Impact of climate variability on the salinization of the coastal wetland-aquifer system of the Po Delta, Italy

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ABSTRACT

Deltaic coastal areas are constituted by a patchwork of brackish lagoons and freshwater bodies; these coastal wetland-aquifer systems are fragile ecosystems that usually respond quickly to climate changes. To understand the hydrological processes occurring within the lagoons and the groundwater system of the Po River Delta (Italy), the contribution of both evaporation and anthropogenic factors on groundwater salinization was assessed. A time series (2002–2015) of monthly average climatic data and a temperature-salinity dataset were used in three adjacent saline-brackish lagoons with the aim to identify the actual evaporation patterns and predict future trends using artificial neural networks (ANN). Moreover, the use of groundwater and surface water equivalent freshwater heads, along with the geological architecture, allowed linking the fluctuation of lagoon salinities with the degree of hydraulic connection between wetland and aquifer system. Results show that the less a lagoon is hydraulically connected with the aquifer, the higher is the salinity peak that could be reached at the end of the summer period. ANN forecasts highlight that in the near future this behaviour would be the rule rather than the exception. The increase in salinity of surface waters could be of serious concern, especially for aquaculture, sensitive to sharp salinity increases.

Key words | artificial neural networks (ANN), brackish lagoons, coastal aquifer, evaporation, salinization

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INTRODUCTION

Coastal lagoons are usually partially connected to oceans and seas; consequently, they can be brackish, saline or hypersaline depending on their geographical location (Newton & Mudge 2003; Webster 2010). Coastal lagoons may be bounded by barrier islands, or sand spits, and connected to the open sea or not, as the case of the wetland-aquifer system of the Bertuzzi lagoons and Lago delle Nazioni, southward to the actual Po River Delta (Italy). This wetland-aquifer system is hydraulically controlled by pumping stations for land reclamation and a dense drainage network, which are the main drivers of the system (Colombani *et al.* 2016a; Gaglio *et al.* 2017). Since the lagoon systems are not directly connected to the open sea and are

exploited for recreational activities (Lago delle Nazioni) and aquaculture (Bertuzzi lagoons), the salinity is not naturally driven during the year but, instead, is closely linked to man-made water input and output through the drainage network. Since accumulation of salts in wetlands can shift species-rich freshwater communities to species-poor salt tolerant communities (Nielsen & Brock 2009), it is of the utmost importance to clarify the mechanisms that regulate this process in anthropized coastal lagoons.

To reach this goal, a prerequisite is knowledge of the geological architecture that allows/limits hyporheic exchanges (Kløve *et al.* 2011), then climatic and salinity data must be recorded for at least a decade to allow an

accurate description of the intra-annual variability and to forecast the short–medium term changes that will affect the system. To model the actual and future changes in salinity within a specified surface-groundwater system, highly specialized numerical models are required (Rasmussen *et al.* 2013; Green & MacQuarrie 2014; Colombani *et al.* 2015). Despite this, numerical models involve a considerable amount of detailed data not always obtainable. In an attempt to overcome this issue, the literature reveals that artificial neural networks (ANN) have been fruitfully applied to model and predict water resource variables (Maier & Dandy 2000) and, recently, even to model and predict groundwater salinization (Banerjee *et al.* 2011). The main benefit in using ANN is its capability to represent the nonlinear dynamics of a given modelled system without any a priori assumption concerning the processes entangled. On the other hand, the main disadvantage in using ANN is the data overfitting, e.g., where an ANN perfectly captures the time series, but does not have enough generalization capacity to make accurate predictions due to 'noise' in the dataset.

With the recent refinement to projections of climate change, namely sea level rise (SLR), and changes in recharge and evapotranspiration patterns, the number of studies reviewing the effects of the intensified pressures on coastal groundwater systems has increased (Ferguson & Gleeson 2012; Werner *et al.* 2013; Re *et al.* 2014). Direct evaporation from surface water bodies like lakes, wetlands and lagoons, will also increase due to temperature increase leading to salt accumulation (Schallenberg *et al.* 2003; Havens & Steinman 2015). These projections will be further exacerbated in the Mediterranean area (Voudouris 2006; García-Ruiz *et al.* 2011). Moreover, predictions of Adriatic Sea level rise according to Lambeck *et al.* (2011) will produce a relative SLR for the next 40 years, ranging from approximately 0.1 to 0.6 m, in the proximity of the Po River Delta. To quantify the effects of climate variability on the shallow coastal aquifer of the city of Ferrara, the predicted changes have been used as input and boundary conditions for a series of scenarios using a complex numerical flow and transport model (Colombani & Mastrocicco 2016; Colombani *et al.* 2016a). Although the shallow lagoons were treated as constant boundary conditions within the aquifer scale numerical model, it would be interesting to study, at

the local scale, their mutual interplay with the coastal aquifer. For this reason, in the presented work, a long-term dataset was processed with ANN to forecast the increase in salinities in coastal lagoons in the short–medium term. The geological architecture and hydrogeological information were both employed to constrain the conceptual model. Following this approach, a robust conceptual model was established.

