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Saltwater intrusion in the unconfined coastal aquifer of Ravenna (Italy): A numerical model

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Summary The Ravenna pine forests represent an historical landmark in the Po River Plain. They have great environmental, historical and tourist value. The San Vitale pine forest is located 10 km north of the town. It is surrounded by an urban area, the city industrial infrastructure and the waterworks of the agricultural drainage system. Most land in this area is below mean sea level. As a result, no natural freshwater hydraulic gradient contrasts the density gradient of saltwater. In the last century, many events (land subsidence; land reclamation and drainage; urban and industrial development and gas and deep groundwater extractions; coastal dune destruction) led to the intrusion of large volumes of brackish and saline groundwater. Today the freshwater in this coastal aquifer consists of low salinity water lenses floating on the saltwater wedge. This study is aimed at understanding how past and present human activities have affected the saltwater intrusion process in the phreatic aquifer and how the predicted future sea level rise will affect the salinisation process. We used a numerical model to quantify these effects on the density-dependent groundwater flow, hydraulic head and salinity distribution, seepage and salt load fluxes to the surface water system. The simulations show that over the last century artificial subsidence and heavy drainage started the salinisation process in the study area and a relative sea level rise will accelerate the increase in salt load in the coming decades, affecting the entire aquifer. Climatic conditions in the area result in limited precipitations throughout the year and preclude efficient aquifer recharge, especially in spring and summer when saltwater seepage is extensive. The lack of a continuous coastal dune system favors salt wedge intrusion.

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Introduction

The San Vitale pine forest near Ravenna represents an historical landmark in the Po River Plain. It extends north—south for 10 km, beginning north of Ravenna, on an area of about 16.6 km^2 (Fig. 1). It is surrounded by the urban area of Ravenna, the city industrial infrastructure and the waterworks of the agricultural drainage system. The surface hydrographic system includes the course of the Lamone River and a complex system of drainage canals that are managed by three drainage-pumping machines. In addition there are numerous small drainage canals within the pine forest, with floodgates regulating their flow. Various surface water bodies are present in the study area: the Valle Mandriole and Punte Alberete wetlands and the Pialassa Baiona, a semi-natural lagoon adjacent to the pine forest and directly connected with the sea (Fig. 1).

Several natural and anthropogenic features threaten this area: saltwater intrusion in the phreatic aquifer and seawater encroachment inland along the rivers; natural and anthropogenic land subsidence; direct contamination from water bodies open to the sea; destruction of coastal dunes and reduction of their barrier effect; land reclamation drainage systems; insufficient aquifer recharge and sea level rise.

The natural subsidence rate, due to the compaction of alluvial deposits, is 1 mm/year (Selli and Ciabatti, 1977; Pieri and Groppi, 1981); in the last century, however, the main topographical variation of the area has been due to anthropogenic subsidence. Since 1950 and during the industrial development of Ravenna (1970—1980), gas winning and deep groundwater exploitation have led to a fast subsidence rate (for the values, see Sections ''The period 1700—1920 AD: natural development'' and ''The period 1920—1996 AD: severe land subsidence'') (Preti, 2000). Land subsidence has dropped most of the territory below mean sea level, modifying the river and normal groundwater flow regimes. A drainage system is necessary to lower the phre-

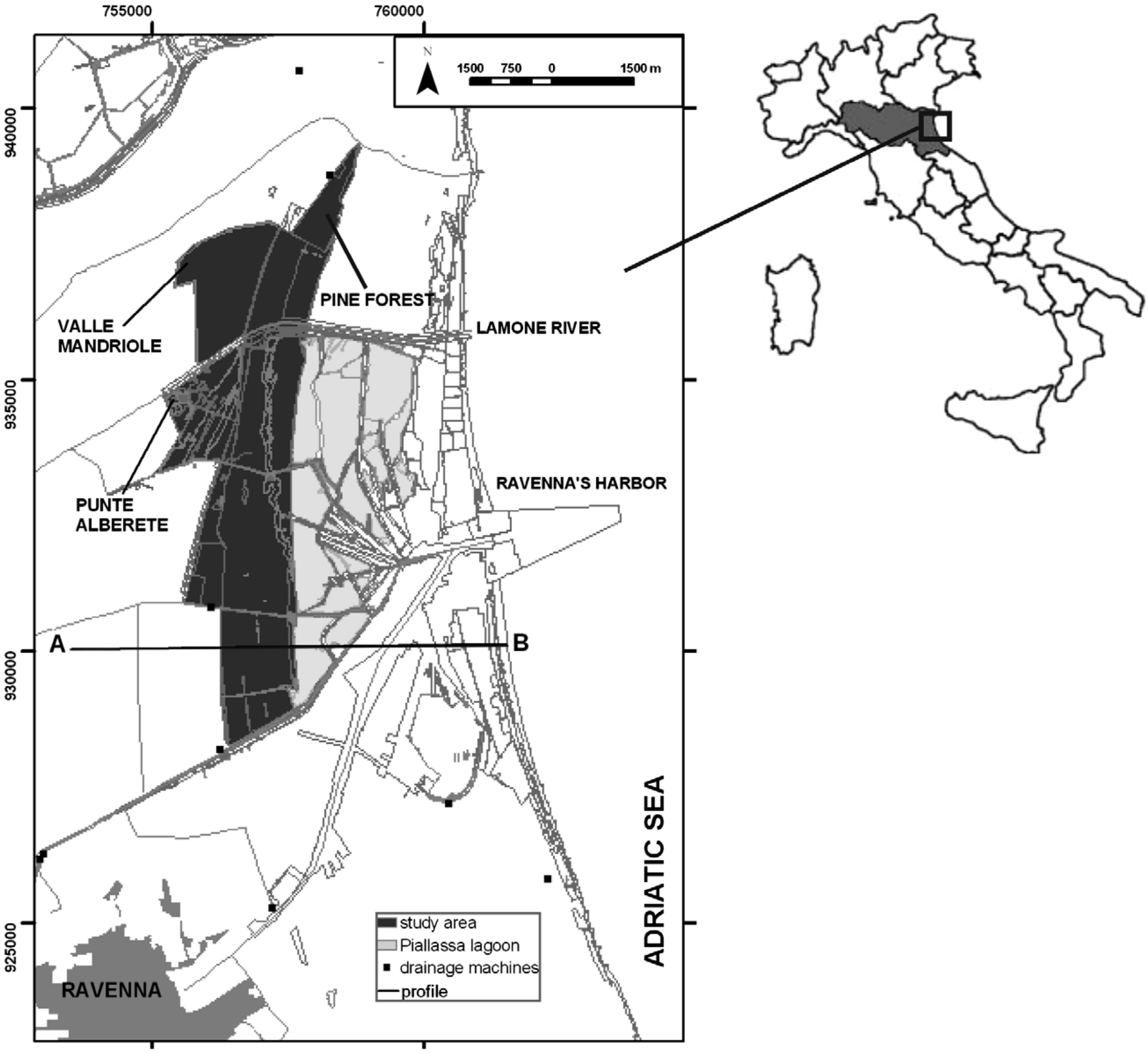

Figure 1 Location of the study area. (*Note:* the location of representative 2D profile selected for the numerical model.)

atic level and keep the agricultural land dry. A second objective of the drainage system is to keep tree roots in the coastal areas above the watertable. The result of the drainage system management, however, is an unstable phreatic level in the aquifer that is not able to contrast saltwater intrusion. In addition, it is not helping much to keep the pine forests healthy, as they are sensitive to salinity. Since the phreatic groundwater level in the area is kept very low and the aquifer is in communication with the sea, saline and brackish groundwater intrudes landwards.

The focus of this paper is on saltwater intrusion in one specific coastal groundwater system where a non-uniform density distribution occurs. The present and future distributions of fresh, brackish, and saline groundwater will be discussed. Firstly, development of the area is discussed, followed by a description of the computer code MOCDENS3D that is used to simulate variable-density groundwater flow in 2D. The results of different scenarios are discussed and some conclusions for possible remediation measures are drawn.

General description of the area

Genesis of the San Vitale pine forest

The Romagna coastal plain, where the San Vitale pine forest is located (Fig. 1), comprises the southeastern part of the wider Po River Plain. Rizzini (1974) and Amorosi et al. (1999) have described the late Quaternary depositional history of this coastal plain.

