Modelling the salinization of a coastal lagoon-aquifer system

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Modelling the salinization of a coastal lagoon-aquifer system

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Abstract. In this study, a coastal area constituted by alternations of saline-brackish lagoons and freshwater bodies was studied and modelled to understand the hydrological processes occurring between the lagoons, the groundwater system of the Po River Delta (Italy) and the Adriatic Sea. The contribution of both evaporation and anthropogenic factors on groundwater salinization was assessed by means of soil, groundwater and surface water monitoring. High-resolution multi-level samplers were used to capture salinity gradients within the aquifer and surface water bodies. Data were employed to calibrate a density-dependent numerical transport model implemented with SEAWAT code along a transect perpendicular to the coast line. The results show that the lagoon is hydraulically well connected with the aquifer, which provides the major source of salinity because of the upcoming of paleo-seawater from the aquitard laying at the base of the unconfined aquifer. On the contrary, the seawater (diluted by the freshwater river outflow) creates only a limited saltwater wedge. The increase in groundwater salinity could be of serious concern, especially for the pinewood located in the dune near the coast, sensitive to salinity increases. This case study represents an interesting paradigm for other similar environmental setting, where the assumption of classical aquifer salinization from a saltwater wedge intruding from the sea is often not representative of the actual aquifer's salinization mechanisms.

1. Introduction

Modelling the salinization of coastal water resources is one of the key issues to properly understand the mechanisms at the base of water quality deterioration induced by climate changes [1, 2]. Nevertheless, the mutual influence of groundwater and surface waters in coastal environments is influenced by many factors [3] and site specific models need to be employed to gain a comprehensive conceptual model of the studied area [4, 5]. So far, most of the attentions of the scientific literature have been focused on the ecological status of surface waters [6, 7]; however, the ecological status of a certain environment is often dependent on groundwater–surface water interactions [8].

In coastal environments, the most important mechanisms that control water salinization are [9]: the composition and amount of the atmospheric precipitation, the evapotranspiration processes, entrapped paleo seawaters, anthropogenic salt sources and biogeochemical water interactions with soils and aquifers. Numerical flow and transport models are a powerful tool to quantify and distinguish among the above-mentioned processes, which could potentially insist in the same environment [10]. In particular, density dependent groundwater flow models are quite promising in evaluating reactive mixing processes due to tidal induced fluctuations [11, 12] or to constant and variable pumping

conditions [13-15]. While coupled saturated-unsaturated flow and transport models can give insights into groundwater recharge and exchanges with surface water bodies [16, 17].

In this study, a coastal area pertaining to the Po River Delta (Italy) was studied and modelled by means of a density driven groundwater flow and transport model to identify the sources, and the processes of salinization, occurring between a saline lagoon, the shallow aquifer of the Po River Delta (Italy) and the Adriatic Sea.