MATERIALS AND METHODS

Study area

The study area is situated in the coastal floodplain pertaining to the Po River, in northern Italy at a latitude of 44.78° and a longitude of 12.22° (Figure 1). It is an area generally characterized by important environmental and ecological values and subjected to frequent land use changes (Gaglio *et al.* 2017). Since this is reclaimed land, the surface hydrographic network serves mainly as a drainage system and the collected water is discharged toward the Adriatic Sea by a set of pumping stations. The shallow coastal aquifer consists of sandy dune sediments (10–12 m thick) interbedded with silty-clay lenses (1–2 m thick), which locally create semi-confined conditions. 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 of the shallow coastal aquifer. Given the nature of these reclaimed lands, the depth of the water table is generally low, between 0.5 and 1.5 m below ground level. The groundwater flow is mainly oriented in the vertical direction and is generally converging towards the drainage network, creating upconing conditions for the saline groundwater residing in the prodelta saline aquitard (Colombani *et al.* 2016a). Within this complex hydrogeological framework, three brackish lagoons, Valle Nuova, Valle Cantone and Lago delle Nazioni, have been studied to understand their relationship with the underlying shallow aquifer.

Valle Bertuzzi is composed of two brackish water sub-basins, Valle Nuova (about 1,406 ha) and Valle Cantone (about 555 ha). Valle Bertuzzi stretches from south of the Po di Volano to Lago delle Nazioni and the reclaimed lands of marsh lagoon deposits. Until 1998, the complex
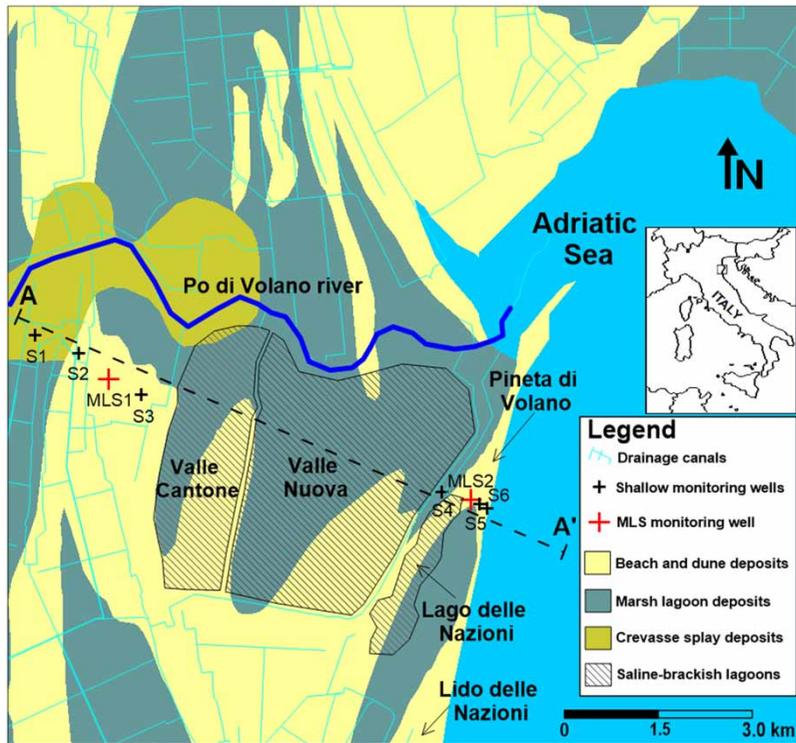
Figure 1 | Surface geological map of the study area. Also shown are the lagoons and the main drainage canals.

of Valle Bertuzzi was owned by the Company for Land Reclamation of Ferrara and was sold to two private companies for extensive fish farming. After the levee re-arrangement of Valle Cantone (1998–99), the complex of Valle Bertuzzi was hydraulically separated into the two sub-basins mentioned above, Valle Nuova and Valle Cantone. The grain size of valley bottom sediments ranges from silty-loam to silty-clay, although some elongated sandy paleo-dunes outcrop in both the lagoons. Overall, the permeability of the sediments constituting the bottom of Valle Nuova and Valle Cantone do not suggest large exchange between the lagoons and the shallow aquifer, except for the sandy stripes represented in Figure 1. The average water depth is about 0.5 m, but there are also areas of 1.5–2.0 m close to lagoonal sub-channels. Siphons ensure the surface water exchange and draining pumping stations connected with the Po di Volano in both the Valle Nuova and Valle Cantone remove the water excess. The average inflow in Valle Nuova is 7.5 Mm³/y, while in Valle Cantone it is 2.9 Mm³/y that correspond to 533 mm/y and to 522 mm/y, respectively.

Lago delle Nazioni is a brackish lagoon of artificial origin. It is located near the seaside town of Lido delle Nazioni (Figure 1). It extends between the Pineta di Volano to the east and Valle Bertuzzi to the west (about 97 ha). The basin was made for tourist and recreational activities in the mid-1960s, together with the excavation of the pre-existing Valle di Volano, a brackish back-barrier lagoon formed since the Middle Ages. The lagoon, which was originated by repeated episodes of ingression of marine waters, has changed form and size several times, following the coastal evolution, and it had been directly connected to the sea until the 1960s. The sediment grain size constituting the bottom of Lago delle Nazioni ranges from silty-loam to sandy, and along the shore the sediment prevalently consists of sand, suggesting a good degree of connection between the lagoon and the shallow aquifer. The average water depth is about 4.0 m, with a maximum depth of 5.5 m and large areas of 1.5–2.0 m (Mistri & Rossi 1999). Currently, the water exchange is ensured by a channel connected to the end portion of the Po di Volano River mouth by means of a siphon and a pumping station.

