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Groundwater flow and solute transport modelling

title: **Flow and transport simulation models in a volcanic-sedimentary aquifer: La Aldea aquifer (Gran Canaria, Canary Islands)**

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INTRODUCTION

La Aldea Valley is located on the western side of Gran Canaria (Canary Islands, Spain) and covers an area of 44 km^2. In the lower part of the La Aldea-Tejeda basin (Fig. 1) the valley presents a flat bottom surrounded by high mountains to the north and south (heights from sea level to 1415 m). It is bounded to the east by the Atlantic Ocean and to the west by impermeable materials of the inner part of the island (intra-caldera border). The climate is dry subtropical. Rainfall and temperature mean values are 160 mm/year and 21°C, respectively. Intensive greenhouse horticulture (mainly tomatoes and cucumbers) is practised and irrigation water is mainly supplied by three dams situated upstream, although more than 370 large-diameter wells also provide crop water requirements in the dry seasons.

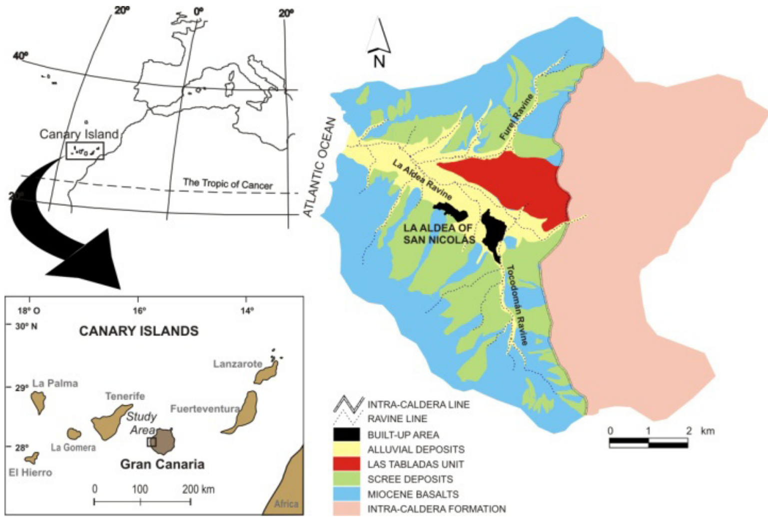

Figure 1. Localization of La Aldea aquifer in Gran Canaria (Canary Islands, Spain) and geological map showing the main geological units.

In this work, the hydrogeological functioning of this sedimentary-volcanic aquifer has been studied and contrasted from flow and solute transport modelling. Results obtained from a model of solute transport are shown in this article.

METHODOLOGY

A groundwater flow model in the area has been developed with previous and current data in steady-state for the average hydrologic year 1991/92 and in transient state for the period 1991/92-1998/99. Subsequently, hydrochemical and hydrogeochemical modelling techniques have been used to characterize and quantify the processes that lead to the chemical composition of the groundwater in the aquifer. Finally, a solute transport model for a saturated porous medium has been developed in steady-state for the average hydrologic year 1991/92, assuming an anisotropic and heterogeneous environment and constant density (Cruz, 2008). The solute selected for the transport model is the chloride ion which is an indicator of the mixing processes. This transport model will allow a comparison of the results obtained in the previous hydrochemical study and flow model.

FLOW AND HYDROCHEMICAL CONCEPTUAL MODEL

A conceptual model of the aquifer flow has been established within the framework of the insular aquifer, which has been conceptualized as a single, stratified, heterogeneous body of groundwater where recharge takes place mainly at the top of the island, with groundwater flowing towards the coast. The discharge flows towards the sea and towards groundwater works (Custodio, 2007). Within this framework, La Aldea Valley represents a discharge area from the aquifer to the sea.

