Water Quality Assessment in the Reclamation of the Meirama Open Pit Mine, NW Spain. Part II. After-Flooding Assessment

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Abstract: - The mining activities in Meirama open pit coal mine (NW Spain) were halted in December 2007 and the mine pit is to be restored as a lake with ~180 m in its deepest point. The flooding is to be carried out with surface waters coming from the upper section of the Barcés river catchment. It is expected that the flooding process will be completed in about 7 years. In 2006, LIMEISA, the company in charge of the mining activities since 1980, entrusted the *Water and Environmental Engineering Group* of the University of A Coruña the assessment of the lake water quality during and after completion of the flooding process. The present paper presents a summary of the work done to assess the water quality parameters in the future lake, carried out with the finite element FREECORE^{2D} software, developed within the group. As a final conclusion, the water quality parameters obtained for the post-flooding conditions will apparently fulfill the requirements set by the environmental authorities.

Key-Words: - Water quality assessment, mine pit restoration, solute transport, hydrochemistry, finite elements, FRECORE^{2D}.

1 Introduction

The coal mining activities in the Meirama open pit mine (A Coruña, NW Spain) finished in December 2007. LIMEISA (*LIgnitos de MEIrama Sociedad Anónima*), the company in charge of the lignite mine since 1980 used the mined coal for supplying of the nearby 550 *Mw* Meirama power station. Since the interruption of coal extraction, the flooding process has started in the pit, with ground and rain waters and still awaits the administrative authorization for the detraction of surface fluxes from the surface waters of the upper Barcés River catchment. According to modeling, it is expected that flooding process will last, at least for some 7 years.

Over the last decade, LIMEISA has entrusted certain institutions and consultants the drafting of different environmental studies associated with the mine reclamation activities and to meet the demands of the environmental authorities and laws in force. A significant part of these reports are concerned with the geological, hydrological, hydrochemical, and geotechnical characterization of the future lake and its surroundings. Several models seeking to assess the environmental effects over the Barcés River catchment have also been developed. The first of these reports on water quality was entrusted to Golder Associates [2] in 2002.

In 2005 to the *Water and Environmental Engineering* Group (GEAMA) evaluated the surface and ground water flow balances associated to the reclamation of the open pit to conform a lake [1]. This report shows the hydrodynamic balance of the surface and ground waters in the basin and provides an accurate assessment of the water flows arriving to the pit. In addition, water flows are not only quantitatively featured but also characterized in terms of the geologic materials they go through or upon.

Taking the results obtained in the former report as an input value, a second assessment was carried out in 2007 to subsequently evaluate the lake water quality parameters and to check its eventual accomplishment with respect the different legal and environmental constrains. This water quality assessment was arranged into two different parts. The first part focuses on the water quality assessment associated to the pre-flooding and flooding stages. To achieve so, a comprehensive sampling survey was performed to complete previously acquired data [2].

In that study, a comprehensive analysis of the natural controls for acidity and metal concentration in the waters surrounding the pit was carried out [3].

With these data, several models that evaluate the hydrochemistry in the lake were developed, based upon the previously mentioned surface and ground water balance model. Thus, the flows of surface and ground water arriving at the pit, were assigned different reference water qualities that were used to make mixing models taking into account several hydrological hypothesis, processes and chemical reactions, so resulting in a prediction of water quality in the future lake. Among the factors that showed the greatest impact over the quality of the lake was the volume of water that interacted with the rock waste dumps inside the pit. Several realistic hydrogeological scenarios were considered, and it was concluded that the quality of the future Meirama Lake would progressively improve as far as the flooding process advances. According to the model, once the lake becomes full, it chemical quality would meet nearly all the regulatory requirements in force. The particulars regarding the first part of this report have been summarized in a companion paper [4].

This second part is devoted to assess the hydrochemical evolution and the reactive solute transport processes taking place in the lake after its flooding. That condition represents the achievement of the quasi-steady flow conditions in the catchment basin and with respect to the discharge flows from the lake towards the Barcés River. In order to evaluate the effect of different processes and scenarios over the chemical evolution of the lake, we developed two approaches. First, a thermo-hydrochemical model was elaborated to check the importance an extent of thermal stratification in the lake. Then, a two-dimensional reactive solute transport model of upper layer of the flooded lake helped us to understand hydrodynamic homogenization processes.

In that contribution we also present the code FREECORE^{2D} [5], with which we performed the numerical simulations.

