Saltwater intrusion in a coastal contaminated aquifer density-dependent finite element model of flow and transport to assess remediation strategies and saltwater intrusion at a coastal gas plant site

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ABSTRACT: This abstract presents a case study about a remediation plan carried out at a Gas Plant site located near the coastline Southern Italy. The aim of the project was to assure an effective containment of the groundwater flow, reducing at the same time the intrusion of saltwater into the freshwater aquifer. Hydrogeology in the area is characterized by the presence of a sandy-loam phreatic aquifer, approximately 30-meter thick. Groundwater level ranges between 0 and 2 meters above mean sea level. Arsenic and total petroleum hydrocarbons (TPH) are the main constituents of interest in the groundwater.
A 3D density-dependent flow and transport model was implemented using the finite element code FEFLOW. The design of the numerical grid, assignment of boundary conditions, hydraulic and hydrodispersive properties were based on previous hydrogeological studies.
Validation procedures were performed including calibration and sensitivity analysis by means of hydraulic heads and total dissolved solids (TDS) estimates derived by electrical resistivity measurements.
Once calibrated, the model was run to verify the effectiveness of the already implemented site emergency remedial actions. The calibration was also performed to support further remediation planning. Remediation strategies included: pumping wells, injection wells, as well as groundwater flow physical barriers.
A coupled pumping–injection barrier resulted the best remediation strategy. The solution allowed either the effective containment of the groundwater contamination and the control of saltwater intrusion. The model demonstrated that installing a groundwater physical barrier would actually increase saltwater intrusion at the site and compromise the groundwater quality in the shallow aquifer in the area between the site and the coast line.

INTRODUCTION

A 3D groundwater flow numerical model was developed using the finite element code FEFLOW®. The design of the numerical grid and assignment of boundary conditions and hydraulic properties were based on previous hydrogeological studies.
The model was developed to confirm the effectiveness of the site emergency remedial actions already implemented, and to support further remediation planning: the aim of the remediation project is to contain the migration of the contaminants out of the site and to stop seawater intrusion. In particular, the remediation strategies included: pumping wells, injection wells and a vertical barrier.

SITE DESCRIPTION

The site, located in the South of Italy near the coast, is a Gas Plant covering an area of 66.000 m^2.
The subsoil of the coastal plain surrounding the site is characterized by alluvial sands and gravels of Quaternary age. Towards the hinterland marine sediments are found, consisting in yellow sands with clay lenses and clays with interbedded sand (formations known as' Yellow Sands' and 'Blue Clays', upper and middle Pliocene).
Hydrogeology in the area is characterized by the presence of a sandy-loam phreatic aquifer, approximately 30-meter thick. Groundwater level ranges between 0 and 2 meters above sea level. The coastal phreatic aquifer flows from West to East, perpendicular to the coastline and heading towards the sea. An impervious clay level located between 32 and 36 m deep from ground level was found which represents the bottom of the aquifer (Blue Clays).
The aquifer is contaminated by arsenic and total petroleum hydrocarbons (TPH). Since the area is located 200 metres from the coastline, groundwater flow and hydrogeochemistry is strongly influenced by seawater intrusion.

3D FLOW NUMERICAL MODEL

The groundwater flow has been simulated using the FEFLOW code (Diersch, 2002), a modular three-dimensional finite element groundwater flow model.
To assign the site boundaries conditions at a sufficient distance not to interfere with the modelling results, the model covers an area of 2’086’543 square meters (m2), while the Gas Plant area has an extension of only 66’000 m2 (Figure 1).
The horizontal mesh refinement includes 12’475 elements and 6’370 nodes. The elements’ dimensions range from 10 m along the coast to 50 m along the western side. This close net has been built in order to have a good detail both in the site area and on the coastal side. The mesh has been tested in order to avoid numerical problems in the zones characterised by discontinuities: the mesh respects the Delunay criterion and it doesn’t include obtuse triangles, nor “holes”.
The 3D numerical domain (Figure 1) has a thickness of 30 m (from 0,5 m a.m.s.l to 35 m a.m.s.l). It includes 10 layers (3 m of thickness) and 11 slices (or surfaces). The first and the last slices, representing respectively the top and the bottom of the aquifer, have been produced by using field data, interpolated by the kriging method. The 3D model has 124’870 elements and 70’136 nodes.

