ABSTRACT: A 3D density-dependent groundwater flow numerical model was implemented using the finite element code FEFLOW, in order to assess the groundwater flow underlying an industrial plant along the coast-line. The model evaluates the effects of different remedial strategies in the containment of the groundwater contamination; in particular a physical barrier has been simulated along the cost line. Hydrogeology in the area is characterized by the presence of a sandy-loam phreatic aquifer, approximately 25-meter thick and total head ranges between 2 and 4 m above mean sea level. The aquifer bottom is composed by blue-gray clay and it is approximately 10 m thick. The domain size is approximately 5,000,000 m², divided in 4 superelements. Mesh refinement includes 205540 elements, 115060 nodes, 10 layers and 11 slices; the close net has been built along the physical barrier. Previous hydrogeological studies permitted to design the numerical grid and to assign boundary conditions and hydrodynamic properties. These properties were based on field data interpolations. Validation procedures on head measurements includes calibration and sensitivity analysis. Once calibrated, the model was run to verify some different settings. The simulations allowed checking the effectiveness of the physical barrier, and the amount of the wells pumping rate required to avoid the flood of the site. The model results demonstrated that the physical barrier will influence the groundwater level causing the rise of the water table. Consequently a coupled physical and hydraulic barrier would be the best remediation strategy, allowing an effective containment of the groundwater movements out the site.

INTRODUCTION

This article presents a case study regarding the application of numerical modeling in order to value the groundwater flow in a coastal aquifer and to support remediation strategies. ENSR Italia was commissioned to plan a remediation design in a coastal site. This project evaluate the construction of a vertical barrier along the costal-line and the pumping wells installation into the site to prevent the groundwater contamination flow to the sea. The vertical barrier has to be 40 m depth to reach the clay bottom of the first aquifer. A 3D groundwater flow numerical model was developed using the finite element code FEFLOW®. The model was implemented to evaluate the effect of different remedial strategies in the containment of the groundwater contamination. The numerical grid design, the boundaries conditions and hydraulic properties were based on site specific data and on hydrogeological studies. The groundwater flow model was integrated with a Geodatabase (Geographic Information System, GIS) to collect all relevant environmental information and easily compare field and calculated results.

SITE DESCRIPTION

The site is an oil facility located in a 5'000'000 m² extent coastal industrial area in Italy. Near the site different coupled hydraulic and vertical barriers are present, in order to prevent the contaminants diffusion into the sea.
The geology of the coastal plain surrounding the site is characterized by alluvional formations; these alluvional series are composed by sand and gravel layers interbedded in clay and loam horizons. Near the coast the thickness of the sand horizons is greater. At the bottom of the alluvional sediments there is a 10 m thick clay formation representing the base of the aquifer.

Hydrogeology in the region is characterized by the presence of a sandy-loam phreatic aquifer, approximately 25 meters thick and total head ranges between 2 m and 4 m a.m.s.l.

The coastal phreatic aquifer flows from South-West to North-East, perpendicular to the coast-line and heading towards the sea, with a 6‰ hydraulic gradient. The hydraulic conductivity ranges from $10^{-3}$ to $10^{-5}$ m/s. The distribution of hydraulic conductivity has been interpolated using kriging algorithm (Figure 1).

![Figure 1: Hydraulic conductivity distribution.](image)

**MODEL DEVELOPMENT**

The domain size is approximately 5'000'000 m$^2$ while the area of interest covers 20'000 m$^2$. The model domain was defined in order to assign the boundaries conditions at a sufficient distance not to interfere with the modelling results.

The groundwater flow has been simulated using FEFLOW code. The domain size was divided into 4 super-elements in order to change the elements dimension in the different model portions. The mesh consists in prismatic elements with triangular base; the elements' dimension ranges between 70 m, along the South of the area, to 10–20 m along the costal-line. The mesh was refined along the vertical barrier system in order to have a good detail in the site area along the coastal side. The 3D numerical domain (Figure 2) has a thickness of about 50 m. It includes 10 layers and 11 slices. 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 includes 205'540 elements and 115'060 nodes.

The mesh has been tested in order to avoid numerical problems in the zones characterised by discontinuities. The mesh respect the Delunay criterion and it doesn’t include obtuse triangles, nor "holes".
Boundary conditions were assigned according to the hydrogeological assessment and hydrography. The physical boundaries of the system are the following: the sea, the upstream hydraulic head, the barriers and the pumping wells. The site boundaries are summarized as follows (Figure 3):

- In the south of the area was assigned a constant flow (II Type condition - Neumann); constant flow rate is about 2000 m$^3$/d;
- In the north the costal-line was represented by a constant head (0 m a.m.s.l.);
- Recharge is simulated by a constant flow boundary condition and it ranges from 31 mm/yr to 63 mm/yr, as calculated using Connor Equation (Connor, 1996);

The vertical barriers have been simulated by low permeability zones ($10^{-8}$ m/s).

The initial head applied to the model is referred to a static piezometric level available for the site.

**Figure 2: 3D grid design.**

**Figure 3: Flow model boundary conditions.**

**CALIBRATION AND SENSITIVITY ANALYSIS**
A sensitivity analysis was performed in order to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions (Anderson and Woessner, 2002). During a sensitivity analysis, calibrated values for hydraulic conductivity, boundary conditions (constant head) and recharge are systematically changed within the previously established reasonable range. The sensitivity analysis was performed changing the values of hydraulic conductivity, constant flux and recharge to see the effects on the groundwater levels.

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, 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 (residuals). The groundwater flow has been calibrated by comparing the simulated hydraulic head and the observed hydraulic head.

The criterion value for convergence required to let out the iterativity process has been set at 10^{-3} m. The comparison between the simulated and the measured levels is showed in Figure 4; all simulated values are included between the confidence level (95%). The quality of the calibration is confirmed by the value of the correlation coefficient (0.96).

Figure 4: Model calibration.

PREVISIONAL SCENARIOS

The calibrated model was run to simulate different scenarios. The simulations allowed checking the effectiveness of the physical barrier and the pumping wells discharge rate required to control the groundwater level in previsional scenarios. In particular, the scenarios are described as follow:

- Scenario 1: Future design considering the pumping from wells inside and outside the site boundaries;
- Scenario 2: Future design considering only the pumping from wells inside the site boundaries;
- Scenario 3: Future design without pumping wells.
In the following figures (Figure 5, 6 and 7) are shown the effect on groundwater flow due to the presence of the vertical barrier and the pumping wells.

Figure 5: Scenario 1. Future design considering the pumping from wells inside and outside the site boundaries

Figure 6: Scenario 2. Future design considering only the pumping from wells inside the site boundaries
CONCLUSIONS
The model was implemented to evaluate the effect of different remedial strategies in the containment of the groundwater contamination. The model results demonstrated that the physical barrier will influence the groundwater level causing the rise of the water table. Consequently a coupled physical and hydraulic barrier would be the best remediation strategy, allowing an effective containment of the groundwater movements out of the site. The simulations allowed checking the effectiveness of the physical barrier and the amount of the wells pumping rate required to avoid the flood of the site. The simulated scenarios allowed concluding that 6 pumping wells inside the site are sufficient to contain the contamination and the rise of the water level. This pumping system is efficient either with external pumping wells or without them, considering an increasing of the pumping rates. The final remediation design will consider a water treatment plant able to manage different amount of water.

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REFERENCE