The Holocene geomorphic evolution of the pine forest area has been controlled by continental (Würmian) and marine deposition (post Würmian transgression) in a coastal environment of the Po Plain (Amorosi et al., 1999; Bondesan et al., 1995). Above the Pleistocene alluvional-plain deposits, the Flandrian transgressive phase (18–5.5 kyear) deposited back-barrier fine-grained deposits and transgressive barrier sands. At peak transgression, approximately 5.5 kyear, the coastline was about 20 km landward of its present position. During the subsequent highstand phase, a progradational pattern of marsh-lagoonal (delta plain) clays, beach-ridge (delta front) sands and shallow-marine (prodelta) clay–sand alternations, was deposited (Marchesini et al., 2000) (Fig. 2). The deposits making up the phreatic aquifer are typical of coastal and delta areas with sand dunes, characterized by north–south orientation, which today are present up to 30 km inland. The San Vitale pine forest was planted by monastic communities on fossil dunes formed in the period 10th–15th century AD. Today the alternation of highs and lows in the topography, which correspond to different coastlines and to a different stage in the evolution of the Po Delta, affects the distribution of vegetation.

The Piallassa Baiona lagoon is located at the eastern boundary of the pine forest. This brackish coastal lagoon was formed three to four centuries ago. During the 18th century, in fact, in its place there was a wide inlet from the Primaro Port, in the North, to the ancient mouth of the Montone River in the South (Fig. 3). This coastal lagoon was formed by artificial interventions related to optimization of the canal and river regime and to other water management interventions needed for construction of the port of Ravenna (Bondesan, 1990). The lagoon is now open to the sea and artificial embankments divide it into several brackish or shallow freshwater basins linked by canals and locks. These canals converge in a main canal (the Candiano Canal) which runs directly to the sea.

Aquifer characterization

In order to characterize the phreatic aquifer, the general lithostratigraphic reconstruction has been done indirectly via processing of data from shallow and deep penetration tests (Ermes, 2002). Two main sandy units characterize the aquifer's stratigraphy: a relatively thick medium-grained sand shallow unit (from 0 m to −10 m a.s.l.) and a lower fine-grained sand unit of a lesser thickness (from − 21 m to −26 m a.s.l.). These two bodies are separated by a clayey-silt and sandy-silt unit (from −10 m to −21 m a.s.l.). Lastly, the Würmian continental silty-clay basement is at a depth varying from −20 m in the western sector to −30 m at the present shoreline (Veggiani, 1971, 1974) (Fig. 2). The lithologic reconstruction of the phreatic aquifer shows a dominant sand composition beneath the forest with high hydraulic conductivity values (about 10^{-3} m/s). The quantity of sand decreases in the western part, towards the agricultural and reclamation areas. Clay–silt content increases with depth; at 25–30 m depth, a compact

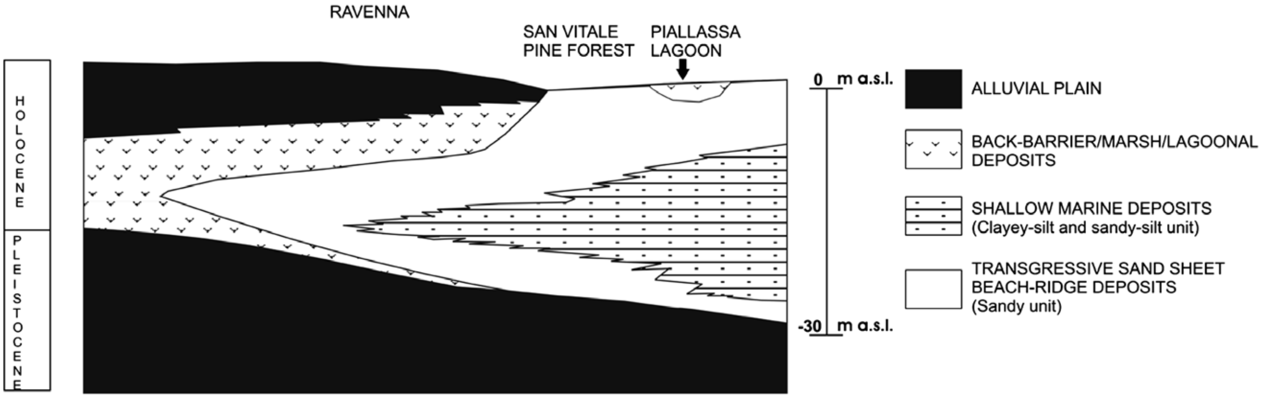

Figure 2 Lithostratigraphic reconstruction of the study area (modified from Amorosi et al., 1999; Marchesini et al., 2000).

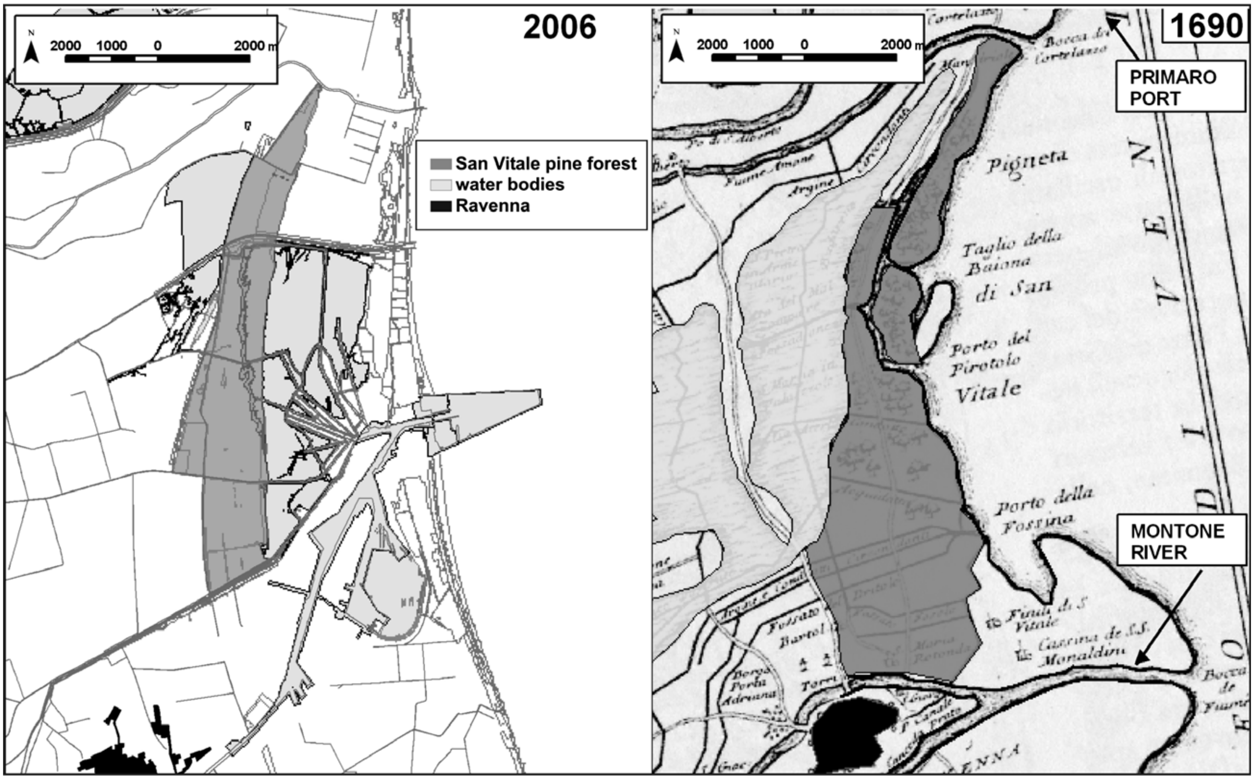

Figure 3 Extent of the area in 2006 (left) and the same area in 1690 (right). Note the absence of the Piallassa lagoon in 1690 and the different area of the San Vitale pine forest and water bodies.

grey clay level forms the phreatic aquifer basement (acquiclude).

Monitoring data over the period of one year (from October 2004 to October 2005) and geo-electrics resistivity surveys, which were carried out in the same area during 2005, suggest that the brackish—freshwater interface is close to the surface. Its average depth is 5—6 m below the mean sea level, but it can go down to 11 m depth where there are high-infiltration recharge areas, as in the fossil dunes of the pine forest (Sabia et al., 2005). Below 15—20 m a.s.l. some saltwater saturated lenses of sand, probably in hydraulic connection with one another, reach down to the clay basement. The brackish—freshwater interface does not reach the bottom-confining layer and does not prevent saltwater intrusion into the aquifer.

The surface salinity maps evidence that salinity is high (about 10—15 g/l) along the eastern boundary of the pine forest (Fig. 4a and b). Here the pine forest borders directly on the brackish—saltwater bodies of the lagoon, favoring saltwater intrusion. Salinisation is also high along the river Lamone, due to extensive landward saltwater encroachment.