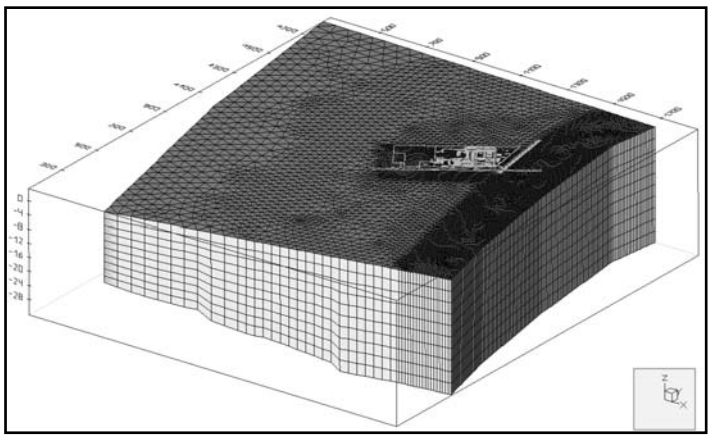

Figure 1: 3D grid design

Constant values of hydraulic conductivity, derived from field data, characterize the whole domain: Kx=Ky=1x10-4 m/s, Kz=1x10-5 m/s. These values were evaluated in the sensitivity analysis. The system is influenced by the following physical boundaries: the sea (inflow-outflow), the up-stream hydraulic head (inflow), the pumping wells of the hydraulic barrier and the water supply wells (outflow). The site boundaries are summarized as follows (Figure 2).
Recharge is calculated using Connor equation (Connor, 1996), and ranges from 43 mm/yr to 86 mm/yr in a sandy-loam soil.

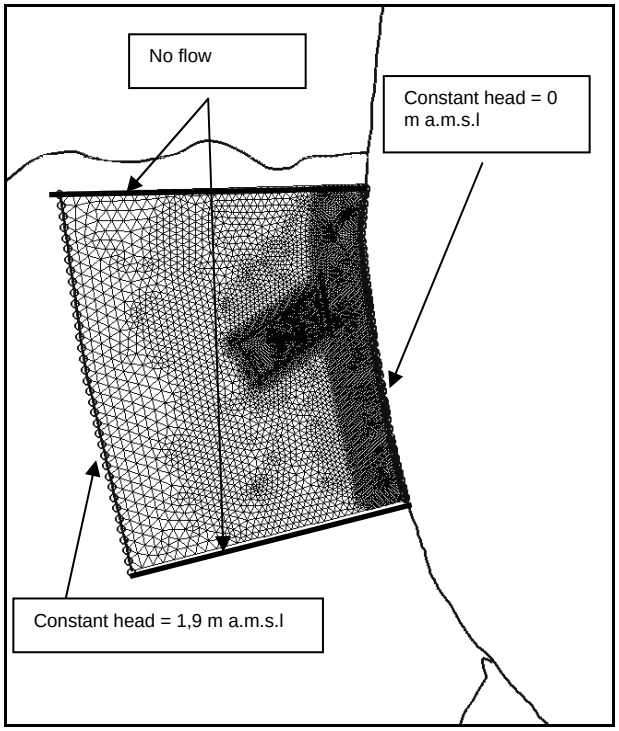

Figure 2: Flow model boundary conditions

The static head has been assigned as initial head. The model has been calibrated initially under steady-state conditions. In the calibration process, a trial and error procedure (Anderson and Woessner, 1992; Spitz and Moreno, 1996) has been carried out, in order to minimize the residuals (difference between the simulated and the measured levels). Model simulation of the aquifer water table and the comparison between simulated and observed head are shown in Figure 3.