2 Model Description

Based on the available hydrochemical information, its interpretation and modelling, a series of constraining geochemical reactions (aqueous speciation, acid/base, oxidation/reduction, mineral dissolution/precipitation and ion adsorption) were defined [4]. In addition, because dissolved mass transport in the free surface of any water body is mainly associated to water flow, it was necessary to carry out a hydrodynamic model of the lake. With this data at hand and combining it with the previously defined hydrogeochemical framework, a numerical model was elaborated and it is summarized next.

2.1 Code and Equations

The finite element code FREECORE^{2D} [5] has been used to assess the reactive solute transport in the Meirama Lake after flooding the pit hole. The model is based upon the resolution of the equation of the solute transport, which takes into account advection, molecular diffusion and hydrodynamic dispersion. Advection refers to the solute migration associated to water flow. If water flows at a specific discharge **q** (volumetric water flux), and c is the solute concentration, the advective solute flux $\mathbf{F}_A$ is given by

$$F_A = qc \qquad (1)$$

On the other hand, molecular diffusion is a transport mechanism related to the continuous brownian motion of microscopic particles (ions, aqueous complexes, ion pairs, molecules, etc.) within the realm of the water phase. Its mathematical expression is given by Fick´s law as

$$F_D = -D_0 \nabla c \qquad (2)$$

where D_0 is the molecular diffusion coefficient in water.

In addition to molecular diffusion, there is another mixing phenomenon known as hydrodynamic dispersion which is caused by the turbulent water motion and produces both longitudinal and transverse solute spreading. It is broadly accepted that this mass transport mechanism can also be evaluated in terms of a formulation analogue to the Fick´s law, that is

$$F_H = -D_h \nabla c \qquad (3)$$

where $\mathbf{D}_h$ is the hydrodynamic dispersion tensor. Further details on the formulation can be found in [3]. The equation governing the free surface solute transport is directly derived from the mass conservation equation and can be written as

$$-\nabla \cdot \left(F_A + F_D + F_H\right) = \frac{\partial(c)}{\partial t} \qquad (4)$$

Substituting equations (1), (2), and (3) into equation (4) the following expression is obtained

$$\nabla \cdot \left(D \nabla c\right) - q \cdot \nabla c + w\left(c^* - c\right) + \theta R = \frac{\partial c}{\partial t} \qquad (5)$$

where w is the fluid source of water flux having a concentration c*, R is the solute sink/source term, and **D** is the diffusion/dispersion tensor.

2.2 Physical Model

The numerical formulation has been applied to a two-dimensional finite element mesh with more than 3000 nodes representing the after flooding surface of the lake. The reactive solute transport model is highly affected by the shallow flow at the lake surface, that constantly moves and rinses solutes (Fig. 1).

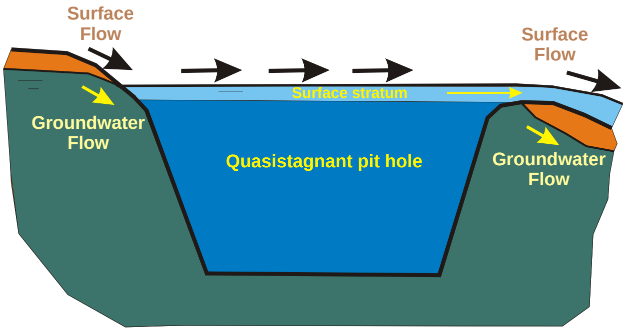

Figure 1. Sketch illustrating a vertical section of the lake and the conceptual model for the post-flooding condition

It is interesting to stress that it should be expected that the advective component of the flow is going to be considerably higher than the diffusive one, although diffusion cannot be neglected. On the other hand, it is likely to find a certain stratification of solutes, with a more or less diluted upper, surficial layer. The mixing and homogenizing of the water will depend upon the eventual vertical velocities induced by a potential thermocline inversion associated to density gradients (Fig. 2).