Based on the geology, four hydrogeologic domains have been defined in the study area: Alluvial formation, scree deposits, Las Tabladas unit and Miocene basalts (Fig. 1), of which the alluvial formation and Miocene basalts are the most significant. The aquifer is unconfined and the alluvial deposits and the basalt rocks can be considered to be a single aquifer with two sub-layers: the upper alluvial deposits layer and the lower basalt layer. The flow has a main east to west direction in the La Aldea ravine, a south-north direction in Tocodomán ravine and a north-south direction in the Furel ravine. Recharge is a result of rainfall, irrigation returns, supply network leaks and inflow from the intra-caldera zone. Rainfall and irrigation returns are the main sources of groundwater recharge. Discharge takes place by pumping wells and seaward outflow. The maximum permeability values are located in the La Aldea alluvial area, 17–106 m/d. In the Tocodomán and Furel alluvial areas it is 5.5–22 m/d. The permeability for Miocene basalts is 0.0009–0.005 m/d and for scree deposits and secondary tributary alluvial areas permeabilities are 0.25–1.2 m/d and 6 m/d, respectively. Coefficient storage oscillates between 0.08 and 0.03 for alluvium and 0.0002–0.03 for Miocene basalts, depending on whether or not they are confined (Muñoz, 2005; Cruz, 2008).

The conceptual hydrochemical model proposes that water flows from the basalts to the alluvial deposits and therefore the extracted water is a mixture of both hydrogeological units and shows hydrogeochemical characteristics consistent with this mixture (Muñoz, 2005; Cruz, 2008). Most groundwater is of the sodium-chloride type, which has been attributed to the aridification of the recharge and airborne salinity. When the influence of marine aerosols is low (at higher altitudes and farther from the sea) the water is of the sodium-bicarbonate-chloride type. The exploitation of basalts produces an increase in the concentration of magnesium and occasionally high calcium concentrations show a geological mark produced by basalts. The geological mark of ignimbrites, trachytes and phonolites in well samples located in the scree deposits points to an increased concentration of sodium. The effect of the irrigation return flows (increased concentrations of nitrate and sulphate) is observed in almost the entire area. In general, there is agreement between the direction of groundwater flow and the increased chloride content, although deviations are observed in samples from wells close to the Las Tabladas area. In this area, a significant increase is observed in the concentrations of chloride, sodium and sulphate (reaching 8100, 3900 and 1800 $mg \cdot L^{-1}$, respectively) attributed to hydrothermal deposits ("Azulejos") located around the Las Tabladas area. Batch experiments run with these deposits have shown that they contribute a high Cl content to groundwater.

NUMERICAL MODEL

A three dimensional groundwater flow model has been developed with MODFLOW-2000 in Visual MODFLOW graphical environment in steady-state for the average hydrologic year 1991/92 and in transient state for the period of 1991/92-1998/99. A model of chloride transport has been realized with MT3DMS in Visual MODFLOW graphical environment in steady-state for the average hydrologic year 1991/92 (Cruz, 2008). Solute transport processes considered are advection and dispersion hydrodynamics.

The modelling area was tridimensionally discretized as cells of 50×50 m; 114,570 cells were divided into 190 rows and 201 columns and vertically into 3 layers. The superficial layer (layer 1) represents the sedimentary material (alluvial and scree deposits) and several metres of the underlying altered basalts, while the other two layers represent altered basalts (separated by an impermeable layer formed by lava flowing over previous soils named "almagre"). The bottom surface (the limit between the altered basalts and the unaltered basalts) has been located at 163 m depth by the previous drilled bore with a Miocene basalts slope between 3° and 5°.

The boundary conditions considered for the transport model were the constant concentration and recharge concentration. The limits of the mountain chains and the bottom surface have been defined as no-flow boundary conditions. The coastal line has been defined as a constant level and chloride concentration (elevation: 0 m and concentration: 20270 $mg{\cdot}L^{-1}$). The eastern limit has been considered to be a constant flow and chloride concentration along the contact line and by the alluvial deposits from the headwater of the ravine (concentration: 200 $mg{\cdot}L^{-1}$ and 270 $mg{\cdot}L^{-1}$, respectively). The upper surface boundary conditions correspond to the recharge. Different recharge origins have been calculated in each cell integrating the different sources: rainfall, irrigation return flows, supply network leaks (considered negligible compared to rainfall recharge in the model), inflow by the alluvial deposits from headwater of the ravine and inflow from the intra-caldera zone. Finally, concentration of water produced by the leaching of Azulejos deposits of the Las Tabladas area of 8500 $mg{\cdot}L^{-1}$ (obtained from water samples of oozes located in this area) has been imposed. The area was discretized in different areas where the recharge Cl concentration is the result of the different sources of Cl considered.