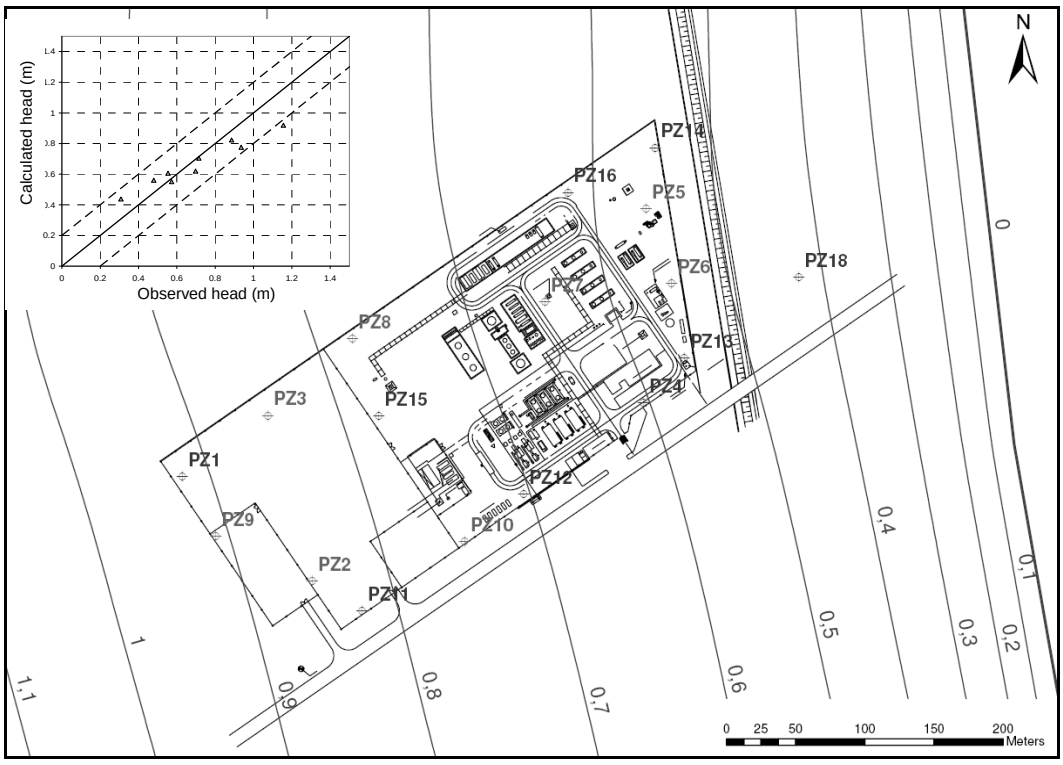

Figure 3: Steady-state simulated head

3D SEAWATER INTRUSION NUMERICAL MODEL

A 3D density-dependent transient flow and transport model has been implemented in order to evaluate the intrusion of seawater (i.e., the movement of seawater into fresh water aquifers due to natural processes or human activities) into the coastal freshwater aquifer.
In an unconfined aquifer that contacts the sea at the shoreline or seaward, the freshwater, which is less dense than seawater floats as a lens-shaped layer on top of seawater and the weight of the overlying freshwater depresses the seawater below sea level. Generally, freshwater recharge in these aquifers moves downgradient and eventually discharges to low-lying coastal areas and into the sea. But pumping out fresh ground water reduces the weight of the overlying freshwater, which in turn can decrease or even reverse the seaward flow so that seawater moves landward into the freshwater aquifer. This migration of seawater into the freshwater aquifer is known as seawater intrusion. The interface between the salty groundwater below and fresh groundwater above is a transition zone of gradually mixing fresh and salt waters. The location of the transition zone depends on several natural and human-made conditions: the relative densities of seawater and freshwater, the tides, the pumping from wells, the rate of groundwater recharge and the hydraulic features of the aquifer. According to the Ghyben-Herzberg Principle (Bear et al., 1999), salt water rises 40 meters for every 1 meter of freshwater depression and forms a cone of ascension.
The transient model development has been based on the 3D steady-state flow model and takes into account the anthropogenic pressure due to pumping wells on the aquifer.
Because of the complexity of the site, a 2D model has been implemented along a section perpendicular to the coast. This approach allowed to estimate the longitudinal and transverse dispersivity of the total dissolved salt (TDS) in the aquifer. These parameters are usually site-specific, obtained by tracer tests. Since tracer tests were not performed, this step is important to calibrate the aquifer dispersivity.
The first step included the estimate of the extent of the natural transition zone. In particular, we modelled a transient simulation of the period between 1800 and 1940 which is characterized by the absence of human activities (pumping wells). The second step included the transient modelling of the pumping wells installed and operated to support industrial activities in the area of interest. The pumping rates were decreased in the last years of the period modelled (1940 to 2008) because of the closure of some of the manufacturing facilities.
After parameters assignment, a sensitivity analysis was performed to understand the uncertainty of the input data, including hydrogeological and hydrodispersive parameters.
The flow boundary conditions were assigned as specified in the previous paragraph; the hydraulic head was assigned to the sea considering the difference of density between sea-water and fresh-water (density ratio), since we are performing a seawater intrusion model.
The TDS transport boundary conditions assumes the following constant concentration of TDS: upgradient constant concentration of TDS is 0 mg/l; downgradient constant concentration of TDS: is 30.000 mg/l.
The static water table has been given as initial head. A 0 mg/l initial concentration of TDS has been assigned.