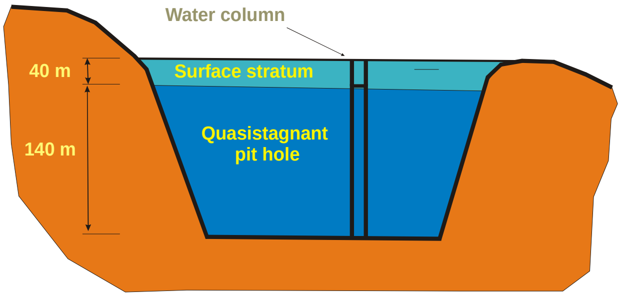

Figure 2. Conceptual model for the thermal analysis of the lake

2.3 Thermal Model

In order to evaluate the likely thermal stratification of the future Meirama Lake and the eventual thermocline inversion, we conducted a thermal study in the nearby Eume River reservoir. This water body has a maximum depth of 90 m and it is located close to our filed area and affected by similar hydro-meteorological conditions. Results of the field survey shows that, at least in the year 2006, there was no thermocline inversion in the reservoir, and that the temperature in its surface stratum (that in winter may achieve a thickness of about 40 m) remained slightly higher than the temperature at the bottom layer. Taking this evidence as a proxy for the Meirama Lake, we developed a numerical thermal model trying to assess the behaviour of the water column with respect to its eventual thermal inversion. In the computations we have assumed a surface and bottom layer thicknesses of 40 and 140 m, respectively and a temperature of 8 ºC for the top water body and 10 ºC for the bottom (Fig. 2). Taking into account that the density gradient that causes the temperature inversion varies not only with temperature, but also with pressure and solute concentration, it can be shown that water density decreases with temperature but increases with the hydrostatic water weight and the solute concentration. This is illustrated in figure 3, where it can be observed that the density variations are not expected to be larger than 0.04%. This should not constitute a significant driving force for thermal inversion. Based on the empirical evidence of the Eume River reservoir and the previous computations, we can assume that, according to the conceptual model depicted in figure 1, the advective vertical solute transport processes can be safely neglected.

2.4 Reactive Solute Transport Model

FREECORE^{2D} allows for the evaluation of flows with heat transfer, and reactive solute transport including equilibrium and kinetic processes. In this work, we have elaborated a 2-D unstructured finite element mesh (6160 triangular elements and 3189 nodes) to model a 20 m thick lake surface stratum in the after-flooding and pouring of lake waters towards the Barcés River. The chemical composition of water flowing to the lake is those derived from the preliminary stages of the study (rain, surface, ground and runoff waters, [2], [4]) and they are taken as boundary conditions. The perimeter of the lake has been divided in 18 regions, each one of them contributing different amounts of water types and qualities.

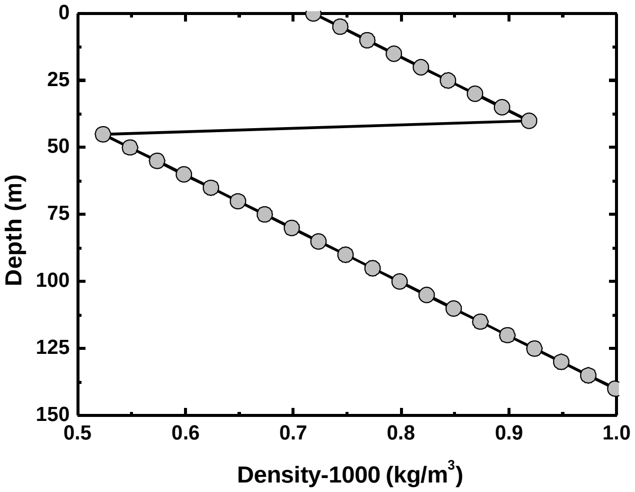

Figure 3. Density variation as a function of pressure (depth) and temperature

A number of hypotheses have been considered in order to construct the reactive transport model: a) The hydrometeorologic situation corresponds the mean of the dry 2014/2015 period; b) 2 injection points for water associated to surface water derivations; c) Constant chemical composition for the inflow waters (including the injection points); d) Allowance of a spillway point towards the Barcés River and possibility for of ground water flowing outwards in the unsteady input values at the rest of model regions; e) Heterogeneous reactions were not considered; and f) 12 unsteady (0.1 days time step) hydrodynamics variations (one per month) associated to the 18 perimeter model regions of the lake (Fig. 4).

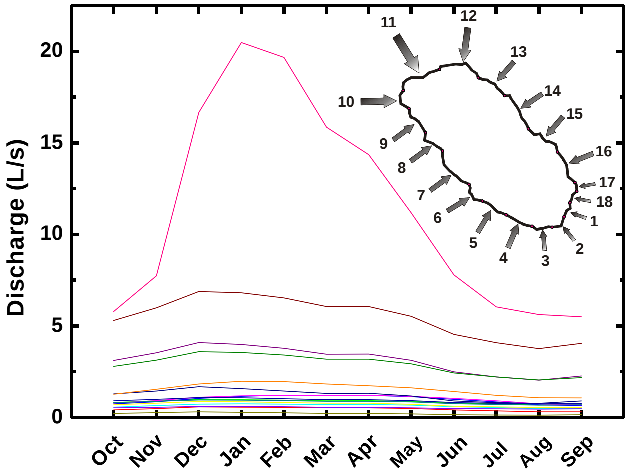

Figure 4. Yearly-distributed discharge through different perimeter sections (numbers in the inset) of the future Meirama lake

Each one of the modelling regions was featured with the parameters of their predominant materials (being schist, sedimentary, rock dump or granite). Neumann boundary conditions (i.e. solute transport associated to water discharge) have been prescribed in all the regions.