The average inflow in the Lago delle Nazioni is 0.5 Mm^3/y, corresponding to 515 mm/y. The climate of the site is humid subtropical with average daily temperatures ranging from 1 °C to 29 °C. Usually, July and August are the warmest and December and January are the coldest months of the year. However, Colombani *et al.* (2016b) have recently highlighted that the mean annual temperature increased from 13.3 °C (1950–2000) to 14.8 °C (2000–2015), leading also to an increase of temperature anomalies of approximately 2 °C in the last period (2010–2015). The rainfall regime is evenly distributed throughout the year, with mean annual precipitation of 650 mm. The mean annual potential evapotranspiration is quite similar to the mean annual precipitation, with a value of 640 mm (Aschonitis *et al.* 2015).

Field sampling and data availability

Two multi-level monitoring wells, belonging to the regional monitoring network of the Emilia-Romagna Region, and six shallow monitoring wells were used to monitor groundwater quality and level. The selected monitoring wells are located along a flow line and are aligned along the fore-stepping direction of the Holocene Po delta system (Figure 1). With respect to the geological map in Figure 1, the two multi-level monitoring wells are located in paleodunes characterized by medium to fine sandy deposits, while the shallow monitoring wells (2–3 m deep) are placed on different depositional environments, from crevasse splay deposits to marsh lagoon and dune deposits.

The groundwater was sampled in 2015 from monitoring wells using Solinst straddle inflatable packers for vertical profiles. The packers' assemblage consisted of a 20 cm long sampling window, set in the middle of two inflatable packers, and a centrifuge pump used for low flow purging (3–5 screen volumes) and water collection. Temperature and salinity were determined at the end of purging using a multi-parameter probe (Hydrolab MS-5). The measurements were converted into equivalent freshwater heads to take into account the variable density effects (Post *et al.* 2007). The data from 2002 to 2013 of temperature and salinity of Valle Nuova, Valle Cantone and Lago delle Nazioni were available online from the regional environmental agency reports (ARPAE 2016), while data for 2014 and 2015 were collected by the authors using a multi-parameter probe (Hydrolab MS-5). Thus, the complete dataset on the lagoons' temperature and salinity is from 2002 to 2015. The monthly climatic data from 2000 to 2015 were also available online (ARPAE 2016).

Evaporation losses from surface water were calculated using the simple mass transfer equation proposed by Rezapour Tabari *et al.* (2014):

$$E_w = 2.262 \times 10^{-8}(1 + 0.25v_2)\left[\exp\left(\frac{17.27T_w}{237.3 + T_w}\right) - R_h \exp\left(\frac{17.27T_a}{237.3 + T_a}\right)\right] \tag{1}$$

In this equation, E_w is the evaporation discharge per unit free surface area (m/s), v_2 is the wind velocity recorded at 2 m of altitude (m/s), T_w and T_a are the water and air temperatures (°C), R_h is the relative humidity of the air (−). In addition, evaporation rates were calculated using the Penman–Monteith (PM) equation (Allen *et al.* 1998), using the climatological data of the meteorological station. Evaporation from Lago delle Nazioni was approximated by multiplying reference evapotranspiration for short grass by a coefficient of 1.05 (Allen *et al.* 1998); while evaporation rates from Valle Cantone and Valle Nuova were calculated by multiplying reference evapotranspiration for short grass crop coefficients suggested by Allen *et al.* (2007).

Development and training of the ANN model

ANN is a computing tool constructed through many simple interconnected elements called neurons with the unique capability of recognizing underlying relationships between input and output events (Rogers & Dowla 1994). An ANN is arranged into discrete layers, consisting of input, hidden and output. A layer is a collection of neurons conveniently arranged in a dimensional array; each layer includes one or more individual nodes or processing elements. The ANN was trained through backpropagation, where at each training epoch the information coming from the input neurons was multiplied by its assigned weight. The result was fed into the activation function, here a bipolar sigmoid function, which fired when a certain threshold was reached and then sent the signal to the output neurons. At each run, the forecasting error was calculated and fed back into the ANN. The

challenge of applying an ANN to a time series forecasting problem is to choose the 'right' design of the ANN. This requires determining how many neurons should be in the input, hidden and output layers. Furthermore, if a neuron is presented with a signal coming from other neurons, the activation function teaches the neuron how to react to that signal. Using a trial and error technique, the ANN architecture was chosen to have four input neurons and six hidden layer neurons to best approximate the observed dataset. The calibration period was set from the beginning of 2002 to the end of 2010; this training period was long enough to provide information from time periods with different climatic characteristics. The validation period was set from the beginning of 2011 to the end of 2015, while likelihood of overfitting was minimized since the number of parameters in the network was much smaller than the total number of points in the training set.

