Groundwater Freshening Following Coastal Progradation and Land Reclamation of the Po Plain, Italy

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ABSTRACT

Many coastal areas historically were inundated by seawater, but have since undergone land reclamation to enable settlements and farming. This study focuses on the coastal unconfined aquifer in the Po Plain near Ravenna, Italy. Fresh water is present as isolated, thin (1-5 m) lenses on top of brackish-salt water. Historical maps show large areas of sea inundation until approximately 150-200 years ago when coastal progradation and construction of the drainage canals began. Since then, the aquifer has been freshening from recharge. A 3D SEAWAT model is used to simulate a 200 year freshening history, starting with a model domain that is saturated with sea water, and applying recharge across the top model layer. Calibration to the observed concentrations is remarkably good for discrete depths within many monitoring wells despite model simplicity. The distribution of fresh water at the end of the 200 year period, representing current conditions, is controlled by the drainage network. Within and adjacent to the drains, the groundwater has high salinity due to up-coning of salt water. Between drains, the surface layers of the aquifer are fresh due to the flushing action of recharge. The modeling results are consistent with cation exchange processes revealed in the groundwater chemistry.

Keywords: Land Reclamation, Groundwater Freshening, Coastal Aquifers, Numerical Modeling, Italy

INTRODUCTION

Coastal regions have experienced significant change due to human development as well as natural geological processes. The construction of extensive drainage networks has been a primary means to reclaim the land for agricultural development, to mitigate the effects of land subsidence, or a combination of both. In the literature (Stuyfzand 1989; de Louw et al. 2011), these drainage networks have been described as leading to upconing of the saltwater from depth, thereby leading to salinization of the freshwater lens (Mollema et al. 2012). However, some coastal aquifers show evidence of high salinity, not because of current anthropogenic activities, but rather because salt water has not been flushed completely by fresh water after the Holocene marine transgression (e.g. Custodio and Bruggeman 1987). The aquifers are in transition from an initial state of a salty aquifer to one that is now exposed at surface and subject to freshening processes. However, if the water table is close to surface due to the low elevation, the land floods readily and must be drained artificially to enable use of the land surface. Within this context, the role of the drainage network either as a means of freshening the aquifer or causing salinization is of interest (Vandenbohede et al. 2014).

In this paper, freshening of a coastal aquifer following coastal progradation and land reclamation activities (construction of a drainage network) is investigated. The study area is the Ravenna coastal plain in Italy, just to the south of the Po River Delta (Figure 1). Fresh water is present as isolated, thin (1-5 m) lenses on top of brackish-salt water. Examination of historical maps for the region has revealed that in 485 AC, a large portion of the coastal region was submerged below sea level. Submergence persisted through the 1000-1200 AC, and at least to 1780 AC in the area south of the city. Thus, the Ravenna territory has evolved over the last 300 years from a brackish lagoonal environment to a continental setting; in the southern area, a gulf was still present around the early- to mid-1800s (Ciabatti 1968). Since then, the coastline has prograded seaward up to 5 km in the area south of Ravenna, although most of the beaches along the Ravenna coastline are currently being eroded. This progradation and consequent transition to a continental setting has been further facilitated through the land reclamation drainage in the last 150-200 years (Stefani and Vincenzi 2005). Today, most of the Ravenna territory is kept dry by the land reclamation drainage system operated by the Land Reclamation Authority (LRA). This drainage system consists of a dense network of canals organized around centralized mechanical pumping machines that lift the water into a main canal and convey it to the sea (Stefani and Vincenzi 2005). The drainage system lowers the water table sufficiently to allow for urban and industrial settlements as well as for agriculture.

