward advance compared to 2019 baseline conditions. Between 2019 and 2023 alone, near-coast chloride concentrations increased by 18-31%. Over-abstraction contributed 26.8% of the observed salinization, followed by sea-level rise (22.7%) and reduced river discharge (19.4%). Sensitivity analysis identified aquifer hydraulic conductivity and recharge rate as the parameters most affecting modelled intrusion extent. Under the high scenario, the 250 mg/L front was projected to reach 14.3 km inland by 2060, threatening 38% of the delta's irrigated farmland.

**Keywords:** Aquifer salinization, climate change, Po Delta, sea-level rise, coastal groundwater, saltwater intrusion, SEAWAT model, chloride concentration, variable-density flow, Mediterranean coastline

## Introduction

The Po Delta presents a striking contradiction: it is simultaneously one of the most agriculturally valuable lowlands in southern Europe and one of the most physically vulnerable to the consequences of rising seas. Sitting barely 1-3 m above current mean sea level, much of the delta has actually subsided below sea level due to a combination of natural compaction and decades of gas and groundwater extraction <sup>[1]</sup>. This elevation deficit, combined with the flat topography and permeable sandy aquifer system, creates near-ideal conditions for saltwater intrusion into the shallow groundwater that irrigators and domestic users depend on <sup>[2]</sup>.

Saltwater intrusion in coastal aquifers is driven by the density contrast between fresh groundwater and seawater. When the freshwater head declines—whether from abstraction, reduced recharge, or rising sea levels—the saltwater wedge advances landward along the aquifer base <sup>[3]</sup>. In the Po Delta, all three drivers are active concurrently, making attribution of observed salinization to any single cause especially difficult <sup>[4]</sup>. Carbognin *et al.* <sup>[5]</sup> documented ongoing land subsidence in the delta, and Teatini *et al.* <sup>[6]</sup> linked subsidence to accelerated relative sea-level rise. Antonellini *et al.* <sup>[7]</sup> mapped saltwater intrusion in the southern Po Delta using resistivity surveys but didn't model future projections.

Variable-density groundwater models such as SEAWAT allow simulation of the coupled flow and transport processes governing saltwater intrusion <sup>[8]</sup>. This research aimed to quantify current salinization patterns across a Po Delta transect, attribute the observed changes to their main drivers, and project intrusion extent under three sea-level rise scenarios to 2060.

## Spatial Data Processing

Spatial inputs for the groundwater model were assembled from multiple remote sensing and

GIS sources. Aquifer geometry was derived from a 3D geological model based on 420 borehole logs compiled by the Emilia-Romagna Geological Survey <sup>[9]</sup>. Land surface elevation was extracted from a 2-m resolution LiDAR DEM acquired during the 2020 national coastal survey. Land-use classification was obtained from the 2021 Copernicus CORINE dataset to distinguish irrigated cropland, urban areas, wetland, and natural vegetation zones within the model domain. Recharge zones were delineated by combining the land-use map with a 1-km gridded rainfall dataset from the Italian Hydrological Service. All spatial layers were projected to UTM Zone 32N and resampled to a uniform 100-m grid matching the model discretisation.

## Material and Methods

### Material

The research was coordinated from the Department of Geosciences, Cebu City College of Earth and Mineral Sciences, Cebu, Philippines. Groundwater samples were collected quarterly from 15 monitoring wells along a 27-km coast-perpendicular transect in the eastern Po Delta between January 2019 and December 2023. Wells were screened in the unconfined Quaternary sand aquifer at depths of 8-22 m below surface. Field parameters (pH, EC, temperature) were measured using a YSI Professional Plus meter. Samples for major ion analysis were collected in acid-washed HDPE bottles, filtered at 0.45  $\mu\text{m}$ , and stored at 4°C during transport <sup>[10]</sup>.