The watertable maps (Fig. 5a and b) show that the lowest watertable is found in the northern and southern parts of the pine forest where drainage is strong in order to keep the farmlands dry. As a result, the hydraulic head is controlled by the drainage system and in the largest part of the aquifer it is too low to stop saltwater intrusion from the brackish lagoon. The only areas where the watertable is above mean sea level are along the embankments of the main rivers.

Numerical simulation

A numerical model is used to simulate the transient groundwater system of the study area. The model can simulate transient groundwater flow of fresh, brackish and saline groundwater in the coastal area where non-uniform density distribution occurs. Numerical simulation is used to assess the effect of past and present human activities on the saltwater intrusion process in the coastal aquifer, and the effect of natural processes (e.g., future sea level rise) on the salinisation process. In order to improve surface water management in the whole area, we numerically tested several scenarios to determine the main factors affecting the phreatic aquifer, such as land reclamation and lowering of phreatic level due to land subsidence. The details of each simulation are better explained in the text below (Section ''Results of numerical simulation'').

Computer code

MOCDENS3D (Oude Essink, 1998, 1999, 2001) consists of two integrated codes:

- Computer code MOC3D (Konikow et al., 1996) which simulates 3D solute transport in flowing groundwater. Using the method of characteristics, this code solves the transport equation on the basis of the hydraulic gradients computed with MODFLOW for a given time step. Implementation of the method of characteristics uses particle tracking to represent advective transport. Dispersive transport is solved by the finite difference method.

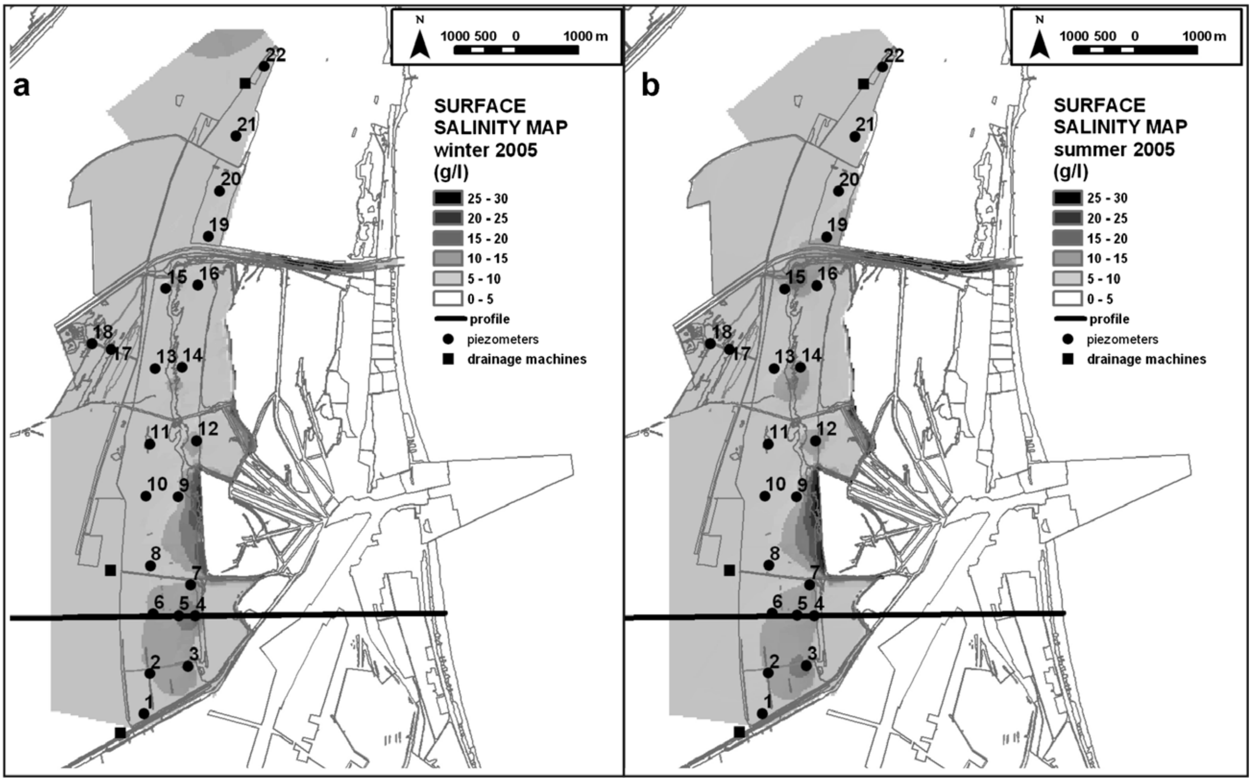

Figure 4 Seasonal surface salinity distribution for the winter (a) and summer (b) period (2005) (derived by Surfer, Kriging method).

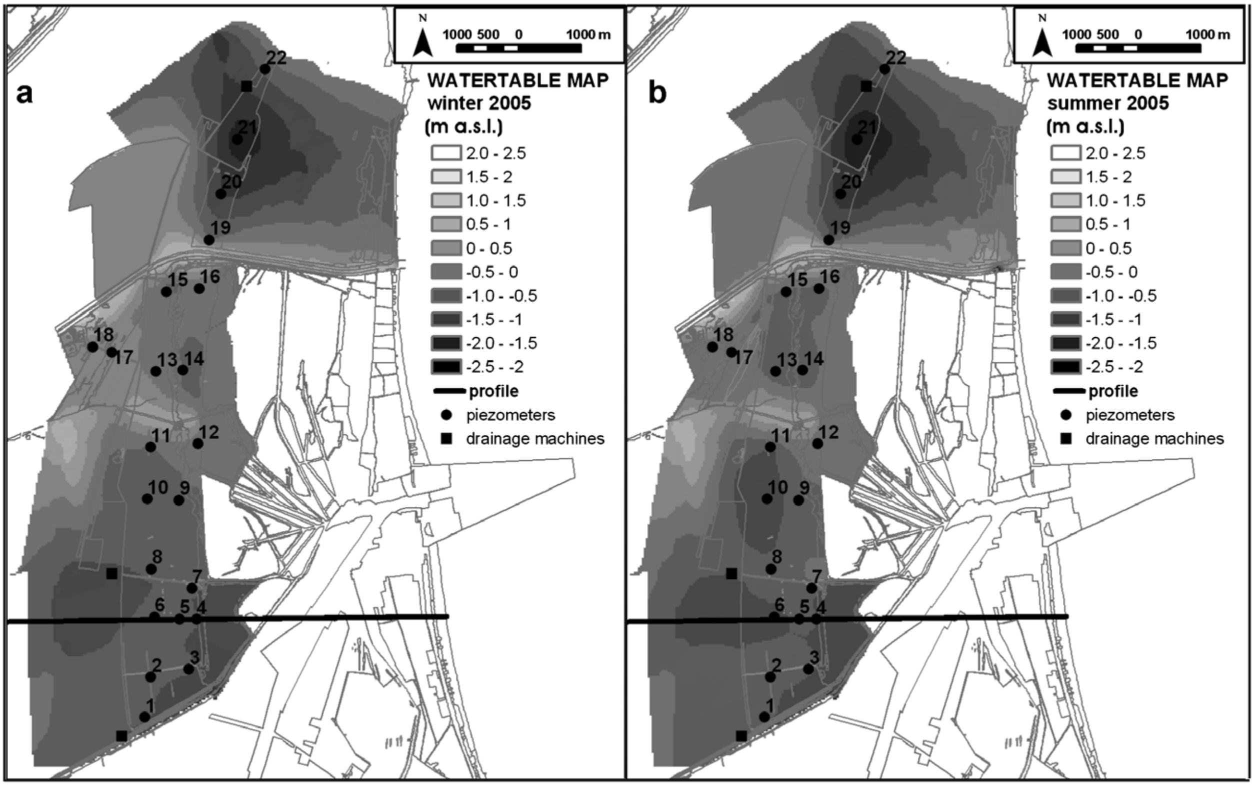

Figure 5 Watertable maps for the winter (a) and summer (b) period (2005) (derived by Surfer, Kriging method).

- Computer code MODFLOW (McDonald and Harbaugh, 1998; Harbaugh and McDonald, 1996), a 3D groundwater flow model that uses implicit finite-difference method to solve the transient flow equation (McDonald and Harbaugh, 1998; Harbaugh and McDonald, 1996). The concept of freshwater head ϕ_f is introduced to take into account differences in density when calculating the heads:

$$\phi_f = \frac{p}{\rho_f g} + z, \tag{1}$$

where ϕ_f is the freshwater [L], ρ_f is the reference density, usually the density of fresh groundwater at reference chloride concentration C_0 [ML^{-3}], p is the pressure [ML^{-1}T^{-2}] and z is the elevation head [L]. See Oude Essink (1999, 2001) for a detailed description of the adaptation of MODFLOW to density differences.

