The influence of surface water evaporation on salt water intrusion in Ravenna, Italy. Implications for climate change.

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ABSTRACT

We investigate to what extent open surface water evaporation contributes now, and in a possible future, to the salinization of quarry lakes in the *Quinto* Basin, Ravenna Italy. Net evaporation rates are currently up to 894 mm/yr. Numerical models show that evaporation is one of the driving forces for salinization of the unconfined aquifer. Evapotranspiration by pine trees and drainage of the polders around the quarries contribute as well. Evaporation depends on many weather variables and in the future IPPC climate scenarios A1B and A2 for the area, evaporation may slightly decrease, because of decreasing wind and increasing air humidity in winter, even though average temperatures will increase.

INTRODUCTION

Gravel deposits at the surface in the *Quinto* basin, Ravenna (Italy) are exploited for building materials since 1935. The older quarries are now abandoned and form lakes up to 20 m in depth, some of which are used for recreational activities. In the active quarries, the pits are filled with water as well. The water in the pits has a salinity that can reach up to 15 g/l. The water in the quarries is well mixed. Rainfall is limited in this area and there is a net evaporation removing fresh water from the lakes (Fig. 1a). Replacement of the net evaporation and of the gravel with salt water coming from the surrounding aquifer may explain in part the high salinity of the quarries (Fig. 1b). It is recognized that many other factors contribute to salt water intrusion in this area: drainage, dune destruction, salt water encroachment along rivers and disaggregated water management (Antonellini *et al.* 2008) and pine tree transpiration (Mollema *et al*. in prep). This causes problems among others to the natural areas (Antonellini and Mollema, 2010) and to the agricultural land.

CLIMATE AND EVAPORATION

The climate data used in this study to calculate the surface water evaporation is based on four local weather stations for the period 1987-2008. The average annual precipitation is 635 mm, the average maximum temperature is 19°C and the average minimum temperature is 8°C. To be able to calculate the future water balance of the basin, climate data were extracted from the model output that IPCC describes in the fourth assessment report (IPCC 2007) since no published model output was available for the area. An ensemble of 13 models for the two scenarios A1b and A2 in the period 2080-2099 was chosen. Eight parameters that were needed for our calculations were extracted from these models and averaged. In comparison with today, the minimum temperature is projected to increase throughout the year in both models. The maximum temperature is higher mostly in winter but will not increase considerably during the summer. The total annual precipitation is projected to decrease from 635 mm to 619 mm (scenario A1b) or to 596 mm (scenario A2). Relatively more rain is projected to fall during the winter: 46% today, 61 % in the future for A1b, 64% for A2. A comparison of historical data of the period 1991-2008 with those of 1961-1990 indicates that the average and maximum temperature have already increased by two degrees in the study area since the 1960's and the precipitation has decreased in winter, spring and summer but it has increased in the fall (Regione Emilia-Romagna, 2010).

Open water evaporation in this study is calculated with Maidment (1992) which is based on the Penman equation (1948) that describes how the available energy from the sun is used for evaporation of water. The output of the climate models do not provide all variables needed to simulate future scenarios. For example the solar radiation available for evaporation is assumed to be the same in 2070-2100 as today. The average annual open water evaporation for 1988-2008 is 1529 mm whereas in 2070-2100 it will be 1466 mm (A1b) or 1467 mm (A2). The decrease in evaporation can be explained by the fact that the maximum temperature from our climate model data is not increasing whereas the relative humidity is increasing and the wind velocity is decreasing in summer.