2. Site description

The investigated site is positioned within the coastal floodplain belonging to the Po di Volano River, a terminal branch of the Po River located in Northern Italy (figure 1).
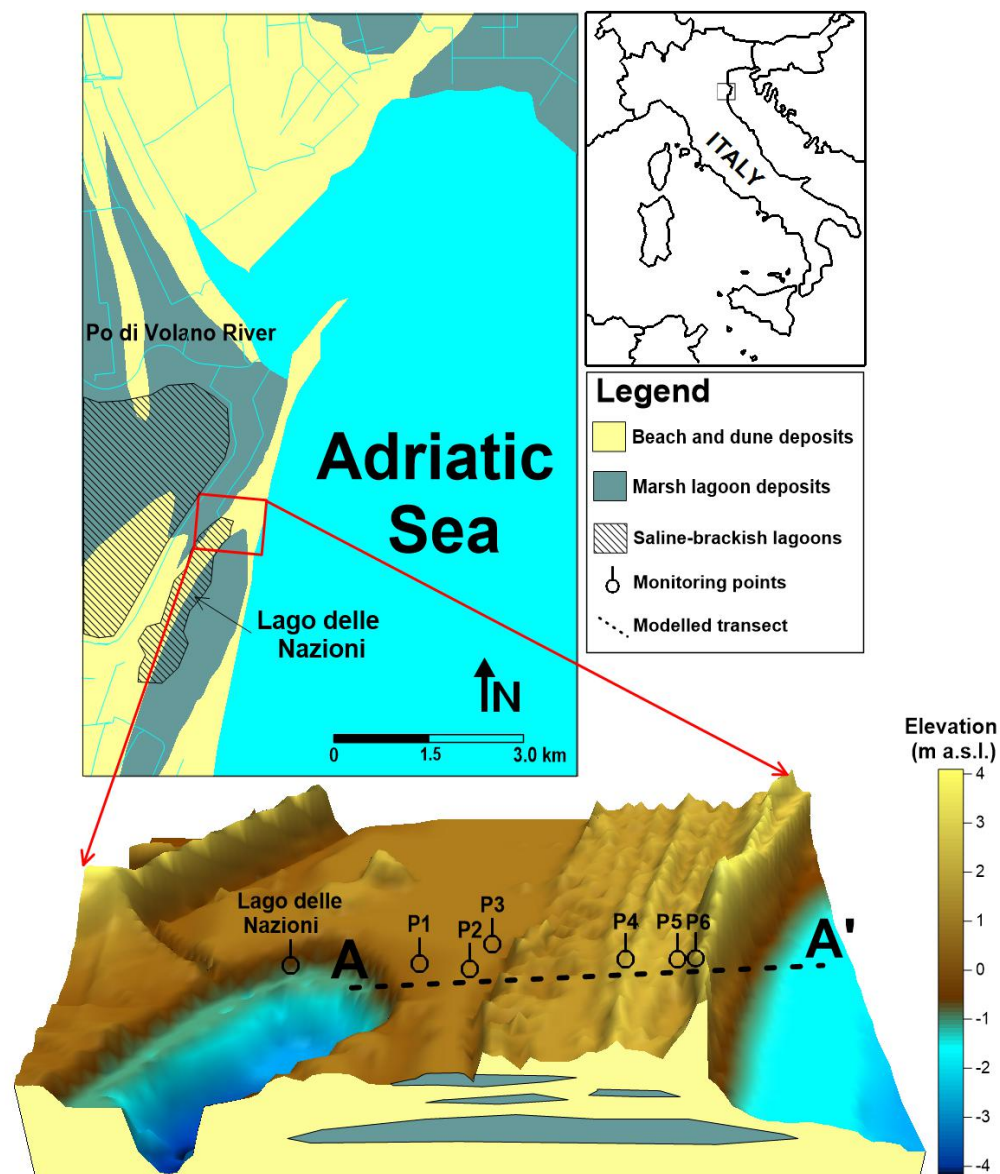
Figure 1. Geological sketch of the investigated site and distribution of the sampling and monitoring points. The density dependent groundwater flow model was built up along transect A-A' and the DTM was obtained interpolating bathymetric data with a LIDAR survey.

The peculiar landscape of the Po Delta is characterized by important environmental and ecological values and is often subject to land use changes [18]. Due to the flat ground elevation respect to the sea, these lands underwent intensive reclamation works [19]. The surface hydrographic network has a double use, first as drainage system serving a set of pumping stations, and for irrigation during the growing season. The shallow coastal aquifer is principally formed by sandy dune sediments (10-12 m thick) interbedded with silty-clay lenses (1-2 m thick), which locally create semi-confined conditions [20]. At the base of the aquifer, the prodelta wedge (4-15 m thick) formed by clay and silty-clay lenses acts as a saline aquitard. The groundwater flow is mainly oriented in the vertical direction and it is generally converging towards the drainage network [21]. Lago delle Nazioni is a brackish-saline lagoon of artificial origin, it is a stretched basin oriented parallel to the coast line of approximately 3 km length and 500 m wide (about 97 ha). The lagoon was in direct contact with the sea until 1960', then in the mid-sixties the Lago delle Nazioni basin was created for recreational purposes. Thus the pre-existing Valle di Volano, a brackish back-barrier lagoon formed since the Middle Ages, was completely reshaped and excavated. The sediments that form the bottom of Lago delle Nazioni range from silty-loam to sandy while along the shore there are prevalently sandy sediments, suggesting a good degree of connection between the lagoon and the shallow aquifer [20]. The average water depth is about 4.0 m, with maximum depth of 5.5 m and large areas of 1.5-2.0 m [22]. Water exchange and recirculation are guaranteed by an artificial channel connected with the Adriatic Sea by means of a siphon and a pumping station. Within this complex hydrogeological framework, the shallow aquifer, a brackish-saline lagoon (Lago delle Nazioni) and the Adriatic Sea, have been modelled to understand and quantify their mutual relationships.