Model development

For the numerical computations the following hydrogeological parameters were considered: site geometry, petrophysical characterization (hydraulic conductivity, porosity and thickness of layers), position and characterization of rivers and drainage canals, natural groundwater recharge, boundary and initial conditions, piezometric heads corrected for density differences, observation wells and distribution of salinity concentration in the system. The selected profile (Fig. 6) is located in the southern part of the pine forest where the highest values of salt concentration and subsidence occur.

The groundwater system consists of a 2D profile 8000 m long and 60 m deep. The profile has been divided into elements 50 m in length and 0.5 m in depth. In total the grid contains 19,200 elements: $n_x = 160$, $n_z = 120$, where n_i denotes the number of elements in the i direction. Each element contains nine particles to solve the advection term of the solute transport equation with the method of characteristics; initially 172,800 particles were used in the model.

The time step Δt to recalculate the groundwater flow equation is set to one month. The total simulation time is different for each scenario.

Considering geological data (Ermes, 2002), slug tests and the geo-electric resistivity surveys that we carried out in the pine forest (2004—2005), we have characterized the aquifer and its geometry (Fig. 7). The figure shows the subdivision of the phreatic aquifer into five main units and reports their hydraulic conductivity K_x and thickness.

The anisotropy ratio, vertical versus horizontal hydraulic conductivity K_z/K_x, is 1/3 for all layers. The effective porosity n_e is 25% (Regione Emilia-Romagna and ENI-AGIP, 1998). The longitudinal dispersivity α_L is set equal to 0.1 m, whereas the ratio of transversal to longitudinal dispersivity is 0.1. All these values are typical for these kinds of aquifers.

For a conservative solute such as chloride, the molecular diffusion for porous media is taken as equal to 10^{-9} m^2/s.

The data for the model were obtained from our monitoring campaigns and from the ''Emilia-Romagna'' Region database (regarding geological data, petrophysical parameters and groundwater information) (Regione Emilia-Romagna, 2005). The data have been converted to the MODFLOW format. The so-called DRAIN, RIVER and RECHARGE packages of the MODFLOW module are applied in the model to represent interaction with the surface water system. The DRAIN package is designed to simulate water discharge from the aquifer by way of ditches or agricultural drains. Where this package is used, the drain water levels vary from 0 m in the agricultural area to −0.4 m in the drain canals within the pine forest, and down to −1.6 m at the waste disposal site in the western part of the profile. The DRAIN package takes into account the features of the drained agricultural areas that are subject to drainage by pumping machines. The DRAIN conductance varies from 0.75 to 1.44 m^2/day and depends on the drainage resistance and on the surface area of the model element. The RIVER package, designed to simulate the interaction of flow between surface water features and groundwater system, is used only for the agricultural area, and the water level is set to −0.5 m with a river

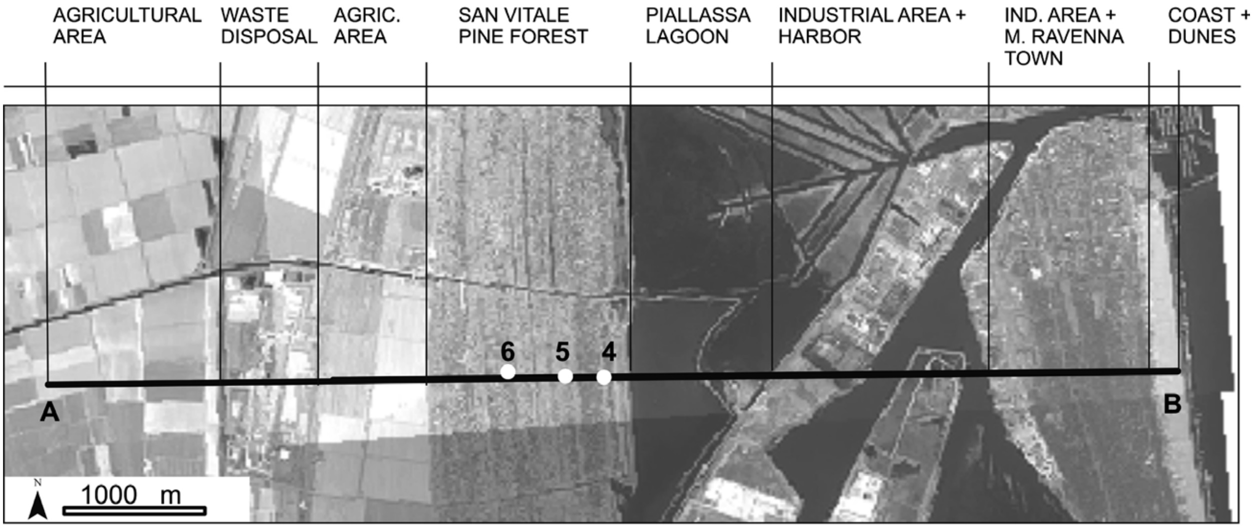

Figure 6 Selected profile in the southern part of the pine forest (note the observation wells: piezometers No. 4—6).

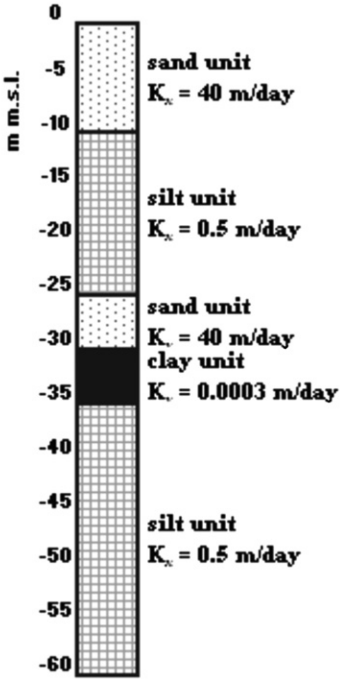

Figure 7 Simplified subdivision of the permeable aquifer and hydraulic conductivity values (K_x), as used in the numerical model.

conductance of 0.4 m^2/day. RIVER conductance depends on hydraulic conductivity and on cross-sectional area of flow. Rivers and drain canals are present at the top of the land surface and they are used or not used, depending on the scenario. In addition, the levels of the rivers change in the simulations due to the subsidence taken into consideration. The RECHARGE package, designed to simulate natural groundwater recharge to the groundwater system, was created using precipitation data (Euro Weather, 2006), runoff, and actual evapotranspiration for different land uses in the study area. At the top of the system, the natural groundwater recharge is different for each kind of land use: pine forest, industry, agricultural area or sand dune area. It varies from a maximum of 0.046 m/month in the sand dune area to a minimum value of 0 m/month in the industrial and urbanization area. These local and seasonal fluctuations in the natural groundwater recharge cause fluctuations of hydraulic head. Hydrostatic conditions are implemented at the four sides of the model with the GENERAL HEAD BOUNDARY package. The bottom of the system is considered a no-flow boundary. For the top system, the mean sea level reference is the ''topographic zero'' of IGMI (Italian Geographic Military Institute) (Surace, 2002). The sea water level is constant in time for all scenarios with the exception of the last simulation, which will be described later (Section ''The period 2006—2106 AD: future sea level rise and land subsidence''), where the sea level rise for the future has been implemented. The watertable level varies along the profile from a maximum value of 0.6 m a.s.l. in the coastal sand dune areas or under local fossil dunes in the pine forest, to a minimum value of −1.5 to −1.6 m in the western part, close to the drainage pumping machine and waste disposal site.

Time evolution was simulated by changing the initial input and parameters for each simulation, as long as we were able to reconstruct the present situation (2006) starting from the initial situation (1700).

The location of the observation wells has been used in the model in order to correlate computed values and monitoring data (October 2004—2005).

Seasonal variations in seawater concentration have been implemented using field monitoring data from Ulazzi (Ulazzi, 2003). At the top of the vertical sea side-border and in the salty water bodies (such as harbor canals, lagoon, etc.) saltwater concentration has been set at the following values: 17.5 g/l for the winter period, 33.0 g/l for the autumn period, 29.6 g/l for the spring period and 34.1 g/l for the summer period. The value of 25.0 g/l has been used as an average value for the rest of the layers at the sea side-border.

Model calibration

Calibration was focused on freshwater heads and chloride concentrations in the hydrogeologic system using the trial and error method. A few major iteration steps were executed, by one-by-one changing the hydraulic conductivity of some units, the general head boundary, river and drain conductances, the initial chloride concentration and the anisotropy (K_z/K_x).