To evaluate the goodness of the selected ANN to reproduce the observed data trend and capture the structural part of the time series in a way that robust extrapolations can be made, a series of statistical tools were used (Makridakis *et al.* 1998). The root mean squared error (RMSE), which is an often-used tool, penalizes large forecasting errors due to the squaring of the error. The mean absolute deviation (MAD) averages the magnitude of the forecasting absolute values of the errors. The MAD is very useful to measure the forecasting error in the same unit as the time series. The mean absolute percentage error (MAPE) is calculated by taking the absolute values of the error at each time period and dividing this by the actual observed value. Then, the average of these percentage errors is computed. The MAPE indicates how large the forecasting error is compared to the actual values of the time series. The mean percentage error (MPE) is calculated similarly to the MAPE. The MPE takes the residual at each time period and divides it by the actual value of the series. Finally, the average of the percentage errors is calculated. The MPE helps to decide whether a forecasting model is biased, meaning if the forecasting model consistently overestimates or underestimates the time series. Theil's U statistic compares the forecasted values to naïve forecasts. A naïve forecast is simply the last observed value taken as the prediction for the next period. The naïve forecast is the simplest forecast to make and the best guess to make when no information

is available. A 'good' forecasting model should outperform naïve forecasts. With Theil's U values greater than 1, the forecasting model is worse than guessing; with Theil's U values equal to 1, the forecasting model is about as good as guessing; while for Theil's U values lower than 1, the forecasting model is better than guessing. Finally, the Ljung–Box Q statistic (LBQ statistic) indicates whether the residuals of a forecasting model show structural patterns. The objective of a 'good' forecasting model is to 'produce' residuals that are randomly distributed. The LBQ statistic measures whether a set of autocorrelation coefficients are significantly different from autocorrelations that are all equal to zero. Randomly distributed residuals should not be autocorrelated to each other, therefore the LBQ helps to test whether some structural part remains in the time series that was not modelled by the forecasting model.

RESULTS AND DISCUSSION

Salinity and temperature temporal trends

Figure 2 shows the temporal trends of the mean maximum and minimum atmospheric temperatures in the last 16 years (2000–2015), compared with the observed temperatures in each lagoon. From a simple analysis of the monthly atmospheric temperatures, a clear trend in the mean monthly values is not evident, except for the minimum values that are slightly increasing. This is consistent with the analysis of Colombani *et al.* (2016b), who reported an increase of temperature anomalies of approximately 2 °C in the period 2010–2015 using time series that span from 1950 to 2015. The lagoons' temperatures oscillate seasonally following the atmospheric trend in all the three surface water bodies, with no apparent lag-phase with respect to atmospheric temperature variations. The linear trends depicted in Figure 2 show very little increase or decrease during the monitoring period of the lagoon temperatures. The temperature increase in Valle Cantone and Valle Nuova could be due to increased evaporation in these large and shallow water bodies, while the Lago delle Nazioni shows a slight temperature decrease probably due to a gradually increased groundwater inflow with lower temperature.
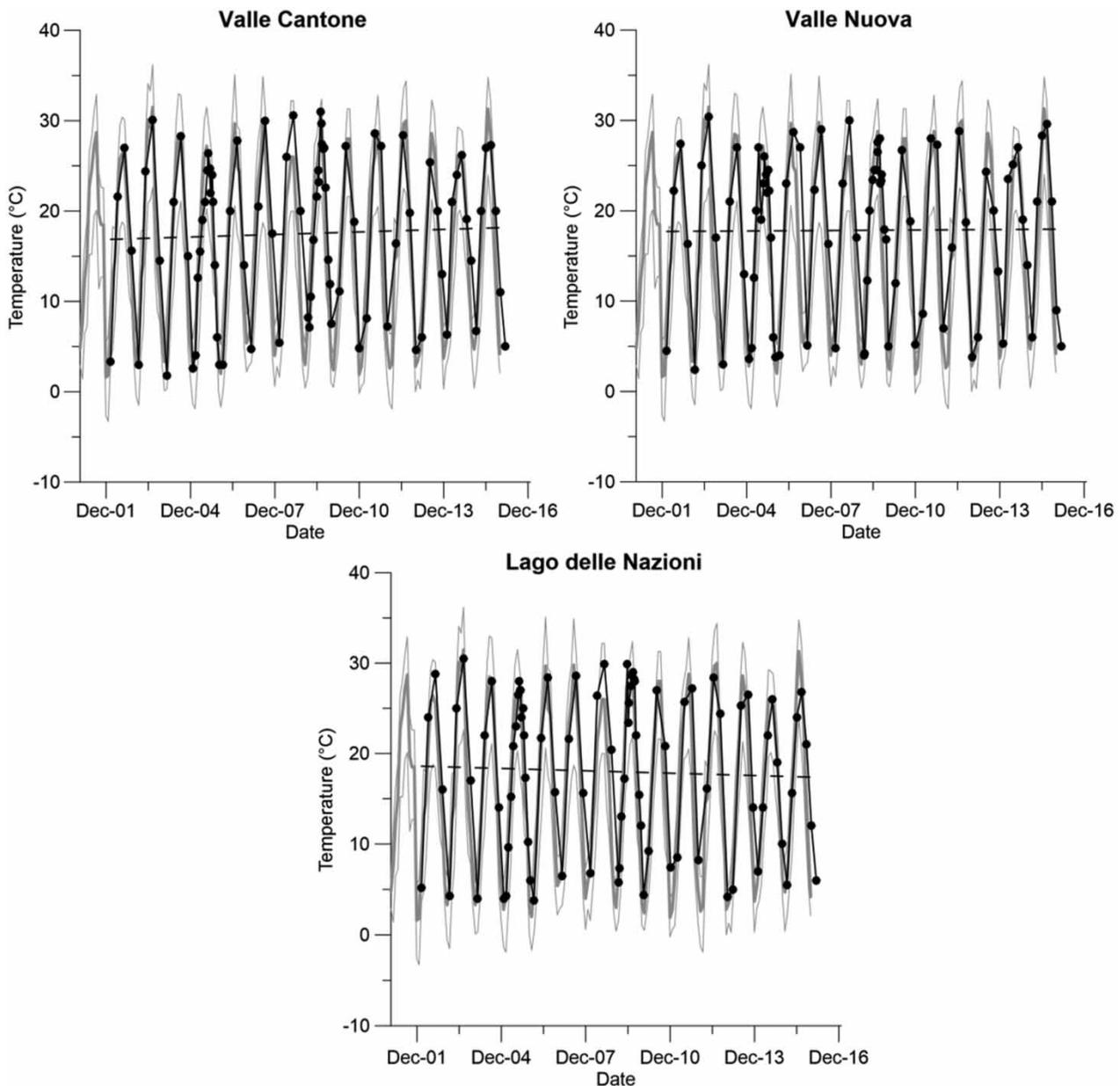
Figure 2 | Temporal trends of mean maximum and minimum atmospheric temperature (grey lines), observed lagoons' temperatures (black lines and dots) and their linear trends (dashed black lines).