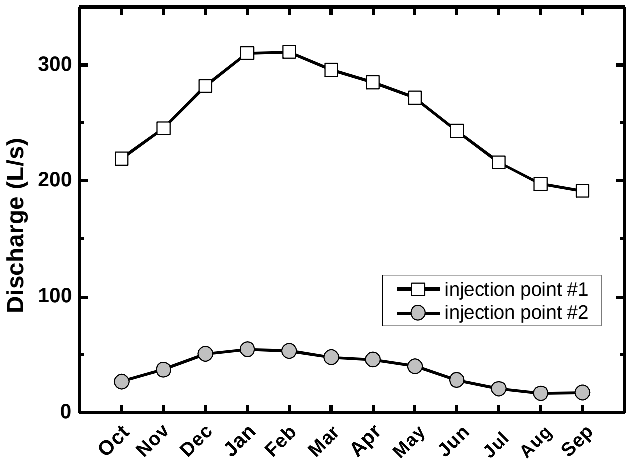

Figure 5. Time-dependent water discharges at the injection points

The hydrodynamic parameters considered for the reactive solute transport model have been the following: Molecular diffusion 10^{-9} m^2/s; Longitudinal and transversal dispersivities 100; Manning coefficient 0.03 $m^{-1/3} \cdot s$. The chemical components considered in the model include H_2O, H^+, HCO_3, Na, Ca, Mg, Mn, Cl, SO_4, K, Al, Fe, NO_3, Co, Ni, Cu, Zn, Ba, As, Cr, Hg, Cd and Pb. More details concerning the initial and boundary conditions assigned to each particular node are given in [1].

3 Results

Reactive solute transport results have been obtained for all the spices considered. For the sake of brevity, only a few of them will be covered here. Figures 6 to 9 show the surface distribution of Al^{+3} and pH at the second (october) and last month (august) of the hydrological year.