Unfortunately, the available measurements are insufficient to obtain a good correlation in the deeper part of the aquifer. The problem is that we had a continuous and reliable dataset only for the period of one year, for a small part of the study area, and other data are not easily available for the rest of the system in other periods. In order to improve the correlation between simulation results and measurements, collection of deep groundwater data should be intensified and the salinisation of the subsoil and the salt load in the pine forest area should be monitored for a longer period of time. The mean error between computed and measured freshwater heads, corrected for density differences, is 0.39 m. Sometimes the difference is quite large, especially during the spring, in the months of April—June. These differences are due to the complexity of the system, an inaccurate initial density distribution and an insufficient and not uniform density of data to calibrate the model.

It was not possible to simply let the system set its own initial density distribution by simulating the current stress situation for a very long time, since the system at present is not yet in a state of equilibrium. In order to reduce errors, we decided that the most productive way was to go back in time (1700) and try to simulate all relevant events that occurred in the past (natural processes and anthropogenic activities). The modeling starts at 1700 with an estimated initial density distribution based on the trial and error method.

Results of numerical simulation

Four main scenarios were selected to understand the evolution in this area. (In all simulations we cut the depth in the figures at −30 m, because below that level the variations in concentration are not significant and the aquifer is not unconfined.)

The period 1700—1920 AD: natural development

This case serves as a reference case to understand the effect of natural subsidence on the coastal aquifer and on the geometry of the brackish—freshwater interface. Starting with the geometry for the year 1700, in fact, the different rates of natural subsidence accepted for the zone of Ravenna were implemented. Various studies have shown, for the Ravenna area, values of natural subsidence equal to 1 mm/year (Selli and Ciabatti, 1977; Pieri and Groppi, 1981) for the period 1700—1890 and 4 mm/year (Preti, 2000) for the period 1892—1950.

At the initial situation (1700 AD) the hydrogeologic system contains saline (>25 g/l) and brackish (10.0 g/l) groundwater. In that period, the surface morphology of the area and its water management were completely different. The pine forest, in fact, was wider, approximately 3 km as against the present day 1—1.5 km. The Piallassa lagoon did not exist and the pine forest extended right to the sea. Moreover, in the western part, there were the wetlands of Savarna and Sant'Egidio, which were swamps with fresh—brackish water (Provincia Di Ravenna, 2005) (Fig. 3). The DRAIN and RIVER packages were not used in this case. Furthermore, a different land use package was created in order to take into account the presence of the swamp and the lack of industrial and agricultural areas. Based on the data of total subsidence in Ravenna, an initial phreatic water level of +1.4 m a.s.l. was implemented at the top of the system, both in the pine forest and in the swamps.

Many approximations of the real situation were introduced into this simulation, because in this period there were considerable modifications of the morphology (creation of the salty lagoon, land reclamation, etc.), and there is not much previous information about groundwater salinity. This simulation is used in order to obtain more realistic output with an original density distribution and a freshwater—brackish water interface, which will be used as a start point for the other scenarios.

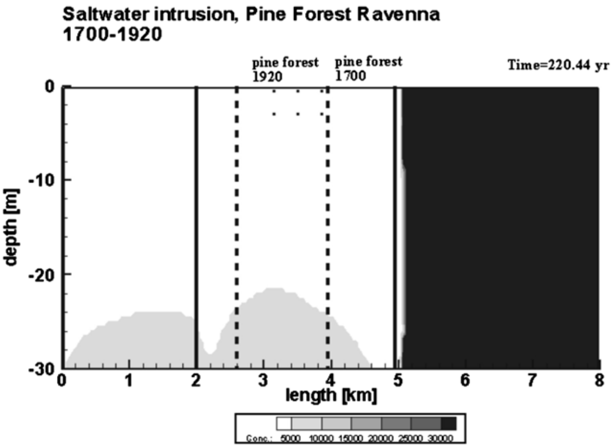

Figure 8 Final salt concentration distribution (g/l) in the aquifer at time 1920, after 220 years of simulation. Note: the different width of the pine forest in 1700 (solid line), and in 1920 (dashed line).

Fig. 8 shows that, in ''natural conditions'', without an artificial drainage system and anthropogenic subsidence, the phreatic aquifer has a hydraulic head that is able to contrast the saltwater intrusion, creating a fresh—brackish water interface close to the coastline and down to the impermeable basement of the aquifer. In the time frame that we have investigated here, natural subsidence does not affect the groundwater aquifer and its salinisation.

The period 1920—1996 AD: severe land subsidence

This scenario is used as a reference case to quantify the effect of saltwater intrusion due to past human activities (such as industrial development and land reclamation) and their effects (anthropogenic subsidence, drainage, etc.). In those years, land reclamation became very invasive on the coastal system by creating a complex drainage system that turned the wetland adjacent to the pine forest into agricultural land. Since 1930 the coast has been transformed rapidly by tourism and urban development (marinas and beach-bar/bathing establishments), which continued in the 1960s—1970s with building of the Ravenna harbor and a big industrial district southeast of the pine forest. So pressure on the environment in general, and on the groundwater in particular, became substantial. During this heavy industrial development, extraction and deep groundwater exploitation induced a strong artificial land subsidence that has caused the area adjacent to the sea to sink below sea level. The output of the previous simulation (1700—1920) was therefore used as an initial condition, and the DRAIN and RIVER packages used for the agricultural area and the pine forest. The hydraulic head in the drainage canals and rivers changes according to the different rates of subsidence.

The subsidence rates assessed in the area, which have been used for this simulation, are (Preti, 2000): 4 mm/year for the period 1920—1950, 25 mm/year for the period 1950—1970, 35 mm/year for the period 1970—1980, and 5 mm/year for the period 1980—1996.

A ''land use'' package was created in order to take into account the changes in land use: agricultural area and industry district, the harbor canals, coastal dunes, etc. For each kind of land use, different values of groundwater recharge have been calculated and implemented in the model.

The model suggests that the saline groundwater enters the system with an average velocity in the order of 20—30 m per year from the Piallassa and from the bottom. The low phreatic level in the industrial area cannot contrast saltwater intrusion from the nearby harbor canals and from the lagoon (Fig. 9). Because of industrial development and urbanization near the coast (Marina di Ravenna), natural recharge areas in the eastern part of the system are reduced. This reduced infiltration causes an inland shift of the water wedge that reaches 1 km inside the pine forest, at the bottom of the aquifer. Saltwater intrusion seriously increased during the 1970s (Fig. 9b) and 1980s (Fig. 9c), especially in the pine forest where the subsidence rate was greater. Lowering of the phreatic water level affects groundwater flow and solute transport. The drainage system, in fact, dominates the hydraulic head and the flow process in the pine forest and the agricultural area. The low values of the hydraulic head in these areas cause a displacement of

