SURFACE AND GROUND WATER FLOW MODELLING IN THE RESTORATION OF THE MEIRAMA OPEN PIT MINE

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Abstract
The interaction between the free surface and the ground water flows in a basin is a fundamental issue in the study of several environmental problems that require a comprehensive knowledge of the balance and quality of the water flows. Nowadays there is a good number of numerical models in the market, that allow for an evaluation of the free surface hydrodynamics, in one side, and for the groundwater flow in the other side. Still, there is a lack of model skills to evaluate the free surface and ground hydrodynamics in a joint way, and moreover including water quality criteria. The *Ingeniería del Agua y del Medio Ambiente* (Water and Environmental Engineering Group) group has been working in these fields for some years and has developed a software that allows for the numerical evaluation of this kind of problems.
In this work it is shown the application of the developed codes to the working out of a model that evaluates the joined surface and ground water flows in an opencast mine to be restored as a lake. The so-predicted results are presented as a conclusion to shortly elaborate other alternatives in order to restore the opencast mine as a lake.

Meirama opencast mine
The mining activities that have been taking place in the Meirama opencast lignite mine are to be abandoned at the end of 2007. The firm LIMEISA (LIgnitos de MEIrama Sociedad Anónima) has been exploiting Meirama mine since 1980. The lignite deposit is situated in the province of La Coruña, north-western Spain, 25 km from the city of La Coruña. A 550 *Mw* power station, fuelled by the lignites of Meirama, was built nearby to produce energy from Meirama coals. At the moment of its closure in 2007 the mine will have produced some 87 million tons of lignite. Mine tailings of some 160 million m^3 were moved to a nearby storage tip. The mine has been producing from 4 to 10 million m^3 per year during the first years of the exploitation and some 3 million m^3 during the last years.

Figure 1. Location and view of the Meirama opencast mine and Power station Meirama pit lake.

During the exploitation of the opencast mine many environmental activities have taken place in order to reduce the environmental impact of the mining and power generating activities. With respect to the earthwork, 350 ha have been restored and 300 ha have been reforested. At the end of the mining activities the firm LIMEISA has planned to recover the mine pit as a lake with a maximum depth of some 180 m and a surface of nearly 2 km^2. To do so, a dam is to be built at the downwind tip with a free spillway at a height of some 180 m. The prospective pit lake is to lie on the Barcés river basin, and affects some 33 km^2.
Based upon the annual mean rainfall and the considered filling alternative, a period of about 7 years has been estimated as a reasonable time to complete the filling of the lake.

Aims of the present work

The management of water during the filling and post-filling periods shows up like a fundamental issue in both their hydrodynamic and water-quality aspects, and deserves a close attention in order to reduce not only the environmental impact but also many unwanted effects that can take place due to a wrong evaluation of the behaviour of such a vast volume of water. The environmental and geotechnical consequences of such a project are still uncertain. Although some effects can be assessed in terms of the previous world-wide experiences in connection with the own features of Meirama open pit, the final consequences are not certain. Within this frame, the authors are carrying out a numerical evaluation of the behaviour of the water during the filling and post-filling periods that may cast some light on the real performance of the water in the basin and on the environmental consequences of the filling of the Meirama Lake. This numerical evaluation is intended to assess the hydrodynamic behaviour of the joined surface and ground water flows in order to be able to shortly analyse the water quality evolution.

The software to be used in the numerical evaluation includes some codes developed within the *GIAMA* group such as MELEF, HIDRAFEM, FREECORE, and some commercial codes such as SMS or TECPLOT. To carry out such a study, many field measures are to be made that provide information about the hydrologic and hydraulic parameters of the basin, such as rainfall, piezometric levels, discharges and geological characterizations, in terms of which some other parameters such as storage coefficient, hydraulic conductivity, Manning coefficient and turbulent viscosity can be calibrated.

As part of the carried out work, some measures have been taken in the nearby Eume reservoir, where temperature and conductivity at different depths and at different seasons have been obtained. The Eume reservoir is of similar climatological, limnological, and geological characteristics to those of the Meirama pit lake, and in this way these data provide with relevant data about the prospective lake. These data show that there is no winter thermal inversion even for tough winter conditions (see Fig. 2), and therefore, no thermal inversion is expected in the Meirama lake.

