The Influence of Three-dimensional Dune Topography on Salt Water Intrusion in Marina Romea, Italy: A Numerical Modeling Study Using LIDAR Data

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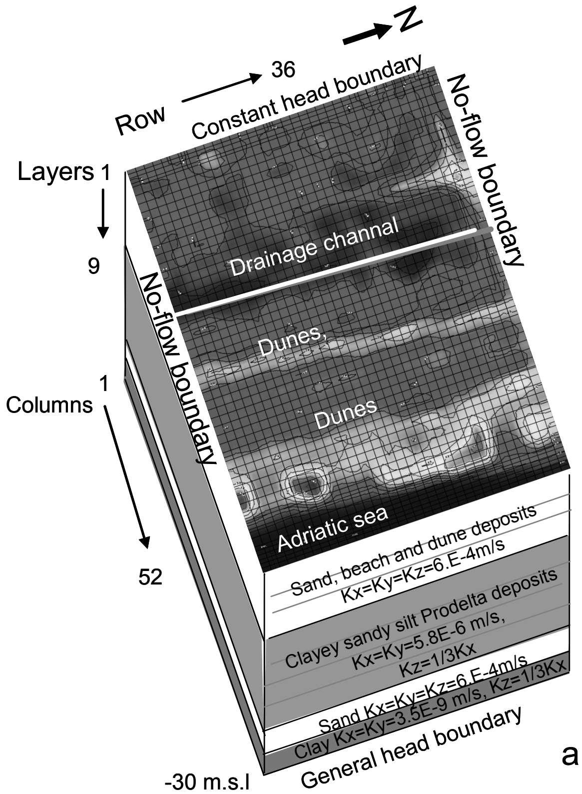
ABSTRACT
This paper presents a 3-D variable density model of an area about 400m by 500 m including the beach, dunes and part of the Pine forest north east of the tourist town Marina Romea along the Adriatic Coast, Northern Italy. The 3D topography, derived from LIDAR data of the area is imported into this model, to test the hypothesis that the interruption of the dune belt for the construction of bathing establishments on the beach has enhanced saltwater intrusion into the unconfined aquifer underneath the Pine forest.

INTRODUCTION
Until the 1950's there was a continuous dune belt along the Adriatic coast of the southern Po-plain. The dune belt, then, was interrupted just north of our study area to create the mouth of the river Lamone and dunes were locally destroyed to create space for bathing establishments, a practice that has continued until now (Fig. 1). Monitoring of salinity in piezometers indicates that underneath the dunes directly adjacent to the beach, the shallow groundwater has a salt concentration of 1-5 g/l and further away from the coast and 150 m into the Pine forest, salinity values reach up to 15 g/l. The Pine forest, originally planted to protect farmland at the back from salt spray, is thought precious because of naturalistic value but the freshwater aquifer that quenches its thirst it is in danger of salinization. Previous work in this general area included the monitoring of the salinity to determine possible causes for salt water intrusion (Antonellini et al in press) and a 2D modeling study by Giambastiani et al (2007), simulating among others the subsidence history of the area.

TOPOGRAPHY
No detailed topographic maps were available and therefore we used Laser Imaging Detection and Ranging (LIDAR) data obtained by local authorities to define the topography. An elevation value was assigned to the nodes of a grid of 10 by 10 m, using the ESRI ArcGIS 9.0 Desktop extension HAWTH's tools, ARCGIS 3D Analyst Tools and the surface spot command. The resulting topographic map (Fig. 2) shows a discontinuous dune belt along the beach with tops up to 5 m high and a second dune belt 140 m from the coast. To the west of this narrow dune belt there is a 200 m wide low area with a drain running north - south along the lowest points at 0 m.s.l.

HYDROGEOLOGY
The coastal unconfined aquifer of our study area contains two main sandy units: a relatively thick (10 m) medium grained sand shallow unit and a lower fine-grained sand unit up to 5 m thick. These two sand layers connect more land inward but are in our study area separated by a clayey silt and sandy-silt unit, the so-called prodelta deposits (Fig. 2). The continental clay basement is at -30 m depth. See Giambastiani et al 2007 for a more detailed description of aquifer characterization and Fig. 2 for the hydraulic conductivity values assigned.



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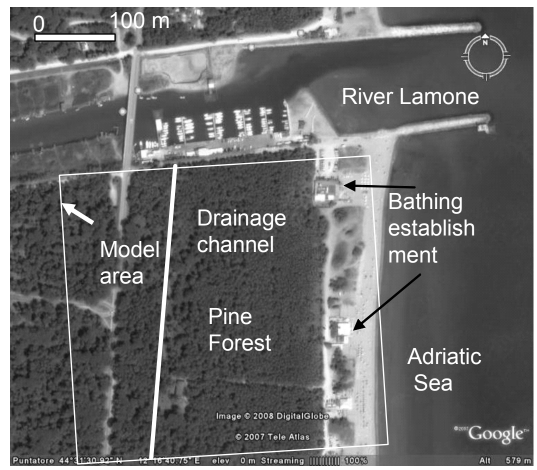

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Figure 1.

a. Sketch of numerical model, including the topography, hydrogeological layering, mesh and boundary conditions. In general, dark colors are topographically low, lighter colors topographically high.

b. Aerial photo made with Google Earth showing bathing establishments and interruption of dunes along the coast