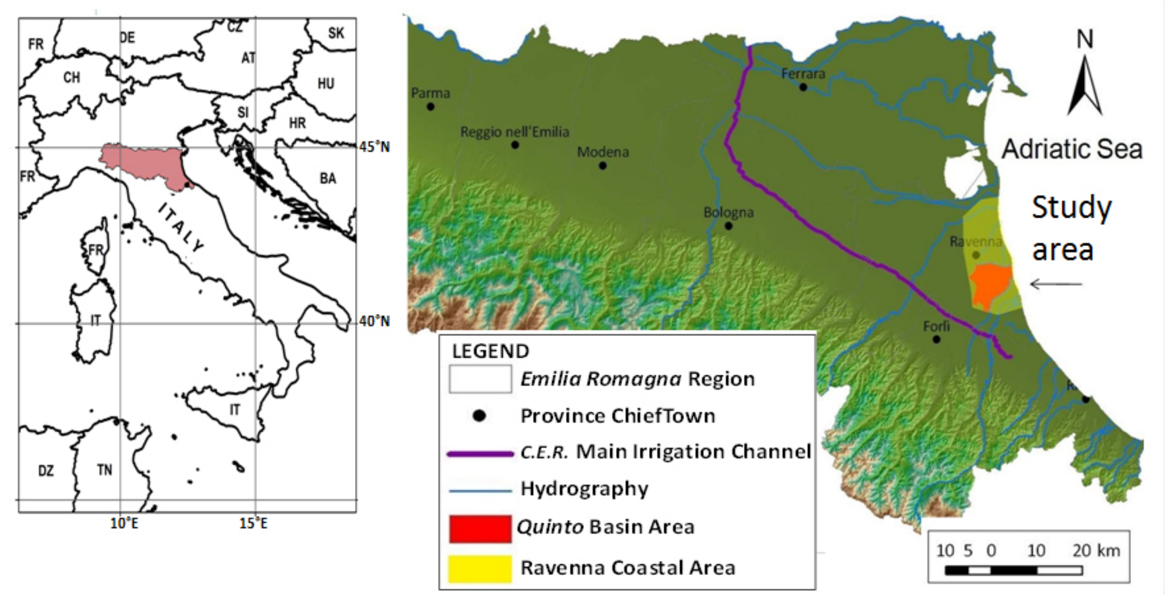

Figure 1. Location of the study region near Ravenna, Italy on the Po Plain

METHODS

Monitoring of the Ravenna coastal aquifer started in 2003 using a network of shallow piezometers belonging to the Ravenna municipality (20 piezometers with depths ranging from 4 to 20 m). In this study, water samples were collected using straddle-packers for full chemical analysis (pH, Eh, BOD, alkalinity, major cations, major anions; Mollema et al. 2013). Water level, electrical conductivity (EC) and temperature were also measured with continuous multi-parameter loggers in the piezometers and in surface waters (69 monitoring points). The BEX index of cation exchange (Stuyfzand 2008) was used to evaluate if there is a trend of salinization or freshening in the aquifer. The index quantifies the cationic exchange, in meq/L, according to the following relationship, which is specific for aquifers that also contain dolomite like the one considered in this study:

$$BEX = [Na^+ + K^+]\ measured - 0,8768 * Cl^- \quad (1)$$

Where the BEX is equal to zero, the cations from sea water and fresh water are in equilibrium. Where BEX >0, a freshening process is underway, and where BEX <0 there is a salinization process underway.

The numerical code SEAWAT-2000 (Langevin et al. 2007) was used to simulate the freshening process in an attempt to explain the salinity distribution and the groundwater chemistry, and to evaluate the effects of the land drainage network on the freshening process. The model domain is approximately 14 km long and 9 km wide and extends to a depth of 30 m with 100x100 m cells. The model is discretized vertically into 16 layers with a thickness of 2 m per layer, with the exception of the upper two layers, which have a thickness of 0.5 and 1.0 m, respectively.

The geologic data used to construct the model were extracted from a 3D RockWorks model developed for the region. Three hydrostratigraphic units were identified: sand, silt and clay. Initial hydraulic conductivity (K) estimates were derived from slug tests, but were adjusted during model calibration. Vertical anisotropy was estimated at half an order of magnitude lower for all material types. Initial porosity (n), specific yield (Sy) and specific storage (Ss) values were estimated from the literature but were also adjusted during calibration. The longitudinal/transverse dispersivity was set to 10 m/ 1m.

The model boundary conditions included no flow (zero flux) at the bottom, western, northern and southern sides, to represent negligible fresh groundwater inflows to the system. A specified head and concentration boundary condition represents the easternmost sea boundary. To simulate the drainage system, drain (Cauchy) boundary conditions were assigned to the network of drainage canals. The conductance values were adjusted slightly during model calibration, but were only varied as a group to avoid over parameterization. Recharge (R) was applied to the top layer of the model according to material type: sand=30 mm/year and clay=20 mm/year. However, R was highly uncertain and was adjusted during model calibration. Zero evapotranspiration (ET) was included everywhere except along a narrow strip by the ocean where pine forests are present. Here ET was set to 40 mm/year (slightly higher than R) with an extinction depth of 2 m. The model was run for a period of 200 years, although longer and shorter periods were experimented with. The initial concentration was 25,000 mg/L.