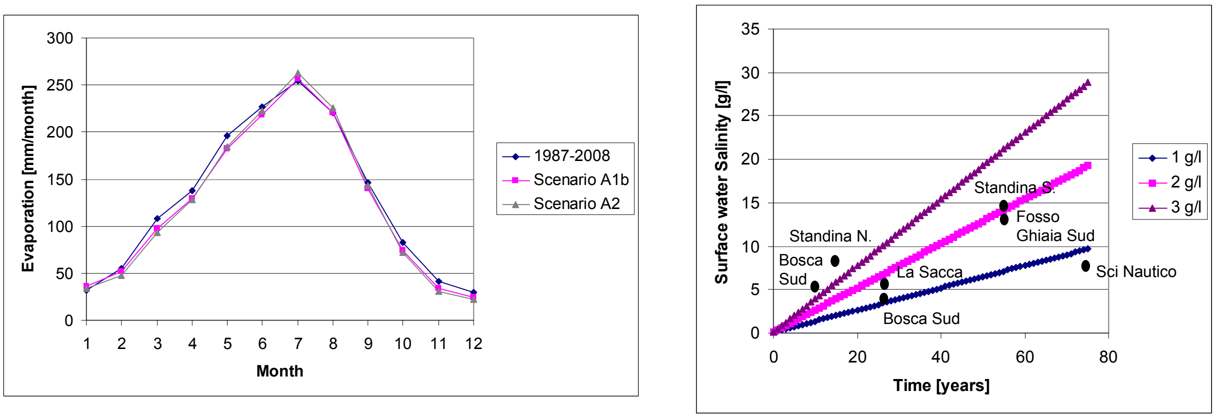


Figure 1a. Graphs of monthly surface water evaporation for different climate scenarios and b. Increasing salinity in quarries over time with a net evaporation of 894 mm/yr, as a function of replacement salinity. The age and water salinity of some quarries is indicated.

SALINIZATION BY EVAPORATION

We assume, for the sake of simplicity, that all freshwater removed from the quarry lakes by evaporation is replaced by water coming from the surrounding aquifer and that no salt disappears from the quarries. We know that the oldest quarry started 75 years ago but most quarries are no older than 56 years. Assuming also that the salt concentration of the groundwater is constant over time, one can construct a graph as in Figure 1b that shows increasing quarry salinity over time as a function of replacement of freshwater with saline groundwater. According to this model, even with a very low groundwater salinity of 1 g/l, over the life span of the quarries, the salinity may reach 9 g/l, which is close to what we measure in the quarry Sci Nautico.

MODELLING

The history of the area is simulated with a finite difference numerical model (SEAWAT, Guo *et al* 2002) to investigate if the simple analytical model of the quarries (Fig. 1b) can be supported with a flow and transport model. A two dimensional 26-km-long cross section is constructed and the first model simulates the location of the coastline at the eastern border of the 3.5 km inland from the current coastline. An initial salt concentration for the groundwater was assigned based on an estimated length of the salt water wedge obtained with the Ghyben Herzberg relationships. A recharge rate of 200 mm/year is applied on the dunes and results in a completely fresh, unconfined aquifer. The planting of the pine forest on the older dunes in the Classe area by the Romans is simulated by reducing the recharge on those dunes to 50 mm/yr (due to evapotranspiration). The coastline moved to its current position around 1690, which is simulated by moving the constant head and concentration boundaries seaward and adding a recharge of 200 mm/yr on the new coastal dunes. The planting of the pine forest in the early 1900's caused again a reduction in the recharge. The drainage for land reclamation started in the 1960's and is simulated with a constant head boundary. The first quarry activities started in 1935 and thereafter new quarries have been started until today. The models show that with a recharge of 200 mm/yr on the dunes along the coast, a time period of 200 years is not enough to flush the salt out of the unconfined aquifer (Fig. 2b). The quarries, simulated with a very high porosity and conductivity column and an evaporation boundary of 500 mm/yr (ignoring drainage), increase the landward velocities but not enough for salt to reach the quarries in 75 years. Adding a constant head boundary on the polder area of -2 m and a general head boundary of -2 m on the quarries, enhances the velocities landward but not enough for the salt to get to the quarries within 75 years.