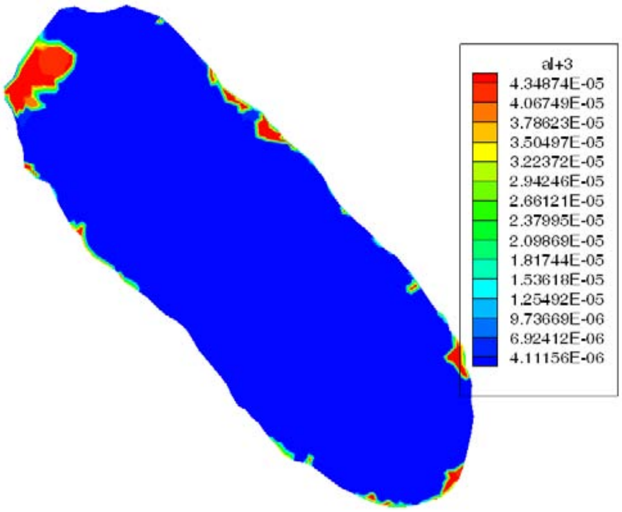

Figure 6. Computed total Al concentrations in the lake in October

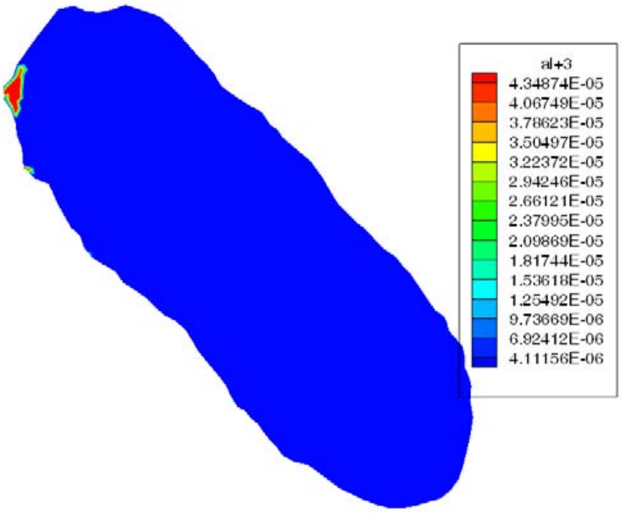

Figure 7. Computed total Al concentrations in the lake in August

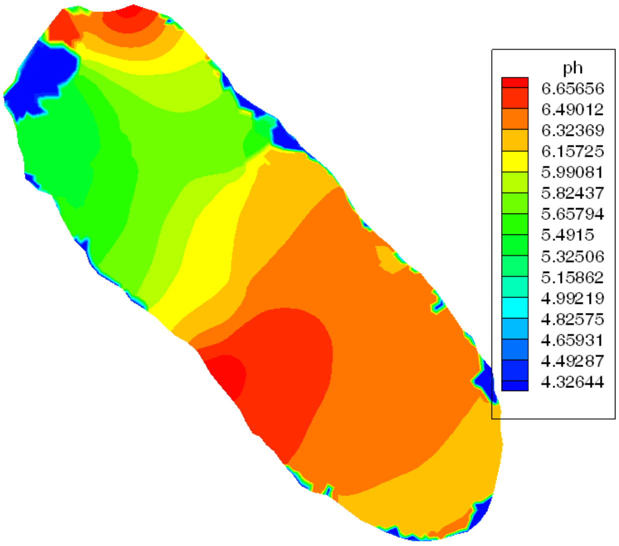

Figure 8. Computed pH of the lake in October

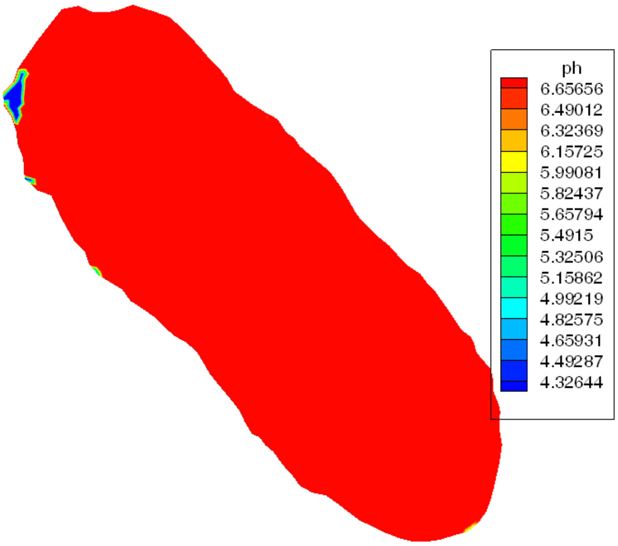

Figure 9. Computed pH of the lake in August

At first glance, it can be observed that an almost complete chemical dilution and homogeneization of species and pH has taken place in the lake, except for some water pockets located at certain points of the perimeter. There, homogenization is to be based on dispersion (which is slower) and not advection.

Figures 10, 11 and 12 show the time evolution of the concentrations of manganese, iron, potassium, aluminum, sodium, calcium, magnesium, total carbonate and pH in the region where the water is spilt towards the Barcés River basin. It can be seen how the Mn, Al and Fe decrease in their concentration with time due to the fact that the inflow water concentration for these species is bigger than the initial concentration of in the lake. On the contrary, the concentration of K becomes greater due to its greater concentration in the inflow waters.

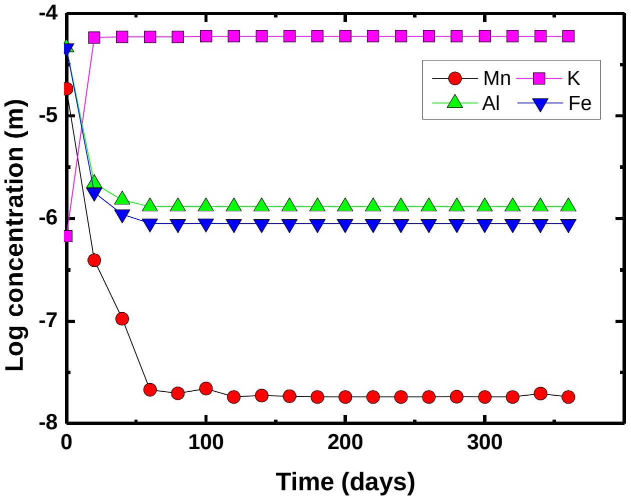

Figure 10. Time evolution of manganese, potassium, aluminium and iron at the lake spill point