3. Materials and methods

3.1. Field sampling
One multi-level monitoring well belonging to the monitoring network of the Emilia-Romagna Region (P2 in figure 1), and five shallow monitoring wells (P1, P3, P4, P5 and P6 in figure 1) were used to monitor groundwater quality and depth. The shallow monitoring wells (from 1.5 to 2 m depth) were drilled using a hands driven auger along a flow line and were positioned approximately perpendicular to the coast line (figure 1). Soil samples were collected every 20 cm from the ground surface during the shallow monitoring wells installation. Porewater salinity of each sample was measured in laboratory after extraction with double deionized water with a sediment to water ratio of 1/5 and correcting the value for the sediment volumetric water content. The monitoring wells were located in actual dunes characterized by medium to fine sandy deposits and brackish marsh lagoon deposits, typical of back barrier environments. The Lago delle Nazioni, P2, P3, P5 and P6 points were monitored for water level, temperature and electrical conductivity every 30 days during 2015 employing a multi-parameter sonde (Hydrolab MS-5).

Groundwater was sampled at various depths in May and November 2015 from P1 using a low pressure pneumatic straddle-packers system (Solinst Canada Ltd.). The packers' system comprised: a two inflatable packers, a 20 cm screen placed between the packers and a 12 V electrical pump employed for well purging and sampling.

3.2. Numerical modelling
Through the designated transect A-A', which is normal to the coast line and to the Lago delle Nazioni (figure 1), a conservative flow and transport model was employed to explore the salinization processes taking place within the unconfined aquifer. The simulations were performed by means of SEAWAT 4.0 [23], to mimic the interconnections between the lagoon, groundwater and the sea. SEAWAT 4.0 was selected since it is able to deal with variable-density processes. Chemical reactions were not considered here because the aim of this study was to explore the physical control on salinity transport, although in some cases neglecting this part can lead to errors in estimating model parameters [24].

The stratigraphic architecture of this area was reconstructed using the most recent literature data available for this zone [25].

The bi-dimensional numerical model was formed by 250 columns with a width of 2 m for a whole length of 500 m. The vertical direction was simulated using 26 layers of variable thickness to permit a fine delineation of the topography and the geometry of local lenses (figure 2). The first layer was thicker than the others, with the purpose of contain the groundwater table variations. In this way, grid cells wetting and rewetting was avoided, thus eliminating the numerical oscillations and solver non-convergence connected with this process.
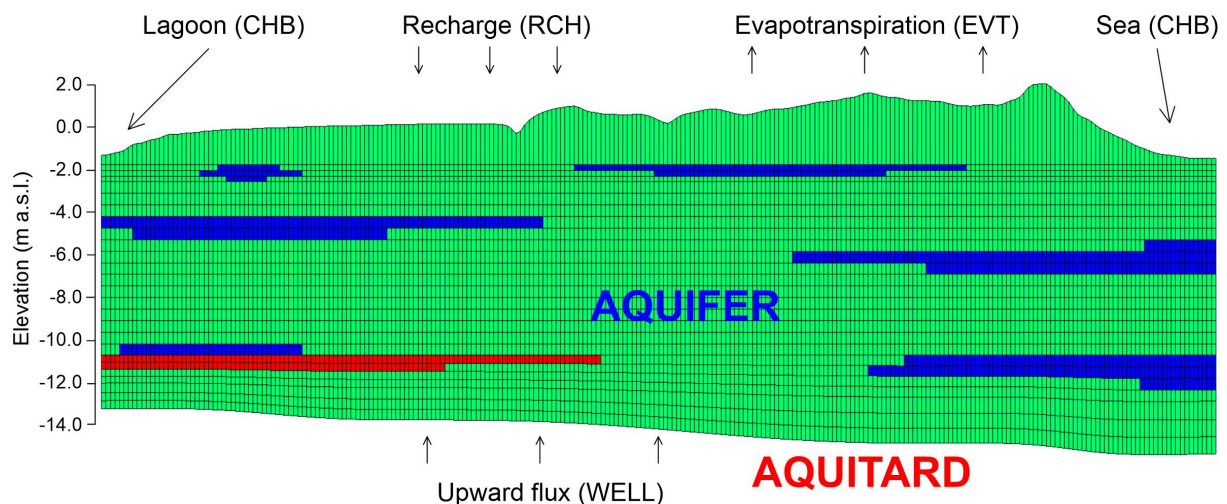
Figure 2. SEAWAT model boundaries and grid dimensions of the A-A' transect.
The colours refer to the properties of the different units described in table 1. Vertical exaggeration is 1:10.

Table 1. Model parameters used in the flow and transport model transect represented in figure 2.