RESULTS

Model calibration used both water levels and concentrations at 20 monitoring wells. The monitoring wells were multi-level; therefore, concentration data were available at discrete depths (3-5 depths in each well). Calibration to observed concentrations involved examining a) the time series results (e.g. Figure 2), b) the spatial distribution of concentrations at discrete depths (e.g. Figure 3), and c) the overall correlation at the end of the simulation.

The 3D numerical model was very challenging to calibrate given the uncertainties in many of the input parameters, not the least of which was the timing of the freshening process. Until the historic maps were found (Andraghetti 2007), which placed some constraint on the timing of land exposure, the potential end time for the simulation (i.e. the time to compare the observed concentrations against the simulated ones) was very uncertain. Based on the historic maps, a time frame of 200 years was considered a reasonable simulation period and this was invariant for the calibration simulations. The surface exposure of the sand and clay was generally well mapped, but the distribution of sediments at depth was less well constrained and was based on interpolation from borehole lithology logs. Likewise, to keep the model as simple as possible, only three hydrostratigraphic units were modeled, and these were assigned uniform hydraulic properties. It is likely that this is a gross simplification of the actual geology at depth, and for this reason, the distribution of hydrostratigraphic units and their hydraulic properties is considered to be the greatest source of uncertainty, and likely a primary cause of poor model calibration at depth in most piezometers. Many piezometers showed insufficient flushing at depth, and it was tempting to increase the K value of some of the deeper clay units as they were actually mapped as clay with thin layers of sand. But to avoid over parameterization of the model, the simplified hydrostratigraphic model was adhered to.

The model calibration was found to be very sensitive to how close the piezometer was to a drain. The drainage canals were modeled as 100 m wide drain cells in the model, when in reality the drainage canals are much narrower (< 10 m). Therefore, while accurate GPS coordinates were used to position the piezometers in the model, their placement relative to the model drains may have been incorrect. Because the drains function to skim water off the surface of the aquifer, and this is fresh water, the result is an upconing of salt water from below along the length of the drain. If a piezometer is placed too close to a drain in the model, then the salinity distribution at depth will be too high. These effects of the drains are similar to those reported by de Louw et al. (2011) and Eeman et al. (2011) in the polders of The Netherlands.

The overall salinity distribution from the model is quite similar to what is observed in the corresponding area south of Ravenna. Three of the four model layers (Layers 1, 4 and 12 in Figure 3) show strong similarity to the observed salinity maps (not shown) lending support to the overall conceptual model of a freshening system for this southern area. Further support for a freshening process, at least in the south Ravenna area, is the dominance of BEX >0. The only areas in the south where BEX < 0 were near the pine forests (PS5 and PS12) and along the coast near MF1,2,3. Interestingly, these piezometers were among the most challenging to calibrate suggesting that perhaps some other process (sea spray, vegetation?) may be influencing the salinity distribution.

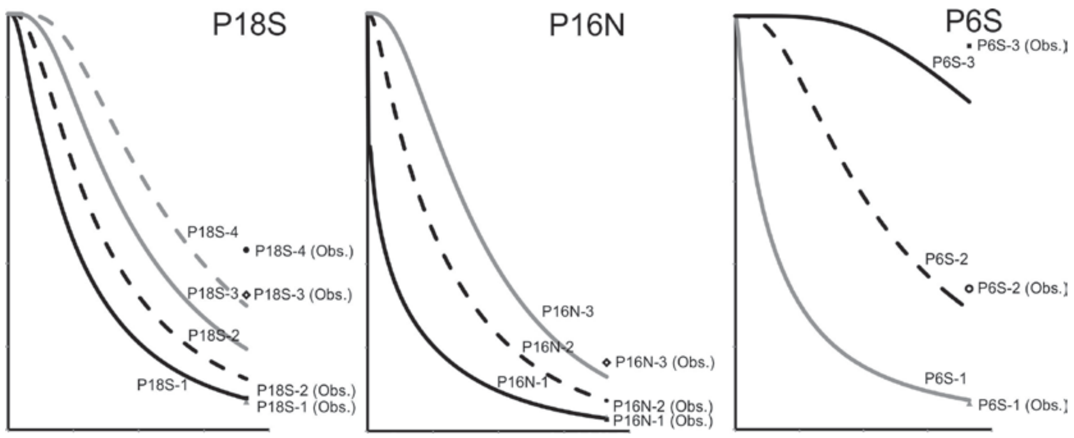

Figure 2. Concentration time series for selected monitoring wells. For all piezometers, the deepest monitoring port corresponds to the highest number (e.g. P18S-4)