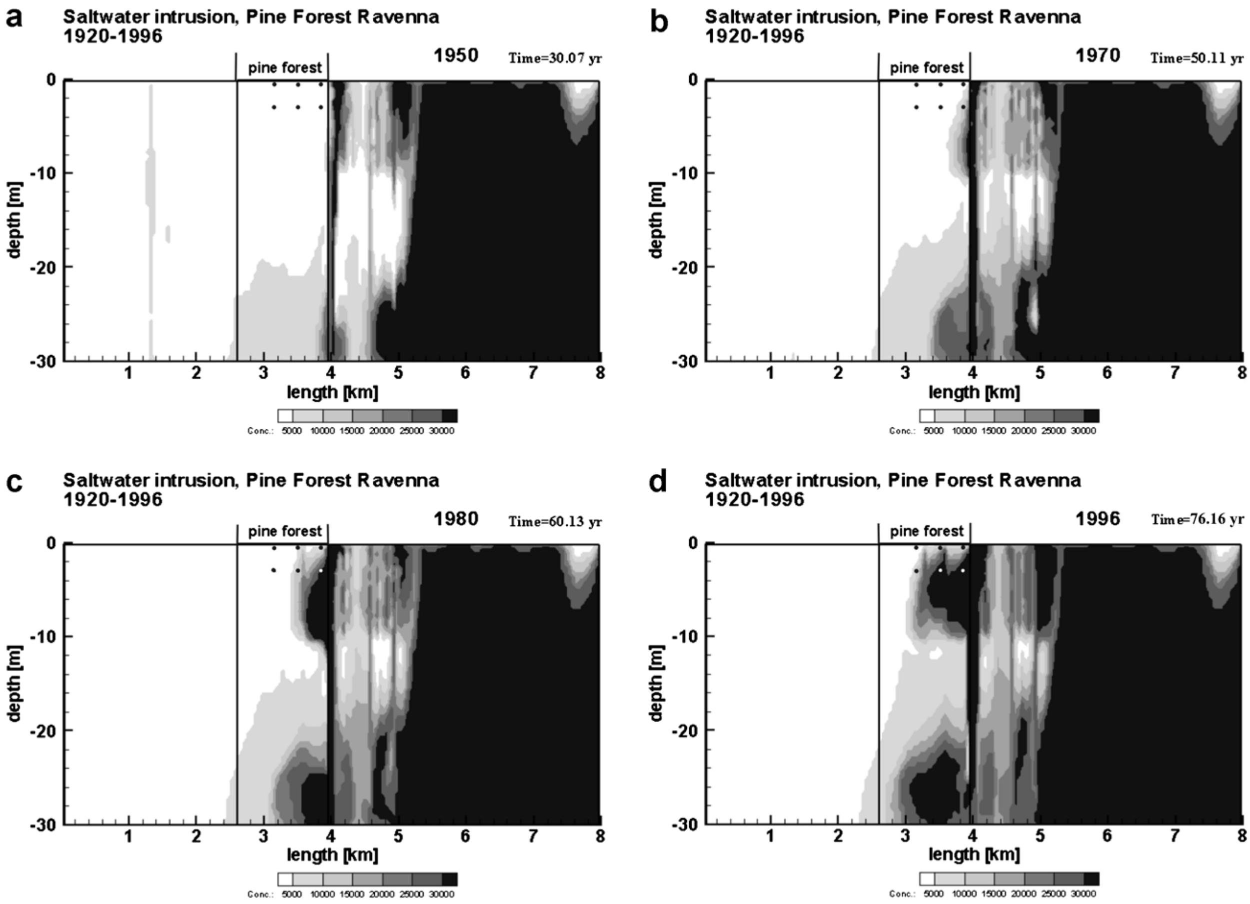

Figure 9 Salt concentration distribution (g/l) in the aquifer at four distinct moments in time: 1950 (a), 1970 (b), 1980 (c), 1996 (d). An increase in salinity is detected in the pine forest during the period of maximum subsidence rate (the position of observation wells in the pine forest is shown by dots).

saltwater from the bottom. A less significant increase in salinity concentration is obtained in the silty unit (from −10 m to −25 m) where hydraulic conductivity is less than at the top of the system.

The period 1996—2006 AD: the closing of the ''Chiaro Pontazzo'' water body

This simulation aims to quantify the effect of the closing of the ''Chiaro Pontazzo'' water body bordering the pine forest. In the years 1996—1997 this part of the lagoon was closed off by an artificial embankment in order to create a fresh shallow water body between the lagoon and the pine forest, thus preventing saltwater intrusion. The water level of the basin is kept equal to sea level (0 m a.s.l) by floodgates and its salinity is about 3.0—8.0 g/l, because it receives fresh water from two drainage canals (the Cerba and Canala canals). Starting from the output of the previous simulation (situation in 1996), a new initial salt concentration for the water body was used; the water level, implemented as a general head boundary condition, is set to 0 m and is kept constant in time. A subsidence rate of 5 mm/year has been implemented for these 10 years.

The closing of the water body and the decrease in its salinity causes a reduction of salt concentration at the top of the groundwater system beneath the pine forest (viz. the first layers, from 0 m to −6 m) (Fig. 10). Here we analyzed the seepage and the salt load. By seepage we intend the product of effective velocity through the porous medium and porosity, whereas salt load is the product of seepage and salinity.

At the end of the simulation (2006), 10 years after the closing of the Pontazzo basin, the salt load had decreased 13% at 1 m depth and 6% at 3 m depth, compared to the initial values (in 1996) (Fig. 10a and c). The brackish—freshwater recharge from the water body increased and, consequently, seepage decreased (−10% relative to the beginning of the simulation) in the first layers. At 3 m depth seepage became three times lower than the initial condition at the start of the simulation, consequently determining a decrease in concentration in the observation wells within the pine forest. The variation in salinity was not significant in the silty unit or at the bottom of the aquifer during this short period.

Fig. 10c shows the situation at the end of the simulation. At present (2006) the salinity concentration is still high in the coastal aquifer, and it increases with depth and in the eastern part of the model, which is close to the sea. At the bottom of the aquifer, beneath the pine forest (−30 m), the brackish—saltwater wedge from the ''Piallassa'' lagoon is already 1.3 km inland. At a depth of

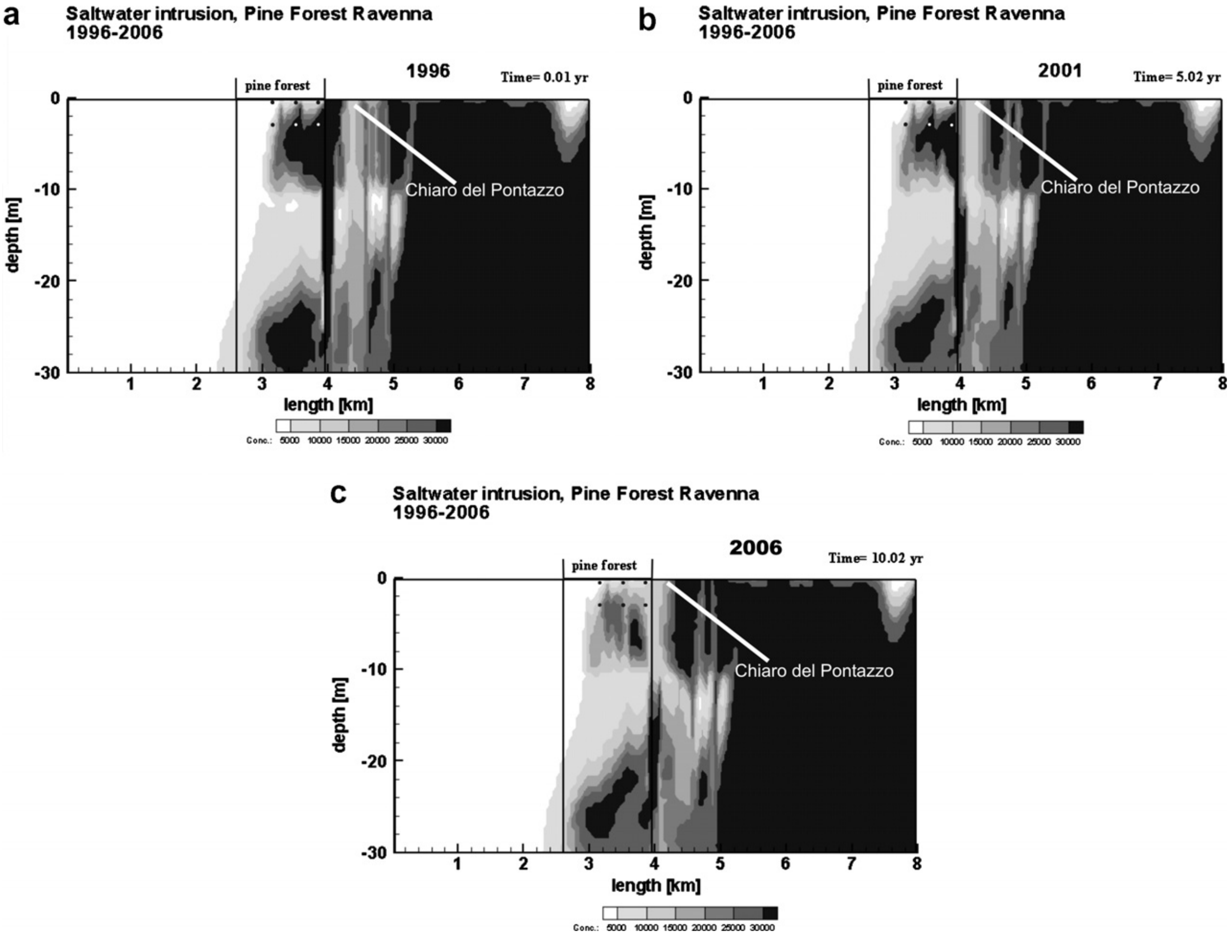

Figure 10 Salt concentration distribution (g/l) in the aquifer at three distinct moments in time after the closing of the water body ''Chiaro del Pontazzo'': 1996 (a), 2001 (b) and 2006 (c). With this solution, a decrease in salinity was detected at the top of the system.

10 m, the brackish—freshwater interface (10.0 g/l) is about 950 m inland starting from the eastern boundary of the pine forest. At the top of the system, fresh water consists of low salinity water lenses floating on the saltwater wedge.