Parameter	Value
Green sand k (m/d)	2.0
Green sand Ss (1/m)	$1e^{-4}$
Green sand Sy (-)	0.2
Blue silty-loam k (m/d)	0.1
Blue silty-loam Ss (1/m)	$1e^{-5}$
Blue silty-loam Sy (-)	0.1
Red sand k (m/d)	5.0
Red sand Ss (1/m)	$1e^{-4}$
Red sand Sy (-)	0.2
Longitudinal dispersivity (m)	0.2
Vertical transverse dispersivity (m)	0.01
Evapotranspiration (mm/y)	360
Recharge (mm/y)	80

The vertical hydraulic conductivity (k_v) was assumed to be 5 times lower than the horizontal one (k_h) for all layers [16], while the effective porosity was taken as 0.25 for the entire model [21]. The specific yield (S_y) and specific storage (S_s) were taken from literature values [26]. The diffusion coefficient was supposed to be equivalent to $1x10^{-4}$ m^2/d.

A fully transient simulation was performed reproducing the changes occurred during the last 160 years. Here the time was segmented into three stress periods to mimic the change of the salinity in the

back barrier environment. In the first stress period (50 years long), a large freshwater recharge from the Po di Volano River was set in the flat topographic zone beneath the coastal dunes, to attain a characteristic distribution of heads and salinity inside the aquifer until 1910. In the second stress period (50 years long), the Lagoon' Constant Head Boundary (CHD) in layer 1 was extended in all the area topographically below the actual sea level to achieve a representative distribution of heads and salinity within the aquifer until 1960. In the third stress period (60 years long), the actual configuration was considered, restricting the Lago delle Nazioni to the first 10 cells at the left side of the model. To account for seawater input in the aquifer from the Adriatic Sea, a CHD was set in the cells of layer 1 located on the right corner of the modelled transect (figure 2). The WELL Package was employed to mimic the ascending flux provoked by the reclamation system; the specific discharge rate was considered employing a published method [27]. The Recharge Package (RCH) was employed to mimic the effective infiltration averaging the yearly recharge value of 155 mm/y for this area as initial estimate [21]. The average salinity concentrations in the porewater of the upper soil samples were employed as salinity concentration of the recharging waters. The evapotranspiration was simulated with the Evapotranspiration Package (EVT), the maximum evapotranspiration rate was initially set to 3 mm/d with an extinction depth of -1 below ground level. The maximum transpirable salinity was set to 5 g/l due to the presence of a pinewood [28].

Dispersivity, recharge, evapotranspiration and hydraulic conductivity parameters were tuned via trial and error calibration to fit the observed heads and salinities collected in May and November 2015, considered representative of the mean water table conditions.

4. Results and discussion

Figure 3 shows the calibration results of measured versus computed hydraulic heads and salinities in all the monitoring wells. Relatively good calibration was achieved for both heads and salinities throughout the aquifer. The plots show the presence of brackish to saline groundwater in the model domain and small heads variations imputable to the flat topographic surface. The trial and error calibration procedure lead to an absolute mean error between simulated and observed heads and salinities of 5.1 cm and 2.5 g/l, respectively. These errors resemble to the 6.9% of the observed piezometric range and to the 7.8% of the observed salinity range throughout the examined time frame. Table 1 reports the calibrated parameters; in general, they are in agreement with previous model parameters applied in this coastal aquifer [2, 5, 21].
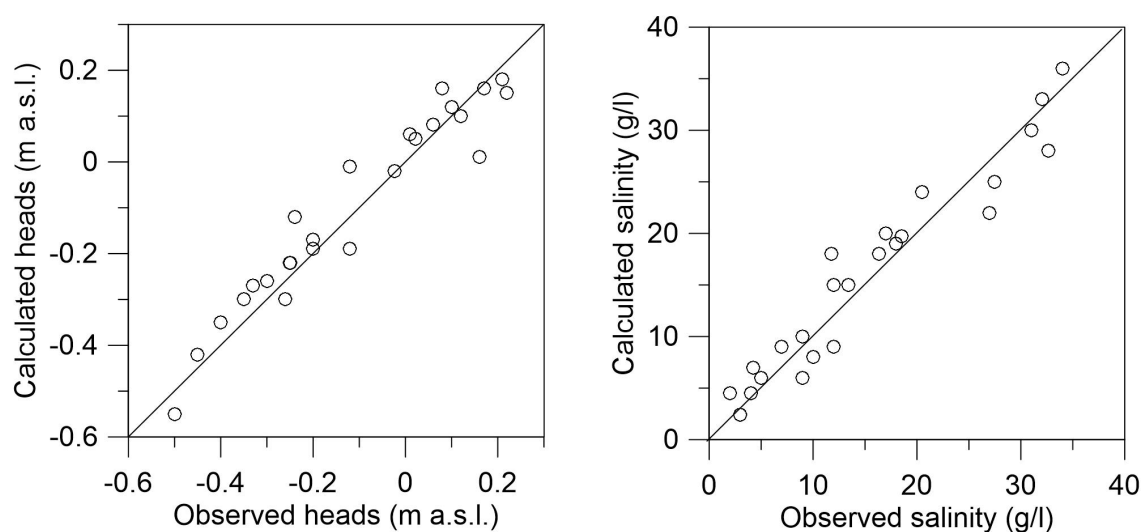
Figure 3. Scatter diagrams of observed heads versus calculated ones (left plot) and Scatter diagrams of observed salinities versus calculated ones (right plot).