Analysing the correlation coefficient (Table 1) and the covariance between water temperature and salinity in each lagoon, it seems that salinity increases with increasing temperatures in Valle Cantone and subsequently in Valle Nuova. While for Lago delle Nazioni a much weaker covariance suggests that the variations in salinity are related to other factors, like rainfall and inflow from both canal and groundwater.

Table 1 | Correlation coefficient and the covariance of water temperature and salinity in each lagoon

Site	Correlation coefficient	Covariance
Valle Cantone	0.61	42.15
Valle Nuova	0.54	22.41
Lago delle Nazioni	0.42	7.58

The correlation between temperature and salinity is best explained by a derived variable, the evaporation rate, shown in Figure 3. In fact, in this figure the seasonal trends of both evaporation rate and salinity in the shallow lagoons of Valle Cantone and Valle Nuova are clear; while, in Lago delle Nazioni, the seasonal salinity variations are much more smoothed and evaporation rates less pronounced. Figure 3 also plots for comparison the evaporation rates calculated with the PM equation; it should be noted that some discrepancies are present between the PM equation and Equation (1). The latter is considered more reliable since it does take into account the water temperature, while the PM equation retains only climatic data. Summer evaporation rates are often lower in the PM equation with respect to Equation (1), especially for Valle Cantone and Valle Nuova. Nevertheless, the PM equation performs better with respect to Equation (1) for wetlands like Valle Cantone and Valle Nuova with correlation coefficients of 0.93 and 0.95, while the correlation coefficient is only 0.89 for shallow lakes like Lago delle Nazioni. The uncertainties
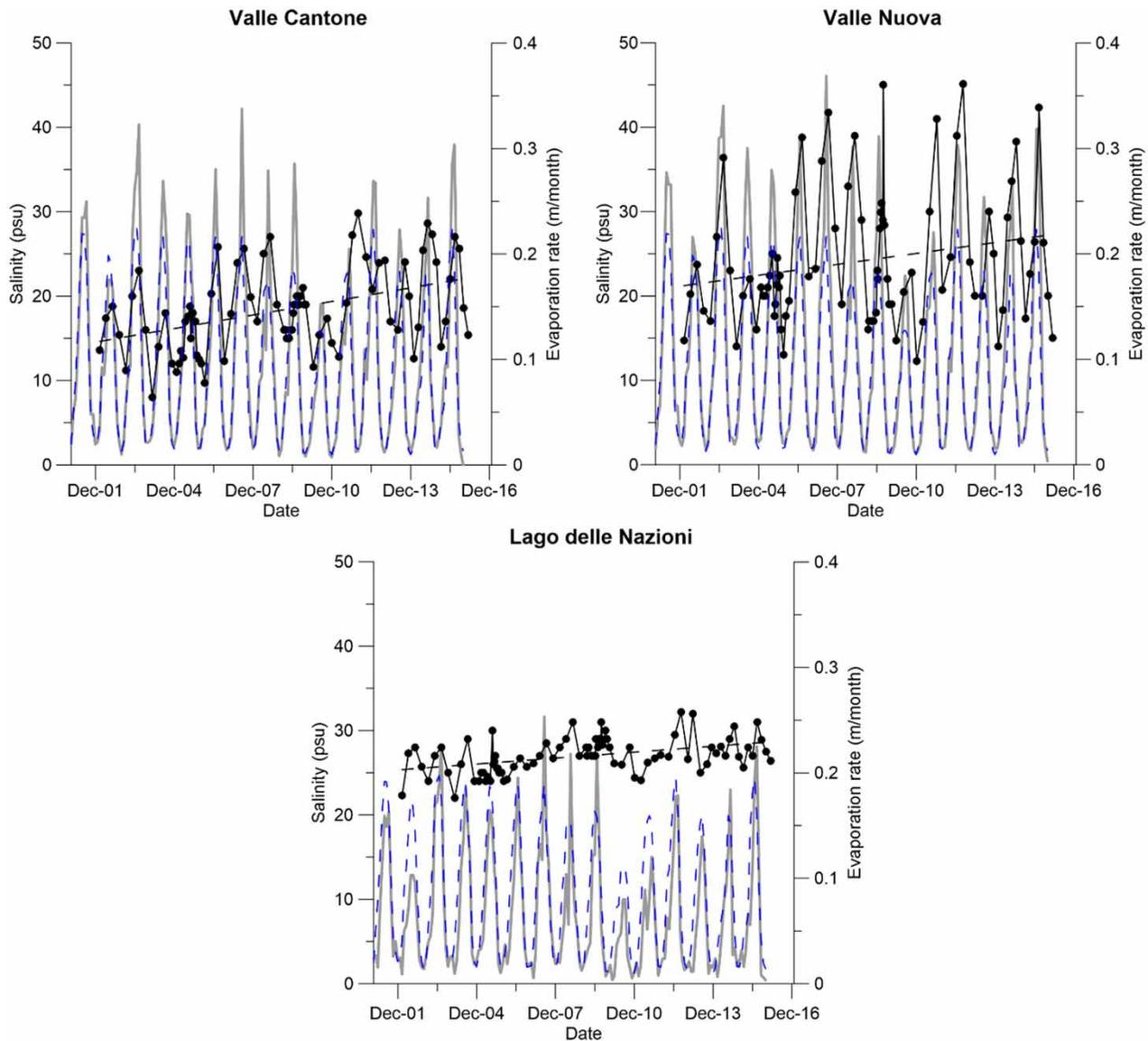