CALIBRATION AND SENSITIVITY ANALYSIS

Validation procedures were performed including calibration and sensitivity analysis.
The sensitivity analysis was performed in order to understand the uncertainty in the model caused by the uncertainties in the estimates of the aquifer parameters, stresses and boundary conditions. During the sensitivity analysis values for hydraulic conductivity, hydraulic head and dispersivity were varied.
The calibration procedure consists in modifying the aquifer parameters and the boundary conditions in order to obtain a model suitable to simulate the groundwater flow and the contaminant distribution, within the calibration target. In the calibration process, a trial and error procedure (Spitz and Moreno, 1996) has been carried out in order to minimize the difference between the simulated and the measured levels/concentrations (residuals).
The groundwater flow has been calibrated by comparing the simulated hydraulic head and the observed hydraulic head on March 2008. Figure 3 shows the simulated water table. The residual analysis highlights the effectiveness of the head calibration.
Total dissolved solids (TDS) estimates, derived by electrical resistivity measurements (Langevin, 2001), has been calibrated. The observation points are the monitoring wells located near the site east boundary, where pumping wells are present. The evaluation includes slice 2, 4, 6 (about 0-18 meters

above sea level). The shallow part of the aquifer represents the most sensible layer that has to be preserved. Figures 4 and 5 show the seawater intrusion after 208 years of simulation.

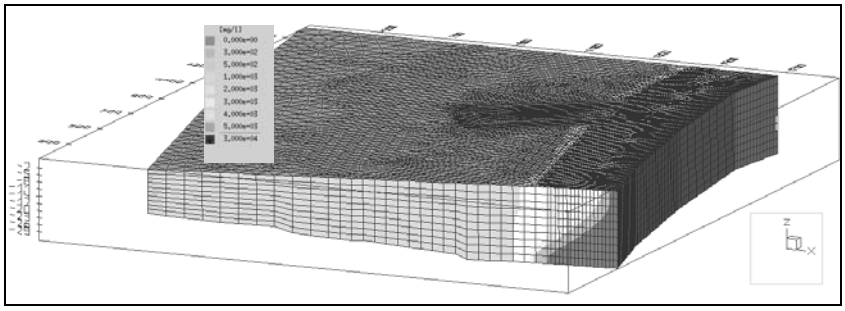

Figure 4: Simulated seawater intrusion (March 2008)

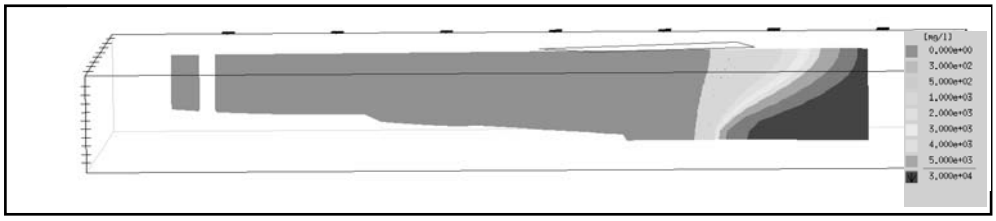

Figure 5: Simulated TDS concentration along a section perpendicular to the coast (March 2008)

The surficial layers have a more stringent calibration target (500 mg/l TDS) than the intermediate one (1000 mg/l TDS). The graph below represents the comparison between the simulated TDS concentration and the observed TDS concentrations (Figure 6). The figure shows that the majority of the points fall within the calibration target.

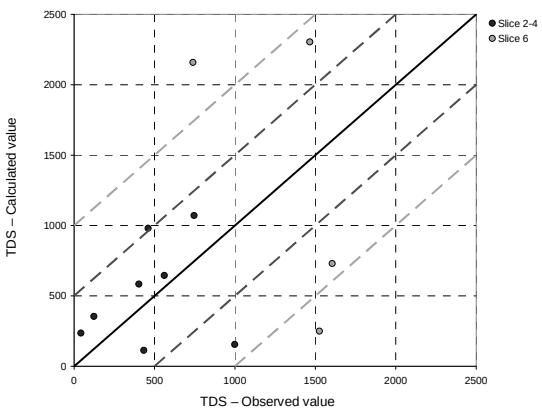

Figure 6: Comparison between simulated and observed TDS concentration; calibration target are represented by broken lines

PREVISIONAL SCENARIOS

Once the model was calibrated, it was run to verify the effectiveness of the site emergency remedial actions already implemented, and to support further remediation planning. In particular, the remediation strategies included: pumping wells, injection wells and vertical barriers.
The following figures highlight the difference between the main solutions:

- Hydraulic barrier (pumping wells and injection wells) (Figure 7);
- Hydraulic and vertical barrier on the sea side (Figure 8).