The unevenness of the recorded groundwater heads and salinities during the monitored period was elevated, due to recharge events, storm events and summer droughts. Thus, to precisely replicate all the variations due to small fluctuations in groundwater heads and salinities a much higher time-based discretization would be need. In any case, the aim of this model was to reproduce the general piezometric head trend and salinity distribution within the aquifer. In particular, figure 4 shows the piezometric heads decrease induced by the Lago delle Nazioni that constantly drains groundwater from the coastal aquifer. The sand dune belt acts as recharge area, constituting a groundwater divide between the Adriatic Sea and the back barrier environment. The groundwater heads map shows a complex flow pattern, mainly driven by differences in groundwater densities, lenses of fine sediments and the upward flux from the aquitard.
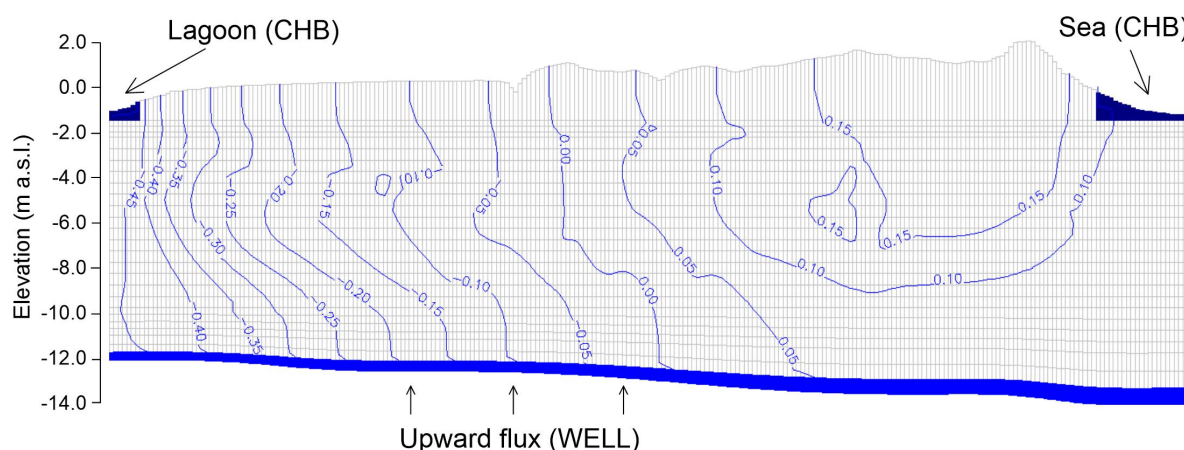

Figure 4. Groundwater heads map calculated at the end of the model simulation (actual conditions). The model grid and model boundaries are also depicted. Vertical exaggeration is 1:10.

To get a more robust idea of the different flow component, table 2 shows the flow budget between the various boundaries. The storage term within the aquifer is quite limited, while approximately 70 l/d flow from the aquifer towards the Lago delle Nazioni. From the Adriatic Sea the actual seawater intrusion is limited to approximately 2.4 l/d, while submarine groundwater discharge is 18 l/d. The upward flux from the aquitard is in general quite limited, although it slowly contributes to salinize the aquifer. The recharge is the prevailing term of this model with 110 l/d infiltrating through the simulated transect, while evapotranspiration accounts for 27 l/d, becoming the second term of the flow budget per magnitude. The model budget is perfectly balanced as denoted by the difference between the inflows and outflows, guaranteeing that the estimated magnitude of the flow components is reliable.

Table 2. Model flow budget at the end of the simulation (actual conditions).