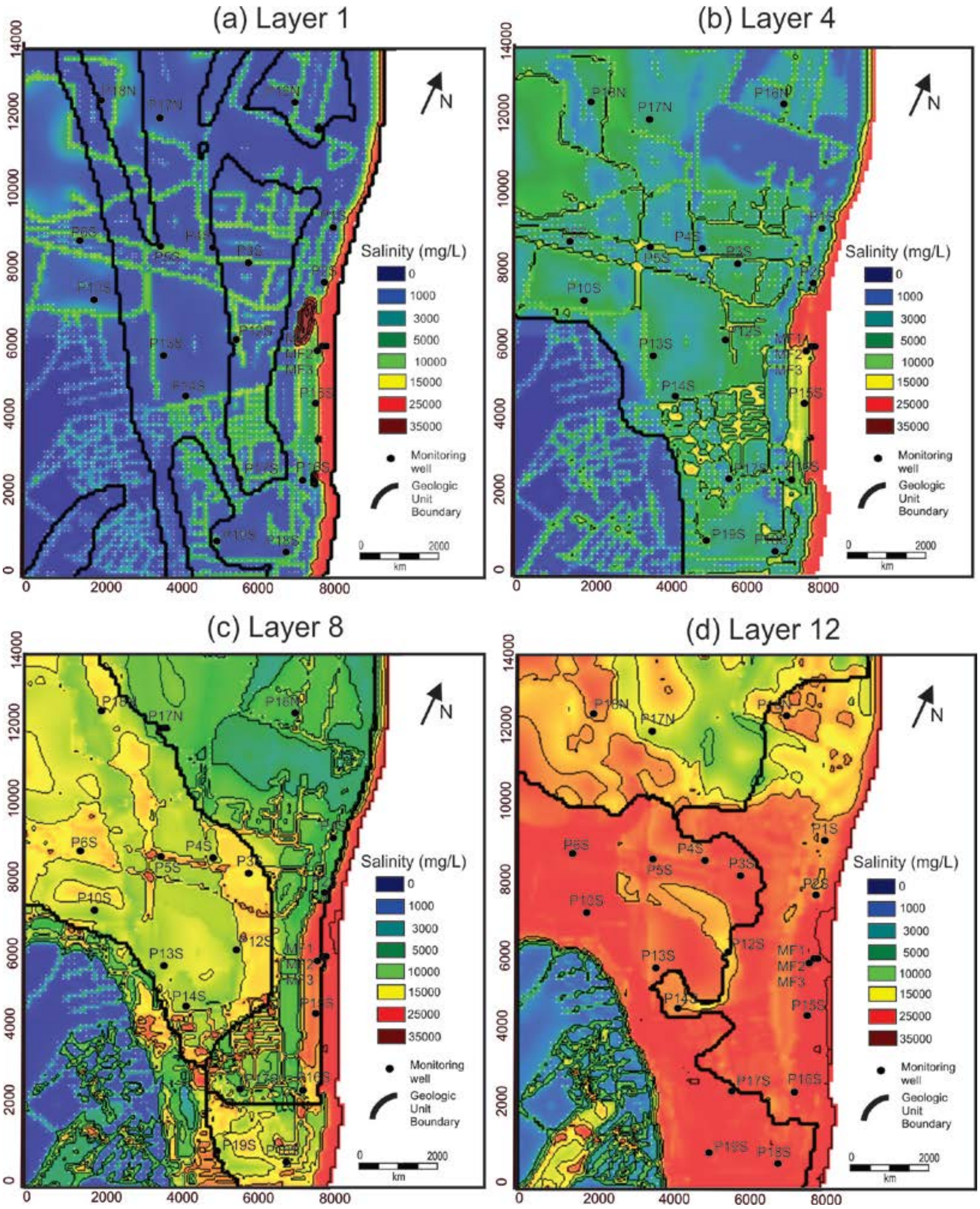

Figure 3. Salinity (mg/L) for four model layers after 200 years of simulation time (a) Layer 1, (b) Layer 4, (c) Layer 8, (d) Layer 12

CONCLUSIONS

The Ravenna coastal plain is very complex in terms of coastal evolution, surface water distribution, land use, coastal hazards (such as coast erosion and land subsidence), aquifer geology, and disaggregated management. A relatively simple 3D numerical model that captures the land development history of the area has been successful in explaining the distribution of freshwater and saltwater in the aquifer and the freshening trend. The freshening trend is also confirmed by the BEX geochemical indicator. The drainage canal network itself, however, has a salinity which is higher than in the surrounding aquifer pointing out that it is also causing upconing of the deeper salt water.

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