Figure 3 | Temporal trends of monthly evaporation rates calculated using Equation (1) (grey lines) and PM (dashed lines), observed lagoons' salinities (black lines and dots) and their linear trends (dashed black lines).

in calculating the evaporation rates are also reflected in the mean annual evaporation losses calculated in each lagoon (Table 2). In fact, the PM equation underestimates the evaporation losses in wetlands like Valle Cantone and Valle Nuova and overestimates it for shallow lakes like Lago delle Nazioni. In addition, the higher salinity values recorded in Valle Nuova with respect to Valle Cantone could be due to higher evaporation rates, or, to a higher infiltration capacity towards the shallow aquifer in Valle Cantone. The latter is likely due to higher permeability of the bottom sediments (prevalence of sand) present in this lagoon with respect to Valle Nuova (prevalence of silty-clay) (Figure 1). The higher infiltration capacity of Valle Cantone probably induces the owners to increase the freshwater inflow during summer periods to maintain a constant water level, thus avoiding the salinity peaks that are instead recorded in Valle Nuova. In any case, all the lagoons show an increasing trend in salinity over time.

Hydrogeological conceptual model

The reason of the salinity increase in all the lagoons can be explained by drawing a conceptual model of the interaction between the surface water bodies and shallow aquifer. Figure 4 depicts a cross section of the aquifer showing the equivalent freshwater heads measured in the monitoring wells. Here, some recharge areas are evident, like the dunes, paleo-dunes, the Valle Cantone and Valle Nuova lagoons, while discharge areas are the main drainage canals, Lago delle Nazioni and the beach too. Since the lagoons' water levels are kept essentially at a given stage throughout the year, with seasonal variations of less than 0.3 m, Valle Cantone and Valle Nuova can be considered permanently leaking water bodies, while Lago delle Nazioni

can be considered a permanently groundwater-fed water body (Table 3).

In addition, there is not a clear saltwater wedge intruding from the Adriatic Sea in this area, since the Po di Volano freshwater plume dilutes the salinity of the Adriatic Sea, as well as some clay lenses complicating the system. Finally, from the prodelta unit an upward saline flux is also present that locally can produce extremely elevated salinities (Colombani *et al.* 2016a). The proposed conceptual model is coherent with other studies located in similar environments around the world (Kirkegaard *et al.* 2011; Rasmussen *et al.* 2013; Haider *et al.* 2015).

Thus, from Figure 4 it is apparent that in Valle Cantone and Valle Nuova the increased salinities can be due to water loss in atmosphere rather than inflow from saline groundwater. On the contrary, in Lago delle Nazioni the major component of increased salinities is owing to groundwater seepage in the lagoon. From the above discussion of the results, it is apparent that understanding the sources of salinization (evaporation, seawater intrusion or paleo-salinity) is not trivial. In fact, a detailed monitoring of surface water levels, piezometric heads and salinities could not disentangle this difficult task, if not carefully planned. Using environmental tracers to support the hydrogeological monitoring can give valuable insights into different sources of salinities in deltaic and lagoonal environments (Re *et al.* 2014; Caschetto *et al.* 2016).

Lagoons' salinity forecast using ANN

Figure 5 shows the results of the ANN training, validation and prediction for all the lagoons studied here. The validation of the ANN was satisfactory for all three lagoons, as shown in Table 4. In fact, RMSE, MAD, MAPE and MPE values are all small compared with the average salinities and their range of variation in the lagoons, with the best performance in Valle Nuova. The Theil's U values are always below unity, indicating that the forecasting model is better than guessing. The LBQ below 70 indicates that residuals are randomly distributed and little autocorrelation is present.