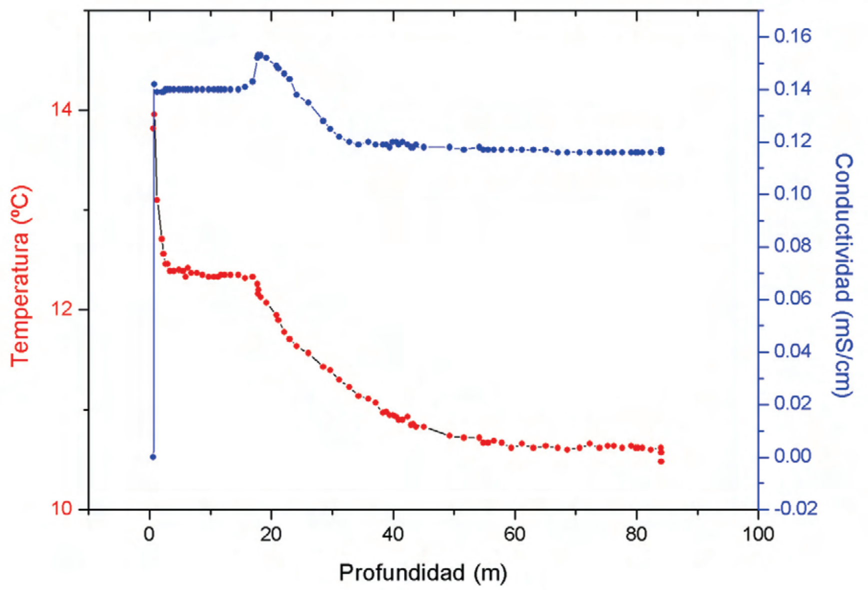

Figure 2. Temperature (lower line) and conductivity (upper line) vs. depth in the Eume Reservoir (December 2006).

Hydrogeological issues

At present (February 2007) the open pit is still in use and some twenty pumping stations are placed in its contours so as to withdraw the water table. To prevent the water getting into the pit, two perimeter canals were built. With a mean annual rainfall of some 1500 mm, a drain capacity of 12000 m^3/h is required to drain water from the pit, leading it to two treatment plants with a total capacity of 10 million m^3. Once the water has been treated, it is spilled into the Barcés river. Geologically speaking there are two main regions in the affected area, one in the NW featured by a granite massif and a second one in the SE characterized by a schist substratum. Most of the excavation works take place on a sedimentary basin with Tertiary materials. The granite and the schist have a scant hydraulic conductivity. This contributes to promote the free flow to the detriment of that of the groundwater. The granite is quite weathered and kaolinized, what contributes to a worse hydraulic conductivity. These materials constitute not only the boundary of the excavation area but also, in some way, its underlying substratum, and therefore are responsible for the hydrological behaviour. For these materials hydraulic conductivities of $1.5 \cdot 10^{-6}$ m/s (schist) and $5 \cdot 10^{-6}$ m/s (granite) could be considered. Nevertheless, these parameters have been adjusted in a calibration process based on the water level measurements during a period of two years.

Physical model

The drainage basin of about 33 km^2 has been discretized in terms of a 7594 node mesh, with 14975 triangular elements, being more refined in the regions where a surface flow is expected. The mesh has been adapted to fit the situation of the gauging and pumping wells. With these data and those of the total rainfall and water uses, the model has been calibrated along the hydrological years 1999/2000 and 2000/2001, adjusting not only the hydrological parameters (namely, hydraulic conductivity and storage coefficient), but also those related to the geology, evapotranspiration rates and some others related to the runoff and the capillary features of the subsoil zone.

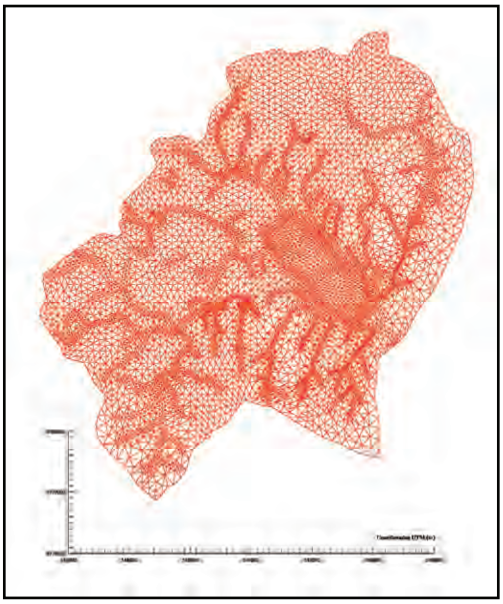

Figure 3. Finite element mesh.