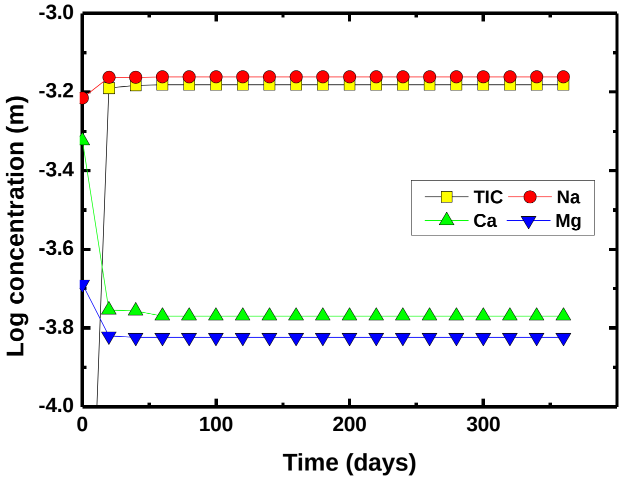

Figure 11. Time evolution of bicarbonate, sodium, calcium and magnesium at the spill point

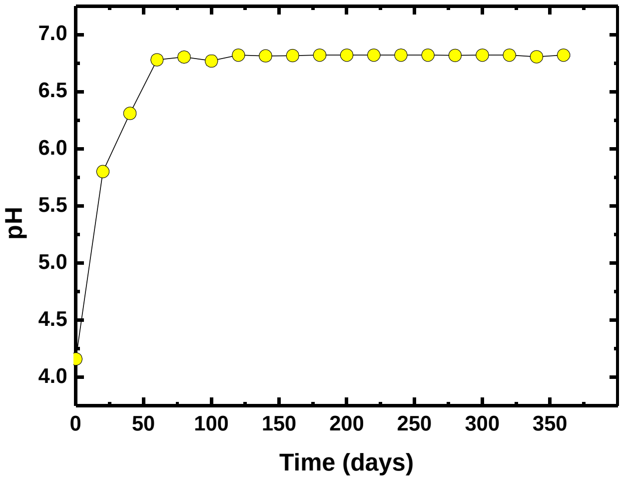

Figure 12. Time evolution of pH at the lake spill point

Calcium and bicarbonate behave differently. While the concentration of bicarbonate increases, the calcium decreases with time due to the reaction leading to the formation of dissolved carbonate, what contributes to the increase of pH (4.16 at the beginning and 6.5/6.9 at the end of simulation). In the overall, the chemical composition of the upper layer of the lake meets the environmental and other legal objectives.

3.1. Sensitivity analysis

A sensitivity analysis has been carried out in order to determine the influence of the variation in certain parameters in the final results. First, the molecular diffusion coefficient has been increased by an order of magnitude because this is the most relevant transport parameter in the nearly-stagnant water pockets. Second, ground water discharge out off the modelling perimeter was not considered as they are very small compared to the localized surface inflows. Results indicate that no major differences with respect the original model occur.

4 Conclusions

In a first approach to assess the quality of the waters that will spill out off the future Meirama Lake, we have developed a detailed two-dimensional reactive transport surface water model. The model is based on previous studies that include comprehensive surface and ground water balances, hydrochemical characterization and geochemical modeling. In order to reduce the uncertainty associated to the need of defining the verisimilitude of a 2-D versus a 3D approach and, considering that lake overturn due to density gradients and/or thermal stratification, field and theoretical analyses have been performed. As a first conclusion, it appears that lake overturn is not a likely scenario as far as thermal stratification tends to remain constant throughout the entire year and density changes are small.

FREECORE^{2D} modelling shows that, along a complete year, the chemical composition of the water of the upper layer of the lake tends to be homogenized and diluted due to the inflow of relatively diluted surface waters. The effect over the top layer surface is to decrease the concentration of the major part of components although some of them slightly increase due to the fact that the concentration of the inflowing waters is higher than in the lake. Small pockets of water in the top layer of the lake may retain certain initial characteristics (nearly stagnant regions) due to geometric constrains.

In general, the chemical composition of the top surface waters, that eventually will spill out towards the Barcés River basin, meet the criteria given in the environmental regulations in force. That means that, on a steady state basis, the inflow of surface waters will tend to improve or maintain the good water quality of the top layer of the lake.

The sensitivity analyses performed do not affect significantly these results. Nonetheless, it is recommended to conduct a water quality monitoring survey during the flooding and after flooding conditions so as to being able to calibrate the model in order to corroborate the results obtained so far.

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