Flow term	IN (m^3/d)	OUT (m^3/d)	IN-OUT (m^3/d)
Storage	$8.52e^{-03}$	$4.58e^{-04}$	$-3.73e^{-04}$
Lagoon	0.00	$6.96e^{-02}$	$-6.96e^{-02}$
Sea	$2.39e^{-03}$	$1.82e^{-02}$	$-1.58e^{-02}$
Upward flux	$2.50e^{-03}$	0.00	$2.5e^{-03}$
Recharge	$1.1e^{-01}$	0.00	$1.1e^{-01}$
Evapotranspiration	0.00	$2.68e^{-02}$	$2.68e^{-02}$
Sum	$1.15e^{-01}$	$1.15e^{-01}$	$9.53e^{-08}$

Figure 5 shows the model results for the simulated salinity distribution within the aquifer cross section at the end of each stress periods. In the upper panel of figure 5 the reconstructed salinity distribution at the beginning of the 1900 is shown, with a thick freshwater lens near to the actual Lago delle Nazioni. This was due to the Po di Volano River that was flowing in a slight different position respect to the actual river mouth [29]. The results of the second stress period are shown in the middle panel of figure 5, where the salinization of the shallow part of the coastal aquifer is evident, due to the connection between the Adriatic Sea and the lagoon. The freshwater lens still persists, but it is pushed down by the saline waters of the embayment. Finally, the present conditions, reported in the bottom panel of figure 5, are a complex mixture of the different conditions that have acted in the last century within this portion of coastal aquifer. Brackish groundwater fingers develop in the model domain, producing a very complex pattern that highly limits the capability to distinguish between modern seawater intrusion processes, evapotranspiration processes and paleo-seawater upconing.
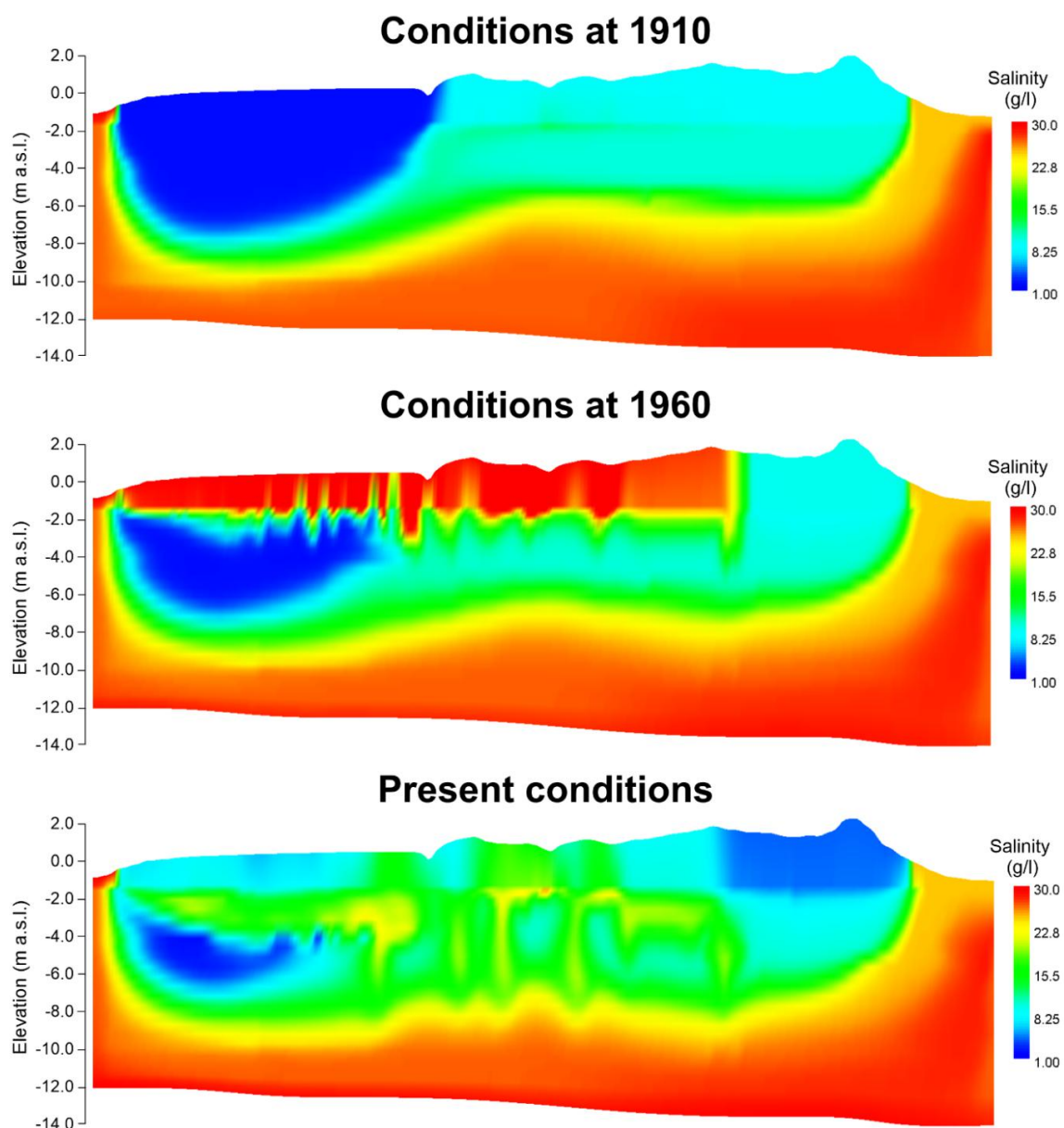
Figure 5. Groundwater salinity maps calculated at the end of each model stress period. Vertical exaggeration is 1:10.