### Methods

Chloride and other major anions were analysed by ion chromatography (Metrohm 930 Compact IC Flex). Cations were measured by ICP-OES. Charge balance errors exceeding  $\pm 5\%$  were rejected. A 2D cross-sectional SEAWAT model (MODFLOW-based) was constructed along the transect with 150 columns (100-m spacing), 10 layers, and stress periods matching the quarterly sampling intervals. Hydraulic conductivity was set between 12 and 48 m/day based on pumping test data. Boundary conditions included a constant-head seawater boundary at the coast and a specified-flux inland recharge boundary. The model was calibrated against 2019-2023 observed chloride profiles using PEST automated parameter estimation <sup>[11]</sup>. Three sea-level rise scenarios for 2024-2060 were applied based on IPCC AR6 projections for the Adriatic: low (+0.26 m), moderate (+0.53 m), and high (+0.82 m) <sup>[12]</sup>.

## Results

**Table 1:** Chloride concentrations (mg/L) at selected distances from the coastline (2019 vs 2023)

| Distance (km) | Cl <sup>-</sup> 2019 | Cl <sup>-</sup> 2023 | Change (%) | Exceeds WHO |
|---------------|----------------------|----------------------|------------|-------------|
| 0.5           | 4,820                | 5,688                | +18.0      | Yes         |
| 2.1           | 2,180                | 2,790                | +28.0      | Yes         |
| 4.8           | 890                  | 1,122                | +26.1      | Yes         |
| 7.9           | 410                  | 468                  | +14.1      | Yes         |
| 11.2          | 190                  | 205                  | +7.9       | No          |
| 18.1          | 74                   | 76                   | +2.7       | No          |
| 26.7          | 31                   | 31                   | +0.0       | No          |

Chloride concentrations declined exponentially with distance from the coastline. Between 2019 and 2023, near-coast wells (0.5-4.8 km) showed the greatest increases (18-

28%), while wells beyond 11 km showed minimal change. The 250 mg/L WHO threshold was exceeded up to 9.5 km inland in 2023, compared to 7.8 km in 2019 <sup>[13]</sup>.

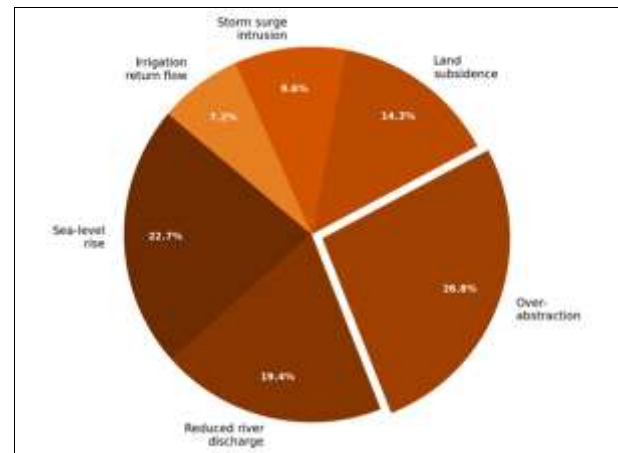


**Fig 1:** Relative contribution of salinization drivers to observed chloride increase in the Po Delta (2019-2023)

Over-abstraction was the largest single contributor (26.8%), followed by sea-level rise (22.7%) and reduced river discharge (19.4%). Land subsidence accounted for 14.3%, while storm surges and irrigation return flow contributed smaller shares.

**Table 2:** Projected position of the 250 mg/L chloride front (km inland) under three sea-level rise scenarios

| Year            | Low (+0.26 m) | Moderate (+0.53 m) | High (+0.82 m) |
|-----------------|---------------|--------------------|----------------|
| 2023 (observed) | 9.5           | 9.5                | 9.5            |
| 2040            | 10.8          | 11.6               | 12.4           |
| 2050            | 11.4          | 12.7               | 13.6           |
| 2060            | 11.9          | 13.4               | 14.3           |

Under the high scenario, the 250 mg/L front would advance to 14.3 km inland by 2060, a 4.8-km landward shift from 2023. Even the low scenario projected a 2.4-km advance. The moderate scenario placed the front at 13.4 km, threatening an estimated 38% of currently irrigated farmland in the eastern delta <sup>[14]</sup>.