The hydraulic conductivities and storage coefficient have been divided into several zones based on the geology and were calibrated using the flow model. The considered dispersivity varies between 0.3 and 61 m for the alluvial and 0.6 m for the basalt. The estimated horizontal transverse dispersivity varies between 1.5 and 5.6 m and the vertical between 0.4 and 1.7 m. Effective porosity for alluvial deposits varies between 3% and 35% and for the basalt, 0.1% and 1% (Custodio, Llamas, 1996). These parameters have been calibrated in the steady state transport model. The molecular diffusion coefficient of water in porous medium is 10^{-9} m^2/d, which was not calibrated, because the model was insensitive to this parameter.

The groundwater chloride data consists of 41 chloride concentration measurements recorded in wells between July and August 1992 and distributed throughout the study zone. The comparison between the observed and the simulated chloride concentration is shown in Figure 3.

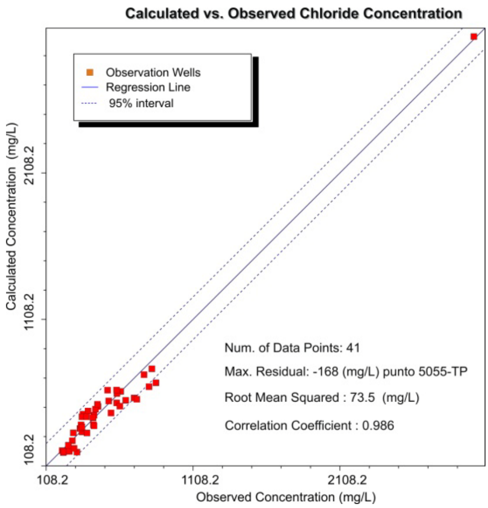

Figure 3. Comparison between observed (points) and simulated (solid lines) chloride concentration.

Longitudinal, transverse and vertical dispersity values obtained in the model calibration for all layers are 1 m, 0.33 m and 0.05 m, respectively.

Chloride map resulting (Fig. 4) fits satisfactorily to the conceptual hydrochemical model.

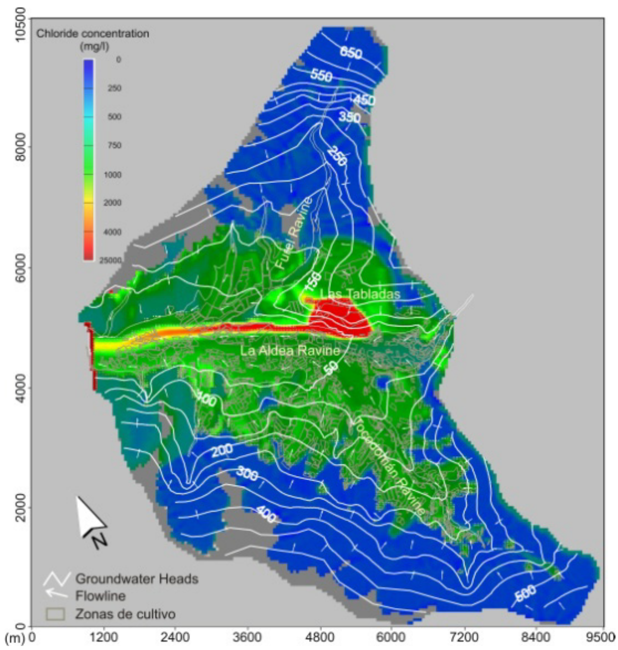

Figure 4. Steady-state water-table map and simulated chloride concentration distribution.

The necessity for groundwater protection is considered in the European Union in the context of its influence on the state of surface water and connected directly with terrestrial and water ecosystems as well in the context of its significance for the drinking water supply of the population. An estimation of ground and surface water quality includes among others the recognition of its biological elements of quality: plankton, macrophytes, phytobenthos and benthic invertebrates (Directive No 2000/60/EC, 2000).