Analysing the results of Figure 5, it can be noticed that Valle Cantone will slightly increase its salinity in the coming 15 years, but the forecasted salinity peaks will not

Table 2 │ Average annual evaporation losses calculated in each lagoon with Equation (1) and PM over the study period (2000–2015)

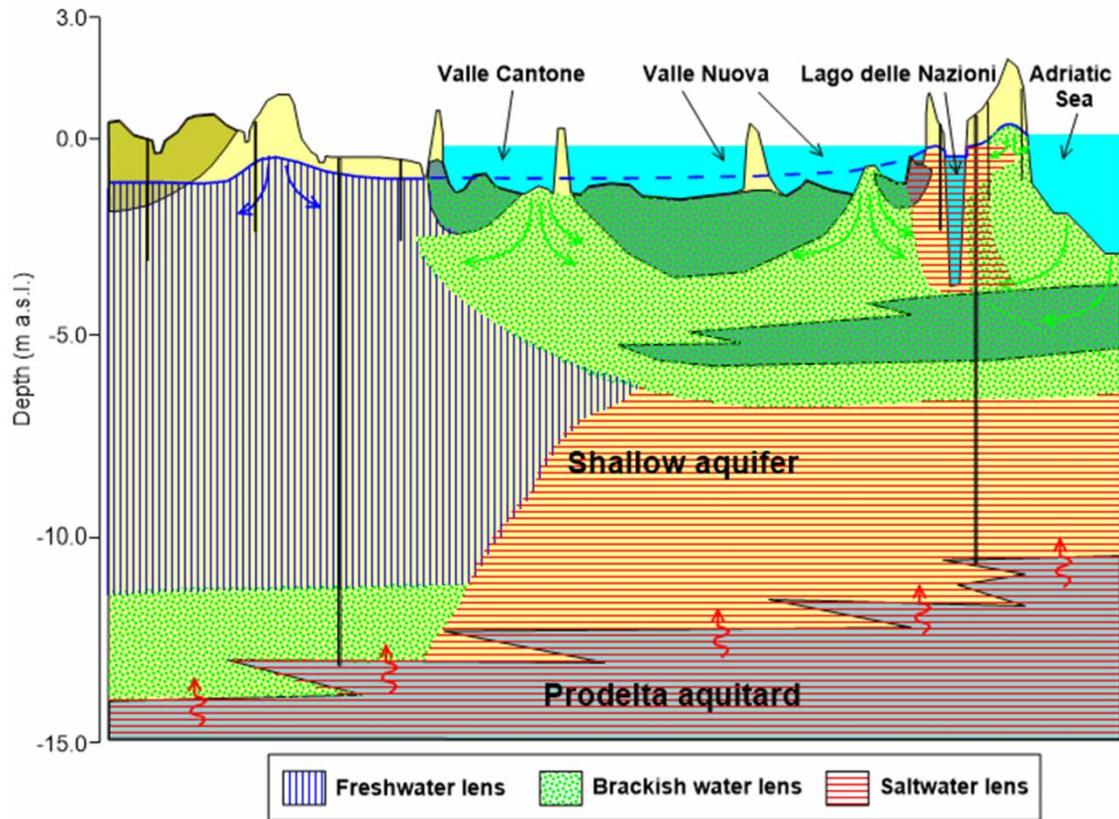| Site	Evaporation losses with Equation (1) (m³/y)	Evaporation losses with PM (m³/y)
Valle Cantone	6,821,700	6,321,300
Valle Nuova	18,885,200	16,014,000
Lago delle Nazioni	774,800	1,012,400

Figure 4 | The conceptual model of groundwater fluxes and salinities and their interplay with the surface water system along the AA' profile shown in Figure 1. The solid/dashed line depicts the water table and the arrows indicate the flow directions: vertical lines pattern is fresh, dotted pattern is brackish and horizontal lines pattern is saline water. The monitoring wells are represented with black lines and salinities are reported in Table 3.

Table 3 | Salinities of groundwater samples in each monitoring well (for location see Figure 1)

Depth above sea level	S1 (g/l)	S2 (g/l)	S3 (g/l)	S4 (g/l)	S5 (g/l)	S6 (g/l)	MLS1 (g/l)	MLS2 (g/l)
−2.0 m	1.3	0.8	1.2	20.3	20.4	17.7		28.3
−3.0 m	1.4	1.1	1.4	31.0	27.6	19.9	0.9	31.1
−4.0 m							1.0	32.6
−5.0 m							0.9	13.4
−6.0 m							1.0	7.0
−7.0 m							1.7	4.2
−8.0 m							1.9	11.8
−9.0 m							1.5	16.4
−10.0 m							4.2	27.5
−11.0 m							9.3	31.0
−12.0 m							15.6	

be higher than the actual peaks. Instead, Valle Nuova will possibly experience salinity peaks higher than the actual ones. In addition, ANN well reproduced also the large salinity shifts occurring over each year. Lago delle Nazioni will also face a general salinity increase in the near future, but with a smaller range of variation during the year. The forecasted increase of salinity in Valle Cantone will not only affect the ecological status of the lagoon, but will possibly contribute to leak saline waters towards the shallow aquifer, as shown in Figure 4. This will, in turn, be reflected in an increased seepage of saline groundwater in the nearby Lago delle Nazioni.