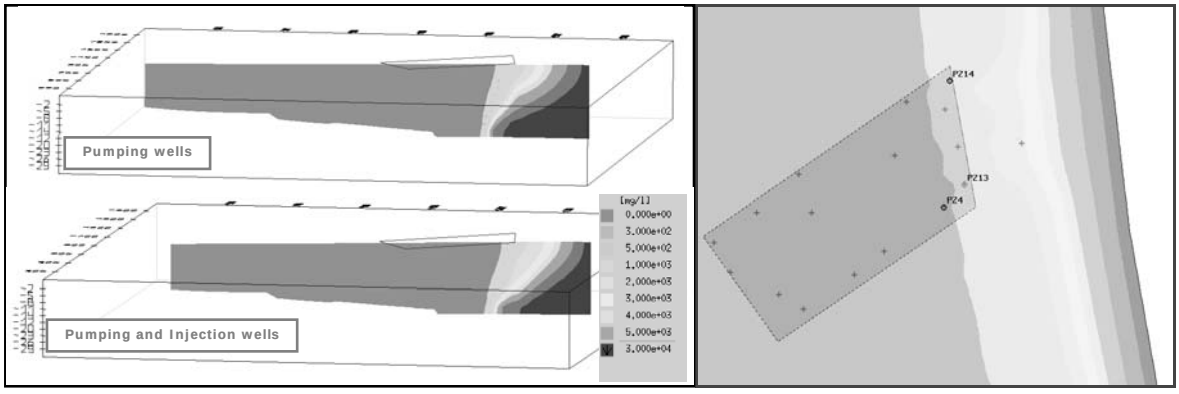

Figure 7: TDS concentration after 5 year of simulation. Hydraulic barrier (pumping and injection wells) – cross sections and plan view

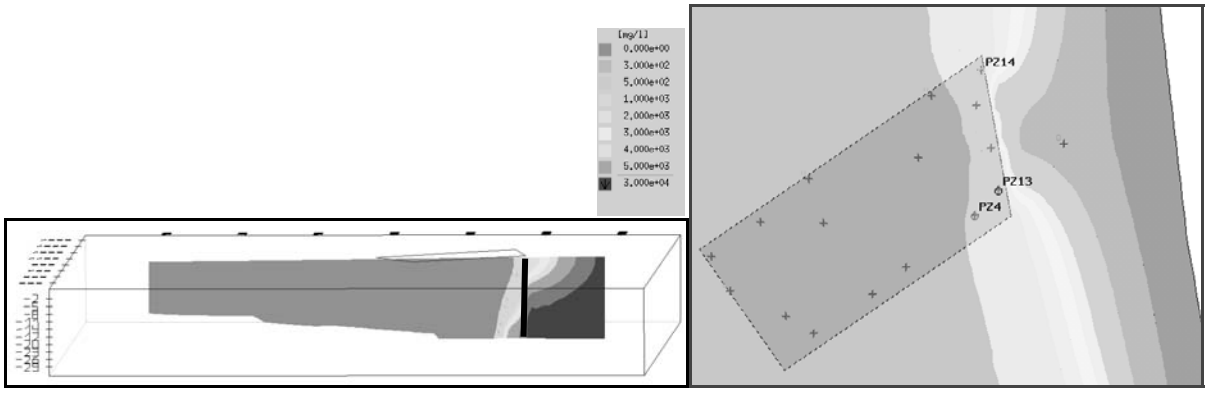

Figure 8: TDS concentration after 5 years of simulation. Vertical barrier on the sea side – cross sections and plan view

The model demonstrated that installing a groundwater vertical barrier would actually increase seawater intrusion at the site, and that the best remedial solution would be a coupled pumping–injection barrier. In fact, this remediation strategy would allow for effective containment of the groundwater flow, reducing at the same time the intrusion of seawater into the freshwater aquifer.

SUMMARY

This article presents a case study of the application of numerical modelling to jointly assess seawater intrusion and the remediation strategy for a coastal aquifer. A 3D density-dependent flow and transport model was implemented using the finite element code FEFLOW (Diersch, 2002).
Based on the model results, a coupled pumping–injection barrier is the best remediation strategy. This solution allows the effective containment of the groundwater contamination and controls the intrusion of seawater. Installing a vertical barrier would actually increase seawater intrusion at the site. The consequence would be a worsening of groundwater quality in the shallow aquifer in the area between the site and the coast line.

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