The authors have carried out an investigative project on this topic. Investigations have carried out on the carbonate massif of the Cracow-Czestochowa Upland (the CCU). This is an area of upland karst not fully developed and differentiated in its inner structure. The Upper Jurrasic aquifer, which is the Major Ground Water Basin (MGWB No 326), is located in this area. In the southern part of the CCU it is a typical unconfined aquifer, which is closely connected with surface water. The Upper Jurassic aquifer is also closely connected with the surface water including living biocoenoses and other biocoenoses which depend on the state of water. With the aim of protecting the natural environment and groundwater resources, most of the area in the CCU is protected by law (Ojców National Park, Landscape Parks, Nature 2000 area). Therefore, this region with its unique karstic features, that is environment extensively managed and protected by law, is an excellent area for hydrogeological studies (Różkowski, 2006).

The presented project refers to hydrogeoecological studies. They include interdisciplinary studies of ecosystems of damp areas under the influence of ground and surface water as well marshes. Investigations have dealt with the water environment regime and also with the presence of subterranean microorganisms and invertebrates in it (Humphreys, 2009).

These habitats connected directly with groundwater outflow are treated in the so-called Habitat Directive of the European Union as very valuable and they have the rank of European cultural heritage. In the area of the CCU there are several hundred springs. They are not only the local groundwater drainage points but they also set composite hydrologic biotic ecosysytems (Springer, Stevens, 2009). The durability and stability of habitat conditions in springs results in the occurrence of a specific fauna (crenobionts) and some relic species, e.g. in the area of the CCU — Crenobia alpina and Bythinella austriaca. The composition of fauna living in springs is influenced by hydrogeological conditions, their surroundings, zonal differences eucrenal–hypocrenal and also by disturbances, especially in the form of anthropopression (Dumnicka et al, 2007). Existing faunistic and ecological studies on the springs located in the CCU indicate that they are highly diverse although the number of taxa found in individual springs was not substantial. However, there are no complex studies on fauna which take into account the presence and conditions of populations of crenobiontic and oligo-stenotermic species in individual springs.

Within the framework of this project in chosen study polygons the unconfined aquifer is investigated. The study is performed in spring drainage areas in zones of unconfined flow systems as well as in caves and outflows from caves, and in water-logged quarries. Such an approach to the natural environment will allow water and terrestrial esosystems connected with the water of the unconfined aquifer to be recognized. An assembly of benthic invertebrates, higher plants, bryophytes will be determined as the biomarkers of the environmental state and then they could be compared (on basis of literature) with porous environmental analogs. The study, done together with the recognition of regional management and pollution sources, will allow the influence of natural and antropogenic factors on water environment and its biotic elements within the karstic area of the CCU to be estimated. They will also show the current trends of this environment is development. In addition to the study aspect the project also has practical and methodological aims. For the purpose of providing the effective protection of karst water and its ecological environment in the area of the CCU, the further development of research procedures typical for the karstic areas is necessary.

DISCUSSION AND CONCLUSIONS

The concentration of irrigation return waters was calibrated during the modelling process. From an initial concentration of 350 mg·L^{-1} in samples of hydroponics crops returns a final concentration of 600 mg·L^{-1} was achieved with the better calibration. This shows that the pollution caused by irrigation returns is generally greater than that obtained from the hydroponics irrigation returns, so this fact may provide evidence that the irrigation return flows cause further contamination to the system. A constant concentration boundary condition (20 270 mg·L^{-1}) was imposed at the mouth of the ravine representing the seawater concentration. This points to the absence of seawater intrusion in the aquifer and confirms the hypothesis proposed in the conceptual model and verified in the flow model.

The simulated values of concentration of chloride have produced a good fit. The resulting map shows a representation of chloride consistent with the flow and transport conceptual models in the study area, reproducing them successfully. The most characteristic feature consisting in the input of chloride due to leaching of the Azulejos deposits located in the Las Tabladas area, with concentrations higher than 8000 mg·L^{-1} has been well simulated by the model. The transport model also shows the relevance of scree deposits in the hydrogeological system, as they are preferential flow pathways that accelerate and facilitate the recharge to the alluvial deposits providing chlorides from the irrigation return flows located thereon.

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