One of the key points in the difficulty of precisely locating the actual seawater intrusion wedge is the anomalous presence of diluted seawater in the near shore portion of the Adriatic Sea in this area. This is due to freshwater plumes originating from the Po Delta river branches, which constantly lower the Adriatic Sea salinity at concentrations that hardly reach 20 g/l in this shallow sea. Another major issue is the evapotranspiration capacity of vegetation in the dune environment; in fact, since the water table is quite shallow, vegetation makes use of groundwater and consequently increases the aquifer salinity. Moreover, vegetation may also increase the unsaturated soil salinity and thus increasing the salinity of the infiltrating water from precipitations. For instance, the measured porewater salinity was always greater than 1 g/l in all the sediment profiles and the highest shallow porewater salinities were recovered within the pinewood, with concentrations ranging from 3.5 to 11.3 g/l. The increase in salinity of groundwater could be of serious concern, especially for the pinewood located in the dune near the coast, sensitive to salinity increases. In fact, even little changes in the hydrological balance due to climate variability or sea level rise could seriously affect this fragile ecotone.

5. Conclusions

To understand and quantify the hydrological processes occurring between the lagoons, the groundwater system pertaining to the Po River Delta (Italy) and the Adriatic Sea, a density driven numerical model (SEAWAT 4.0) was set up and calibrated through a cross section perpendicular to the coast line. The contribution of anthropogenic and natural factors on groundwater salinization were assessed by past reclamation activities and actual groundwater and surface water monitoring. The results of the actual flow budget show that the lagoon (Lago delle Nazioni) is hydraulically well connected with the aquifer, and its salinity is kept constant by saline groundwater. The major sources of actual salinity are: (i) the upconing of paleo-seawater from the aquitard situated immediately below the unconfined aquifer; (ii) the evapotranspiration processes that increase soil and shallow groundwater salinity. In contrast, the Adriatic Sea (diluted by the freshwater outflowing from the Po River branches) creates only a limited brackish water wedge. This case study represents an interesting paradigm for other similar environmental setting, where the assumption of classical aquifer salinization from a saltwater wedge intruding from the sea is often not representative of the actual aquifer's salinization mechanisms. Thus more accurate hydrogeological analyses must be performed to accurately distinguish between actual and paleo seawater intrusion processes.

References

[1]　Oude Essink G H P, Van Baaren E S and Louw P G 2010 Effects of climate change on coastal groundwater systems: A modeling study in the Netherlands *Water Resour. Res.* **46(10)**

[2]　Colombani N, Osti A, Volta G and Mastrocicco M 2016 Impact of climate change on salinization of coastal water resources *Water Resour. Manage.* **30(7)** 2483-96

[3]　Bratton J F, Böhlke J K, Krantz D E and Tobias C R 2009 Flow and geochemistry of groundwater beneath a back-barrier lagoon: The subterranean estuary at Chincoteague Bay, Maryland, USA *Mar. Chem.* **113(1)** 78-92

[4]　Beekman H E, Eggenkamp H G M and Appelo C A J 2011 An integrated modelling approach to reconstruct complex solute transport mechanisms–Cl and δ 37 Cl in pore water of sediments from a former brackish lagoon in the Netherlands *Appl. Geochem.* **6(3)** 257-68

[5]　Caschetto M, Colombani N, Mastrocicco M, Petitta M and Aravena R 2016 Estimating groundwater residence time and recharge patterns in a saline coastal aquifer *Hydrol Proces* **30(22)** 4202-13

[6]　Newton A, Icely J, Cristina S, Brito A, Cardoso A C, Colijn F and Ivanova K 2014 An overview of ecological status, vulnerability and future perspectives of European large shallow, semi-enclosed coastal systems, lagoons and transitional waters *Estuar. Coast. Shelf Sci.* **140** 95-122

[7]　Basset A, Elliott M, West R J and Wilson J G 2013 Estuarine and lagoon biodiversity and their natural goods and services *Estuar. Coast. Shelf Sci.* **132** 1-4

[8]   Miller D C and Ullman W J 2004 Ecological consequences of ground water discharge to Delaware Bay, United States *Ground Water* **42(7)** 959-70