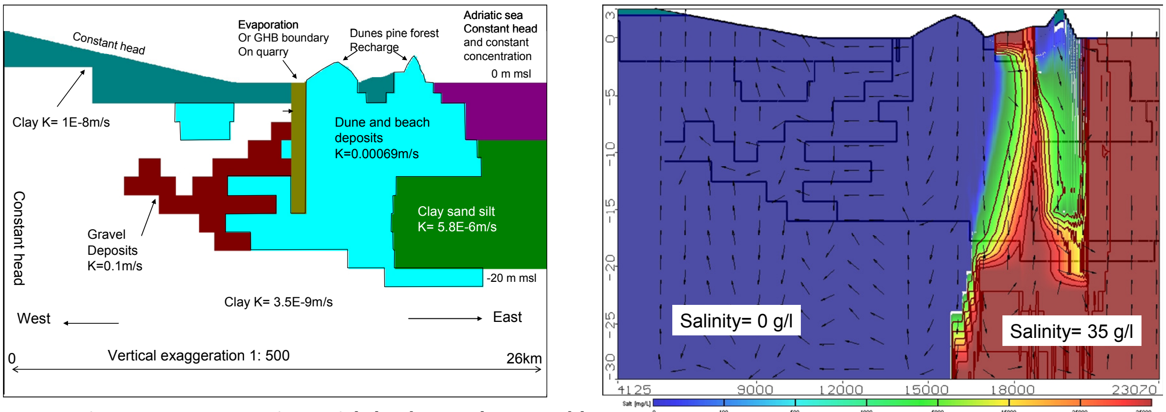
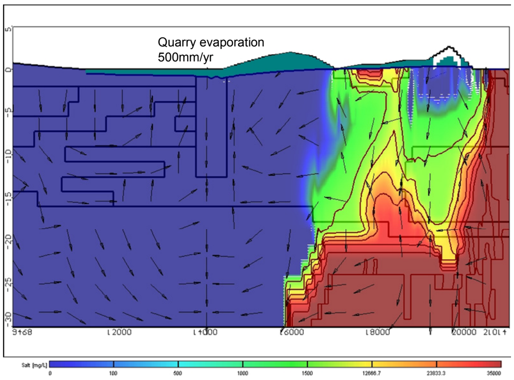


Fig. 2 a. Cross section with hydrogeology and boundary conditions of numerical model.
b. Salt concentration at beginning of quarry activities. Contour interval is 5 g/l.
Velocity vectors indicate direction of flow only.

CONCLUSIONS.

Evaporation from quarry lakes promotes salt water intrusion from the Adriatic Sea. Assuming that evaporated water is replaced by salt groundwater from the aquifer and all the salt remains trapped in the quarries, the groundwater salinity does not need to be high (about 1 – 2 g/l) to cause salinities of up to 15 g/l in the quarry lakes. The modelling of the history of the area suggests that drainage, evaporation and reduced recharge on the dunes all enhance salt water intrusion towards the quarries. As a result, the groundwater salinity below the Classe dunes and the coastal dunes has been increasing over time. This is confirmed by geochemical studies (Marconi *et al*. in press). The current numerical models do not yet explain the high salinities of 15 g/l observed in the quarries or the existing seasonal freshwater lenses below the dunes but other factors so far not built into the models are or may have been playing a role, such as up coning due to pumping in water wells within the aquifer. These may have increased the salinity in the aquifer before the onset of quarrying activities. Even though higher average temperatures in the future may enhance evaporation, decreasing wind velocities and increasing air humidity may actually cause reduce annual evaporation rates. It is unlikely that the current water deficit is going to be eliminated in the future. As a result enhanced salt water intrusion may occur in the future.



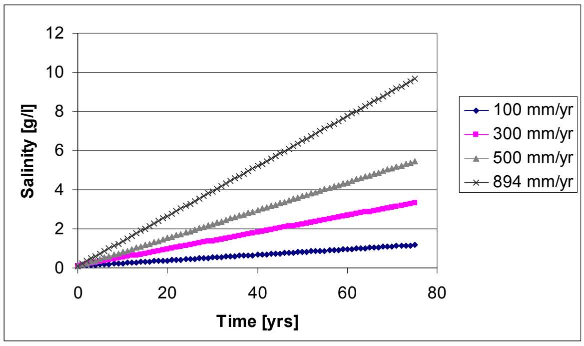


Fig. 3a Results of numerical simulation after simulation time of 75 years. Velocity vectors indicate direction of flow only. b. Salinization rate as a function of net annual evaporation with replacement salinity 1 g/l.

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