CONCLUSIONS

This study presented field evidences of increased salinities in coastal lagoons of the Po Delta region in Italy and the
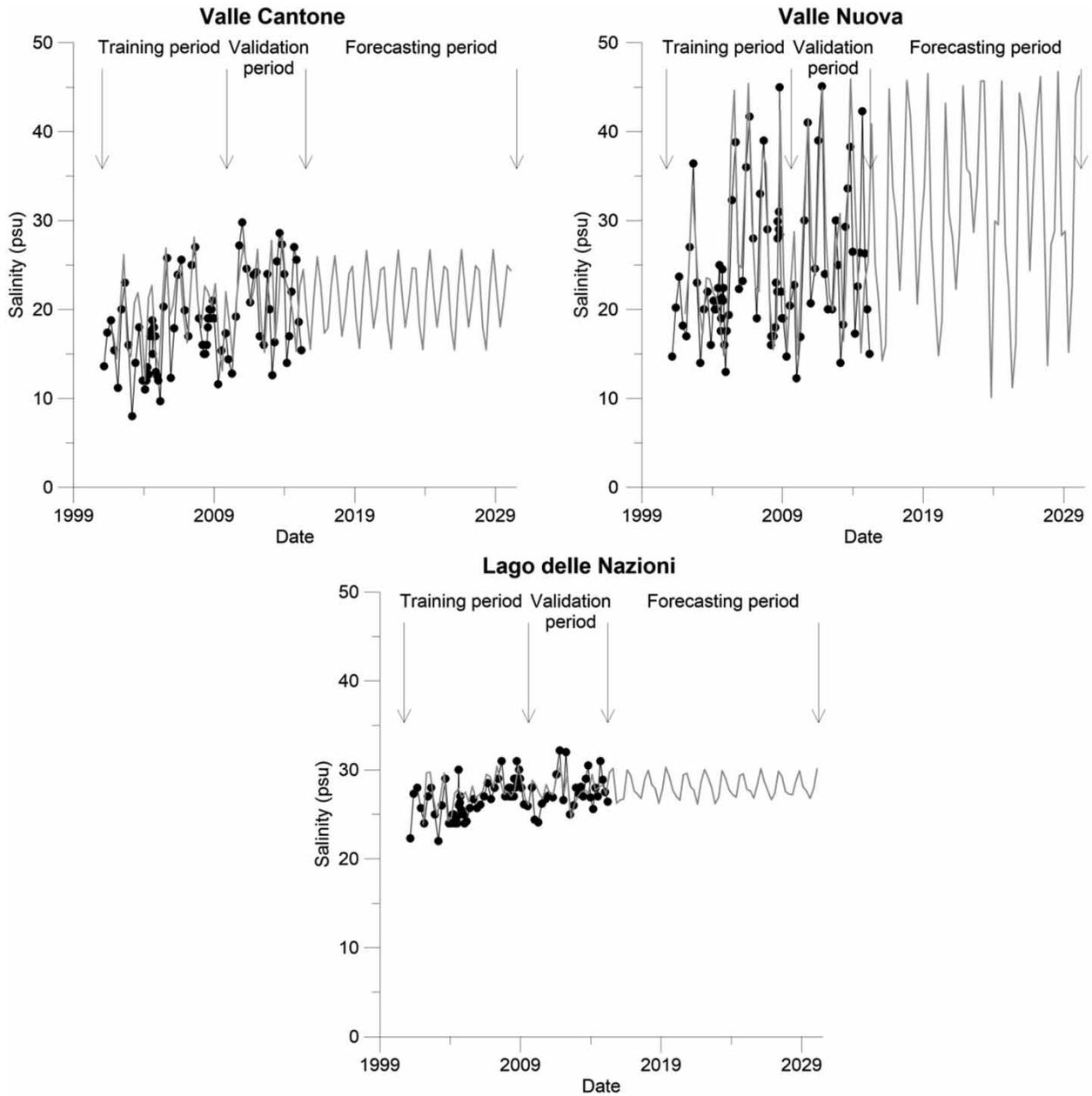
Figure 5 | Temporal trends of monthly salinities calculated by the ANN (grey lines), observed lagoons' salinities (black lines and dots); the training, validation and forecasting periods are also shown.

Table 4 | Statistical parameters used to evaluate ANN degree of fit to data in each lagoon

Site	RMSE	MAD	MAPE	MPE	Theil's U	LBQ
Valle Cantone	3.45	2.73	0.17	0.13	0.64	57.70
Valle Nuova	1.48	1.14	0.04	0.03	0.62	63.59
Lago delle Nazioni	4.08	3.18	0.14	0.07	0.43	54.80

subsequent ANN modelling to predict short–medium term salinity changes. The presented methodology could help water managers to better understand the processes of the surface/groundwater continuum in coastal lagoonal environments, and to put in place prevention and/or mitigation measures to avoid water resources deterioration. This study highlights that accurate and long-term monitoring is

needed to understand the mutual exchanges that characterize the coastal wetland-aquifer systems. In fact, the increase of salinity in surface waters could be of serious concern, especially for fish farming sensitive to sharp salinity increases, while the increase of salinity in groundwater could be detrimental for agriculture, since the upward groundwater flux could increase soil salinization. The main limitations of the applied methodology are the long-term datasets needed to perform these analyses and the need of high resolution vertical data to distinguish the salinization sources in the aquifer. The latter are extremely important to accurately define the conceptual model of the surface/groundwater continuum.

Finally, this study indicates that the shallow lagoons' water quality could be negatively affected by climate variability due to increased evaporation rates; this key point must be explicitly taken into account when modelling future scenarios of water resources management in coastal areas.

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