[9]   Hart B T, Bailey P, Edwards R, Hortle K, James K, McMahon A, Meredith C and Swadling K 1990 Effects of salinity on river, stream and wetland ecosystems in Victoria, Australia *Water Res.* **24(9)** 1103-17

[10]   Anderson M P, Woessner W W and Hunt R J 2015 *Applied Groundwater Modeling: Simulation of Flow and Advective Transport* (London UK: Academic Press)

[11]   Mao X, Enot P, Barry D A, Li L, Binley A and Jeng D S 2006 Tidal influence on behaviour of a coastal aquifer adjacent to a low-relief estuary *J. Hydrol.* **327(1)** 110-27

[12]   Campana C and Fidelibus M D 2015 Reactive-transport modelling of gypsum dissolution in a coastal karst aquifer in Puglia, southern Italy *Hydrogeol. J.* **23(7)** 1381-98

[13]   Qahman K and Larabi A 2006 Evaluation and numerical modeling of seawater intrusion in the Gaza aquifer (Palestine) *Hydrogeol. J.* **14(5)** 713-28

[14]   Mastrocicco M, Colombani N and Petitta M 2011 Modelling the density contrast effect on a chlorinated hydrocarbon plume reaching the shore line *Water Air Soil Poll.* **220(1-4)** 387-98

[15]   Bobba A G 2002 Numerical modelling of salt-water intrusion due to human activities and sea-level change in the Godavari Delta, India *Hydrol Sci J* **47(S1)** S67-80

[16]   Colombani N, Di Giuseppe D, Faccini B, Ferretti G, Mastrocicco M and Coltorti M 2016 Inferring the interconnections between surface water bodies, tile-drains and an unconfined aquifer–aquitard system: A case study *J. Hydrol.* **537** 86-95

[17]   Wilson A M and Gardner L R 2006 Tidally driven groundwater flow and solute exchange in a marsh: Numerical simulations *Water Resour. Res.* **42(1)**

[18]   Gaglio M, Aschonitis V G, Gissi E, Castaldelli G and Fano E A 2017 Land use change effects on ecosystem services of river deltas and coastal wetlands: case study in Volano–Mesola–Goro in Po river delta (Italy) *Wetlands Ecol. Manage.* **25(1)** 67-86

[19]   Correggiari A, Cattaneo A and Trincardi F 2005 The modern Po Delta system: Lobe switching and asymmetric prodelta growth *Mar. Geol.* **222** 49-74

[20]   Colombani N, Giambastiani B M S and Mastrocicco M 2017 Impact of climate variability on the salinization of the coastal wetland-aquifer system of the Po Delta, Italy *J. Water Suppl. Res. T.* (in press)

[21]   Colombani N, Giambastiani B M S a nd Mastrocicco M 2015 Predicting salinization trends in a lowland coastal aquifer: Comacchio (Italy) *Water Resour. Manage.* **29(2)** 603-18

[22]   Mistri M and Rossi R 1999 Structure and production of the benthic macroinvertebrate community in a shallow lagoon of the Po River Delta *It. J. Zool.* **66(4)** 361-8

[23]   Langevin C D, Thorne D T Jr, Dausman A M, Sukop M C and Guo W 2007 S*EAWAT Version 4: A Computer Program for Simulation of Multi-Species Solute and Heat Transport: U.S. Geological Survey Techniques and Methods* book 6 Chap. A22 pp 1-39

[24]   Mastrocicco M, Prommer H, Pasti L, Palpacelli S and Colombani N 2011 Evaluation of saline tracer performance during electrical conductivity groundwater monitoring *J. Cont. Hydrol.* **123(3)** 157-66

[25]   Amorosi A, Centineo M C, Colalongo M L and Fiorini F 2005 Millennial-scale depositional cycles from the Holocene of the Po Plain, Italy *Mar. Geol.* **222** 7-18

[26]   Fetter C W 2001 *Applied Hydrogeology (4th); Upper Saddle River* (NJ: Prentice Hall, 598)

[27]   De Louw P G, Eeman S, Oude Essink G H P, Vermue E and Post V E A 2013 Rainwater lens dynamics and mixing between infiltrating rainwater and upward saline groundwater seepage beneath a tile-drained agricultural field *J. Hydrol.* **501** 133-45

[28]   Antonellini M and Mollema P N 2010 Impact of groundwater salinity on vegetation species richness in the coastal pine forests and wetlands of Ravenna, Italy *Ecol. Eng* **36(9)** 1201-11

[29]   Simeoni U and Corbau C 2009 A review of the Delta Po evolution (Italy) related to climatic changes and human impacts *Geomorphol.* **107(1)** 64-71