Mathematical model

The *GIAMA* research group works in the development, validation and application of a numerical model in good accordance with the free surface and ground behaviour of the water, capable to evaluate the physical and chemical variables of the flow, taking into account the interaction of all the water resources in a watershed. Thus, many environmental problems, such as natural or induced floods, the evolution of water in ponds, and continental and coastal basins, could be evaluated with a special regard to the aspects concerning the water quality of regions subject to natural or accidental spilling due to industrial, agricultural, mining or urban activities. The code is based upon the finite element software MELEF, which solves both surface and groundwater flow by making use of a numerical diffusive wave approach that takes into account the continental, coastal and wetlands environments, together with an evaluation of the evapotranspiration hydrological components. The set of partial differential equations to be solved are:

$$(n_d)\frac{\partial h_d}{\partial t} = \frac{\partial}{\partial x}\left(K_{xx}(h_d - P)\frac{\partial h_d}{\partial x}\right) + \frac{\partial}{\partial x}\left(K_{xy}(h_d - P)\frac{\partial h_d}{\partial y}\right) + \frac{\partial}{\partial y}\left(K_{yx}(h_d - P)\frac{\partial h_d}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}(h_d - P)\frac{\partial h_d}{\partial y}\right) + Q$$

where the source term Q includes an evapotranspiration model developed by the authors (for details see Méndez et al., 2003).

The computer model MELEF is also able to evaluate the free surface flow making use of a kinematics wave approach through the continuity equation, and provides in that way just a rough approximation. The code MELEF is being improved by including a module that solves the free surface flow on a Navier-Stokes basis that, therefore, includes (together with the continuity equation) the resolution of the dynamic equation for the mixed unknowns velocity (u_i) and pressure (p_i):

$$u_{i,t} + u_j u_{i,j} = -\frac{1}{\rho} p_{,i} + \nu u_{i,jj} + f_i$$

The algorithm to be used in the resolution of the free water flow incorporates a stabilization procedure in order to avoid the instability problems that show up when solving the Navier-Stokes equations even for refined meshes. The code HYDRAFEM, developed by the authors of the paper (see Vellando et al., 2002 for details), is the one chosen to be incorporated to the resolution of the free surface water. A module that incorporates reactive advection-dispersion flows is also to be included.
Once the hydrodynamics of the surface and ground water flows has been obtained, the transport equation is solved for the concentration *c,* in terms of the given velocities ***q***. Possible solute sinks and sources are added to the left-hand-side of the equation.
For a fluid source *r* having a concentration, c^*, and a solute sink/source term, *R* (solute mass added per unit time and unit fluid volume), the transport equation becomes:

$$\nabla \cdot (\mathbf{D}\nabla c) - \mathbf{q} \cdot \nabla c + r(c^* - c) + R = \frac{\partial c}{\partial t} \quad ; \qquad R = \frac{\partial C_j}{\partial t} + \frac{\partial (P_j)}{\partial t} + \frac{\partial (W_j)}{\partial t} + \frac{\partial (Y_j)}{\partial t} \qquad j = 1,2,\ldots,N_C$$

where *R* are the homogeneous and heterogeneous chemical reaction rates, C_j are the total dissolved, precipitated, exchanged and sorbed concentrations of the j-th aqueous chemical species, and *N* is the number of species

Results and Conclusions

After the calibration process has been completed, the software has been applied to the resolution of the hydrological regime to be expected in the Meirama open pit at different conditions, namely, at present, during filling and post-filling stages.