The period 2006—2106 AD: future sea level rise and land subsidence

These last simulations have the objective of quantifying the effect of sea level rise on saltwater intrusion during the next century. It is assumed that climate changes will cause a rise in mean sea level in the Mediterranean region. According to the Intergovernmental Panel on Climate Change (IPCC, 2001) and others studies (Comune Di Ravenna, 2005; Raper et al., 1996), a sea level rise of 0.47—0.48 m is to be expected during the next 100 years in our study area, with an uncertainty range from 0.09 to 0.9 m. As various estimates of future sea level rises are still possible, we wanted to evaluate the effect of different values for sea level rise. In this paper, three scenarios of sea level variation have been considered for the next century: no sea level rise (Fig. 11b), a sea level rise of 0.475 m/century (Fig. 11c), and a sea level rise of 0.9 m/century (Fig. 11d). The sea level rises have been implemented at the sea-boundary of the model in steps of 0.00475 m for the first and 0.009 m for the second, per each time step of one year, starting from 2006 AD. These last scenarios are compared with the present situation (2006 AD) (Fig. 11a).

Fig. 11 shows the comparison between the initial situation (2006) and the computed salt concentration in the system for the three different sea level rise scenarios after 100 years of simulation (2106). It is apparent that in the eastern part of the aquifer and in the first layers beneath the pine forest, salinity increases significantly in all cases in comparison with the present situation. In the first layers salinity increases most, especially in the pine forest area close to the lagoon. This is where seepage is extensive due to the heavy drainage system that causes an upcoming interface of saline groundwater from the bottom. Since the phreatic water level in the pine forest is low relative to sea level (about −0.30 to −0.4 m a.s.l.), salt has a natural gradient landward.

The differences between the three different scenarios of sea level rise seem small because groundwater flow and solute transport are slow processes. Considering the concentration data (Fig. 12) for the observation wells in the pine forest, an increase in salinity is evident within the first few meters of the aquifer. Here, most of the salinity in-

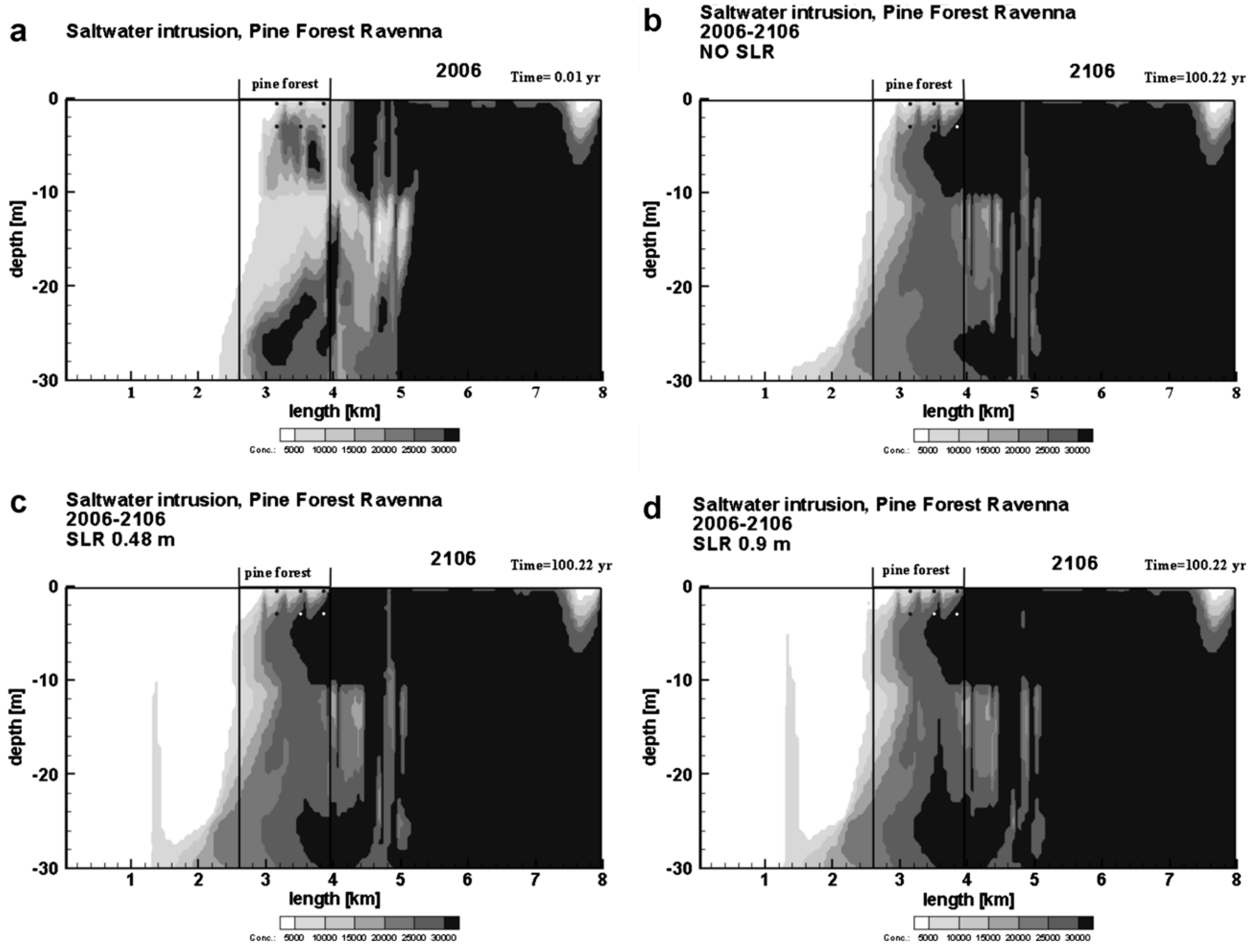

Figure 11 Salt concentration distribution (g/l) in the aquifer for the initial situation (2006) (a) and for the year 2106 for the various climate change scenarios: no sea level rise (b); a sea level rise of 0.475 m/100 years (c) and a sea level rise of 0.9 m/100 years (d).

crease occurs for the 0.9 m/century sea level rise scenario, with an increase of 49% at −3 m a.s.l. In this sea level rise scenario, at the top of the system (−0.5 m a.s.l.) salinity is three times greater than in the initial situation (2006).

After the 100 years simulation the freshwater lenses initially present (Fig. 11a) at the top of the system have been replaced by brackish water (Fig. 11b–d). There is also a significant increase in salinity in the middle part of the system, through the silty unit (−10/ − 25 m a.s.l.). At that depth, values of salt concentration with values of 28.0 g/l are obtained at the end of all simulations, with a factor three relative to the initial concentration. In the deeper layers (from −25 to −30 m a.s.l.) the differences in concentration are not so significant, because the system already has high values of salinity to start with (Fig. 11).

Considering the aquifer below the pine forest area at a depth of −3 m a.s.l., Fig. 13 shows that in the ''no sea level rise'' case the infiltration-seepage values (Fig. 13a) remain more or less the same during 100 years of simulation, while the salt load increases by 28% relative to the initial situation (2006) (Fig. 13b). Even if there are not large variations in hydraulic head during the coming 100 years due to sea level rise, the saltwater, already presents in the eastern part of the system at the beginning of the simulation, will be driven towards the pine forest. At the initial situation (2006) the coastal aquifer is not yet in a steady state and during the simulations the saltwater wedge moves inland.

Climate changes (inducing sea level rise) will intensify the salinisation processes by increasing seepage values by +133% for a 0.475 m sea level rise and by 290% for a 0.9 m sea level rise. As a result, the salt load in the pine forest system will increase +41% in the first case and +44% in the second with respect to the current state. The salt load will increase so much because the saline groundwater is already present in the lower part of the aquifer system from the start, and more of it will enter the upper part.

Conclusion and recommendations

The objective of our study was to understand how past and present human activities have affected the saltwater intrusion process in the coastal aquifer near the town of Ravenna and how the future expected sea level rise will affect the salinisation process.