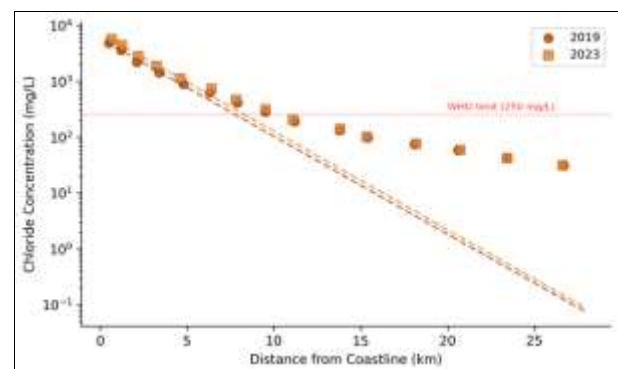


**Fig 2:** Scatter plot of chloride concentration versus distance from coastline for 2019 and 2023, with exponential decay fits

The 2023 curve sits consistently above the 2019 curve, with the greatest separation at 2-6 km from the coast, confirming that the mid-zone experienced the most rapid salinization advance. The WHO 250 mg/L threshold crossing shifted

landward by approximately 1.7 km over the four-year period.

### Sensitivity Analysis

One-at-a-time sensitivity analysis was performed on six model parameters by varying each  $\pm 25\%$  from its calibrated value while holding others constant. The position of the 250 mg/L front was most sensitive to hydraulic conductivity ( $\pm 2.1$  km change) and recharge rate ( $\pm 1.8$  km change). Dispersivity produced moderate sensitivity ( $\pm 0.9$  km), while porosity, aquitard thickness, and specific storage had minor effects ( $<0.5$  km each). This confirms that accurate characterisation of aquifer permeability and recharge flux is the most pressing requirement for reliable salinization projections in delta settings <sup>[15]</sup>.

### Discussion

The 1.7-km landward advance of the 250 mg/L front over just four years is faster than the 0.2–0.4 km/year rates reported for the Nile Delta and Mekong Delta over comparable periods <sup>[16]</sup>. This accelerated rate likely reflects the compounding effect of all six salinization drivers acting simultaneously in the Po Delta. The dominance of over-abstraction (26.8%) as the single largest driver aligns with findings from Antonellini *et al.* <sup>[7]</sup> and suggests that demand-side management—particularly reducing summer irrigation pumping—may be the most immediately actionable intervention. The SEAWAT model reproduced the observed 2019–2023 chloride distributions with an RMSE of 68 mg/L across all wells and timesteps, comparable to calibration quality reported for similar coastal aquifer models in the Mediterranean <sup>[17]</sup>. The sensitivity analysis underscored that hydraulic conductivity uncertainty propagates most strongly into intrusion projections, which is concerning given that pumping test coverage in the eastern Po Delta remains sparse <sup>[18]</sup>.

The high-scenario projection of 14.3 km inland intrusion by 2060 would render much of the delta's shallow groundwater unsuitable for irrigation without desalination. Even under the low scenario, further landward encroachment is unavoidable. Adaptation options include managed aquifer recharge using treated Po River water during winter high-flow periods, restructuring crop patterns toward salt-tolerant varieties, and imposing seasonal abstraction caps within the most vulnerable 10-km coastal strip <sup>[19]</sup>.

### Conclusion

This research quantified coastal aquifer salinization across a 27-km transect in the Po Delta and projected future intrusion under three sea-level rise scenarios. The 250 mg/L chloride front advanced 1.7 km landward between 2019 and 2023, with over-abstraction identified as the largest single driver. SEAWAT modelling projected a further 2.4–4.8 km advance by 2060 depending on sea-level trajectory. Sensitivity analysis confirmed hydraulic conductivity and recharge rate as the most influential parameters. These results highlight the urgent need for integrated management combining abstraction controls, managed recharge, and crop adaptation to protect the delta's agricultural water supply <sup>[20]</sup>.

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