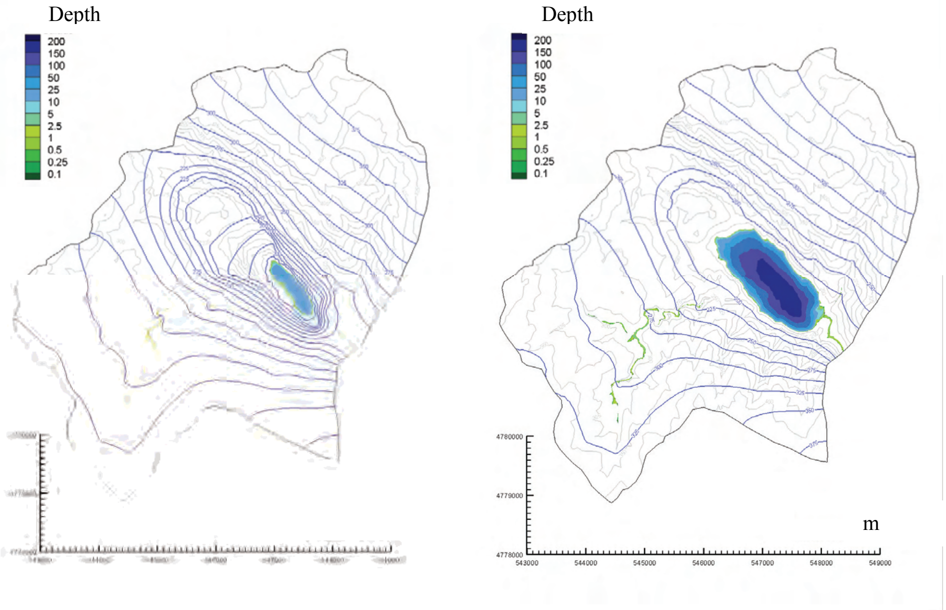

Figure 4. Water table level expected in September 2007 (left) and September 2012 (right).

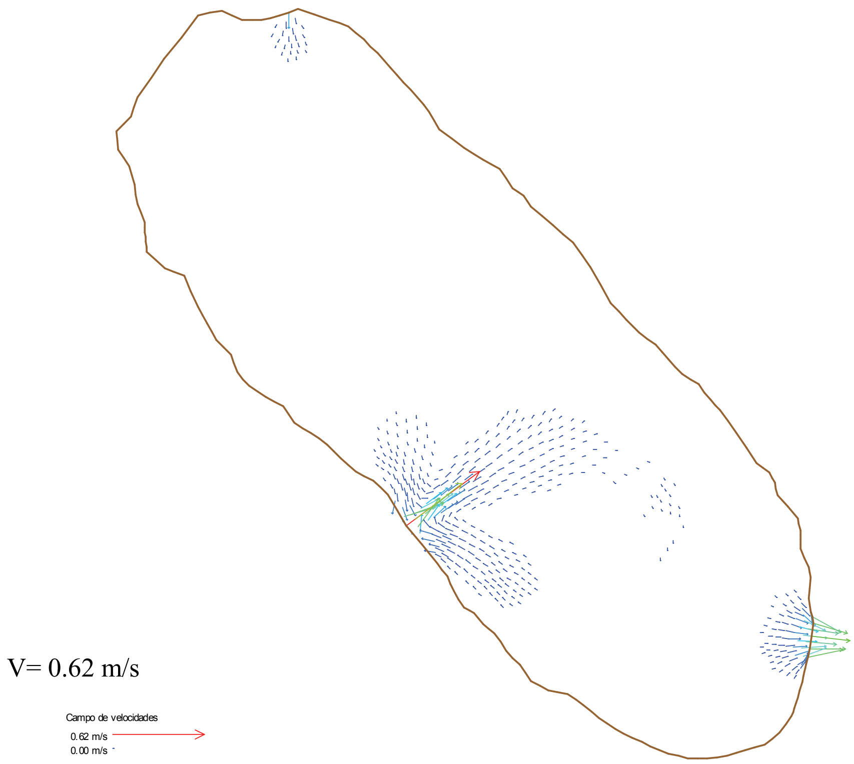

Figure 5. Velocity fields in the prospective pit lake at February 2015.

The results provide data about the height and velocity of the water flow in the basin which are fundamental in order to depict the environmental effects of the mine closure and the creation of the artificial lake. The results concerning the water quality issues are still in progress. Some results concerning the flow variables during the filling and post filling situations are shown in Figures 4 and 5.

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