By using a numerical model (MOCDENS3D) we have been able to better understand in a quantitative fashion the influence of different lithologic layers within the aquifer, of

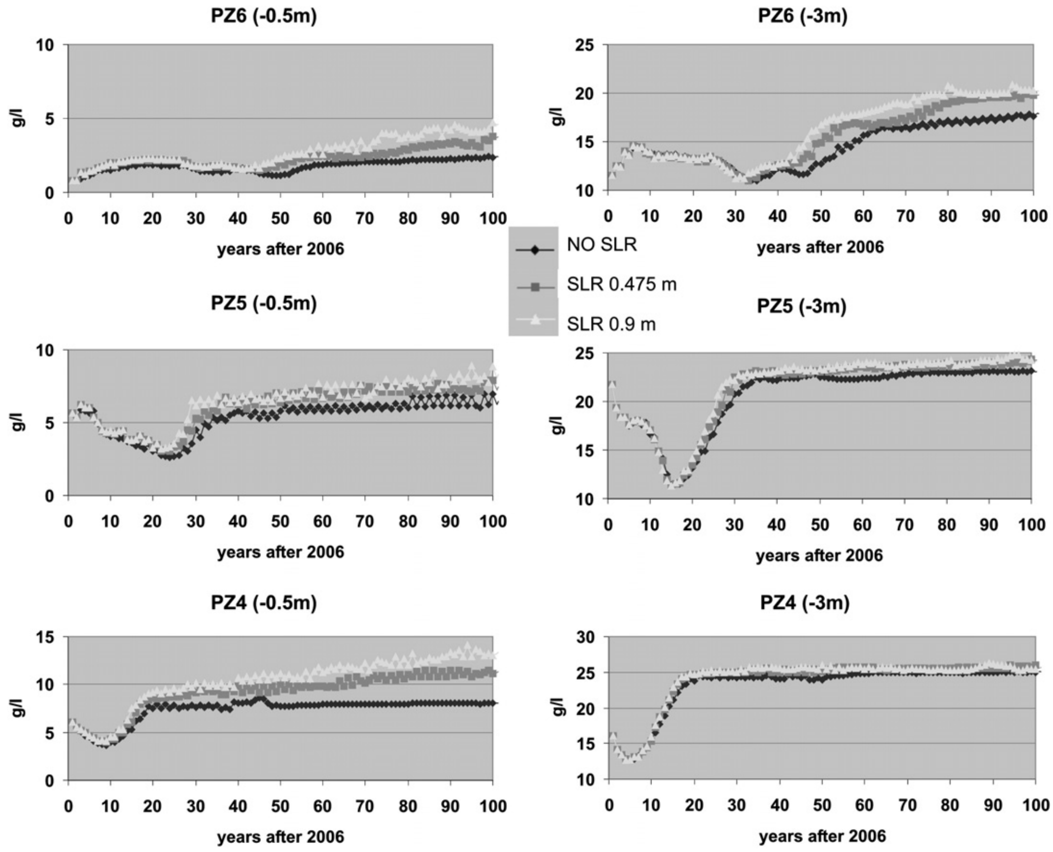

Figure 12 Concentrations at −0.5 and −3 m a.s.l. for the three observation wells in the pine forest (piezometers No. 6, 5, 4), as a function of the time for each climate change scenario. The initial drop of salinity in all curves is caused by an initial shift of freshwater that was accumulated below the ''Chiaro del Pontazzo'' water body after its closing. These freshwater lenses are pushed toward the pine forest by saltwater coming from the lagoon.

their hydraulic conductivity, and of the recharge magnitude related to land use. The analysis of salinity variations in the pine forest system has been focused on the first meters from the surface (−3 m a.s.l.) because this top system is severely affecting pine growth and future survival. The study of the unconfined aquifer, and its surface part, is also fundamental to an understanding of how water management and land use can accelerate aquifer salinisation.

The variable density groundwater model of the study area shows that over the last century (1920—2006) artificial subsidence and heavy drainage started the salinisation process in the area beneath the pine forest by depressing the phreatic water level. Fig. 14 shows the salinity trend for the observation wells in the pine forest (at −3 m); it is evident that salinity increased quickly after 1960 when industrial development and groundwater exploitation intensified, inducing considerable artificial land subsidence. The decrease of salinity in the last part of the graph (1996—2006) for piezometers No. 4 and 5 is due to the local effect of brackish—freshwater recharge from the ''Chiaro del Pontazzo'' water body after its closing (1996).

The numerical model supports the hypothesis that at the end of this simulation the present situation (2006) is not yet in a steady state.

Climatic conditions in the area mean limited precipitations throughout the year and an absence of efficient aquifer recharge, especially in spring and summer when seepage is extensive. This situation is more critical due to urban development and high hydraulic conductivity values. For these reasons and because freshwater in the wetlands is strategic for the survival of the ecosystem (fauna and vegetation), groundwater withdrawal for domestic, agricultural and industrial use needs to be reduced during periods of insufficient recharge so that saltwater intrusion is diminished. In fact, the waters contained below agricultural lands are polluted by nitrates but are still used for irrigation in agriculture and gardening.

In most parts of the study area the watertable depth is below sea level, so a natural freshwater hydraulic gradient cannot contrast the density gradient of saltwater. Certain remediation measures could reduce this phenomenon. The simulation of the Pontazzo basin closing (Section ''The period 1996—2006 AD: the closing of the ''Chiaro Pontazzo'' water body'') in fact demonstrates that a brackish—freshwater recharge causes a salt load drop and a salinity decrease at the top of the groundwater system. If the hydraulic heads were kept above sea level (as it should be) a greater quantity of fresh groundwater from the bottom of the ''Chiaro Pontazzo'' water body would flow into the aquifer system beneath the pine forest as fresh—light brackish seepage.

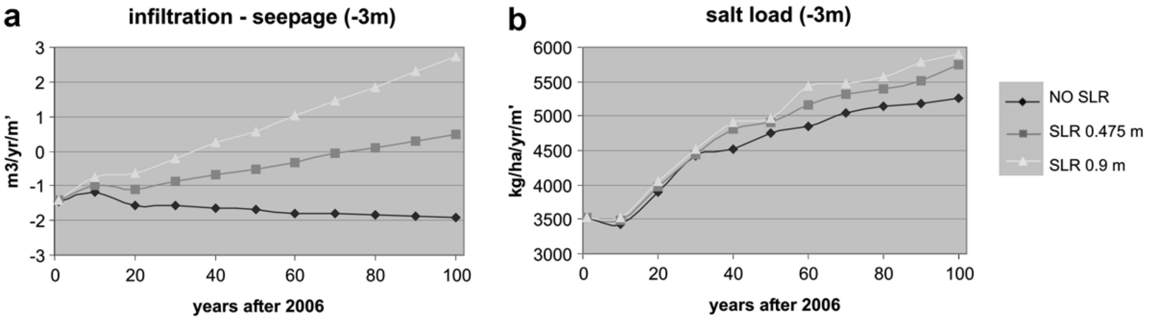

Figure 13 Infiltration-seepage (in m^3/year/m′) (a) and salt load (in kg/ha/year/m′) (b) through the model layer at −3 m a.s.l. summarized for the entire pine forest, as a function of 100 years for the three climate change scenarios. (*Note:* in the graph on the left, the negative values indicate the quantity of the infiltration, the positive ones indicate seepage.)

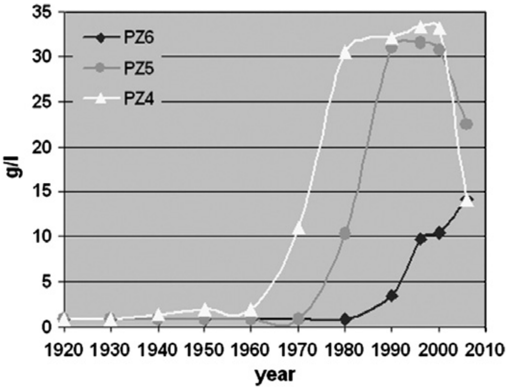

Figure 14 Computed salinity trend at −3 m for the three observation wells in the pine forest (piezometers No. 6, 5, 4) as a function of the 1920—2006 simulation period.

A relative sea level rise will accelerate the increase in salt load during the coming decades, affecting the entire hydrogeologic system and groundwater flow. In all scenarios salt load quantities and seepage increase considerably due to salinisation of the hydrogeologic system; there will be seepage increases of +133% for a 0.475 m/century sea level rise and salt load will increase by 40% relative to the present situation. In this simulation the mixing zone between fresh and saline groundwater will be shifted 800 m farther inland. Since the soil becomes more saline, farmland degradation and pine growth problems would also occur.

Lastly, the simulations show that absence of a suitable coastal dune system eases the salt wedge coming in. Dunes in fact, thanks to their elevation and good infiltration capacity, provide a sufficient freshwater recharge and a hydraulic head above sea level, allowing hydrostatic control of saline intrusion possibly down to the basement of the aquifer. As a result of the very low elevation of the coastal dunes in the study area, this ''barrier effect'' is either reduced or absent. In our simulations the freshwater lenses, which are created along the coast, cannot contrast the salinisation of the aquifer at the basement, because the brackish—freshwater interface is too shallow. Coastal dune restoration could be one of the possible solutions to compensate the salinisation but a more specific study is required to find effective countermeasures in order to contrast saltwater intrusion into the coastal aquifer.

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