3D MODELLING

The numerical model used SEAWAT (Guo et al 2002), is a computer program for simulation of three-dimensional variable-density groundwater flow, based on two other programs MODFLOW and MT3D, in our study steered with the interface of Visual Modflow (Waterloo Hydrogeologic, 2006). Our numerical model of the study area consists of 9 layers, 52 columns and 36 rows. The mesh is refined vertically close to the sea (east) and in land (west) boundaries. A recharge boundary dependent on land use is imposed at the top: 15 mm/year for the area covered with forest based on water budget calculations (Antonellini et al. in press) and 200 mm /year on the dunes close to sea. See Fig. 1 for the other boundary conditions. In some models a north south drain boundary condition is added in the lowest area, conform to the existing drainage channel. The conductance of the drain assigned is 10 m^2/day. Two different initial salt concentrations were used for all models, one with a uniform *low initial concentration* of 1 g/l and one with a so-called *high initial concentration* where the upper 3 layers have a concentration of 1 g/l, layers 4, 5 6 and 7 have 15 g/l and 8 and 9 layers 30g/l. The initial salt concentration is thought to have a large influence on the final result (e.g. Oude Essink, 2004) in variable density models. Because our aquifer was actually covered by the sea not so very long ago (320 years, Giambastiani et al 2007) there is the possibility that connate sea water is present at the bottom of the aquifer.

SUMMARY OF SIMULATION RESULTS

In the models *without a drain* and *low initial concentration*, salt invades mostly the high conductive sand layers in the first 13000 days of the simulation, advancing with a linear front. After about 18000 days, also the prodelta deposits between the more permeable sand layers are invaded and the fresh-salt water interface has the typical shape of a wedge leaving about 3 m of fresh water underneath the dunes and about 20 m of fresh water at the inland boundary. The total simulation time is 22000 days, about 60 years equal to the time that passed since the dune destruction and the drainage of the lower part started. The flowmodel has not yet reached equilibrium; the salt concentrations are still changing with time. The model *without a drain and high initial concentration* shows a similar pattern except that after only 5000 days the prodelta deposits fill up with saltwater.

In the models *with a drain and low initial concentration* of *the* intrusion of salt water into the upper sand layer is much faster and further. At 10000 days, the salt water in the upper sand formation has reached 200 m inland forming a horizontal saltwater tongue with the tip underneath the second row of dunes (Fig. 2), leaving a fresh water bubble in the prodelta deposits underneath. After 22000 days the fresh water bubble has almost disappeared and the front of the saltwater starts to approach wedge shape, although it is still changing at the end of the simulation. Results of the model *with a drain and high initial concentration* are very similar except that the low conductivity formation is invaded faster.

The models B *with high dispersivity and isotropic conductivity in all layers* result after a simulation time of 22000 days in a less distinct interface vertically between salt- and fresh water, leaving only small pockets of fresh water underneath the higher dunes. The horizontal advancing of the salt front is irregular with protrusions that correspond to gaps in the dunes along the coast.

DISCUSSION AND CONCLUSIONS

Both observed and modeled salinity values underneath the dunes closest to the coast fall between 1 and 5 g/l suggesting that the combination of positive topography and high recharge in this area is enough to sustain a freshwater lens. This holds also for the models with a drain. The second row of dunes inland seems to play an important role in halting the intrusion that is enhanced by the drain. Except Models B, all models do not show high salinity values in the low lying areas between the two dune belts or at the back of the dunes. Models B do show higher salinity value between the two dune belts but not around the drain. Therefore, perhaps the dispersivity and vertical conductivity are much higher than we thought realistic or other factors are contributing to saltwater intrusion such as the Lamone River to the north, the saltwater marshes to the West, or unknown water managing activities. Some conclusions from this study are: Lidar data has proven to be very useful in defining the topography. A high versus a low initial salt concentration only influences simulation results in early simulation times. The models with the drain do not seem to reflect a stable fresh-salt water interface after 22000 days or 60 years, suggesting that in reality also the salt –fresh water interface is still changing. Mitigation measures to protect the remaining fresh water must include strategies to preserve the dunes not only directly along the coast but also and perhaps foremost, the continuous row of dunes in the middle of the Pine Forest.

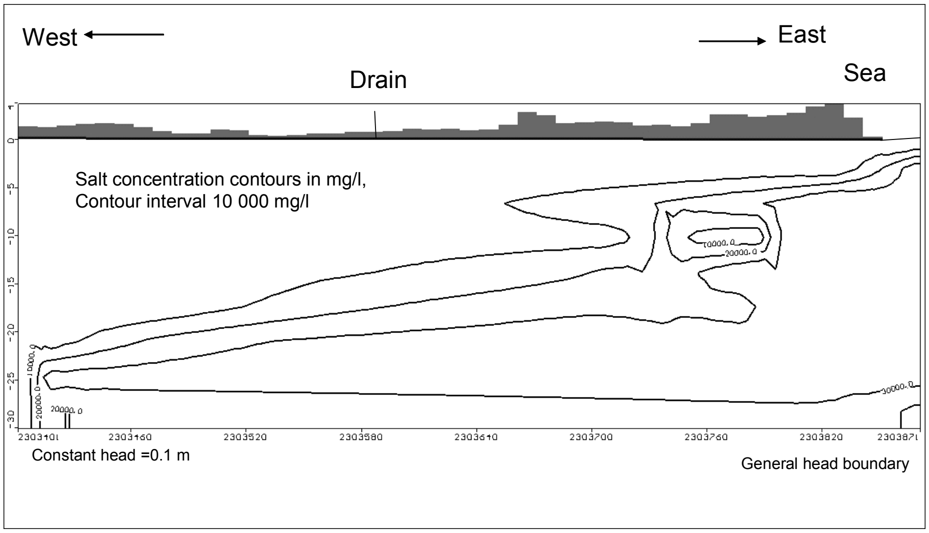

Figure 2. Contour plot of Simulation results for the case with a low initial concentration and a drain. Simulation time 22000 days.

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