STEADY-STATE THREE-DIMENSIONAL FLOW SIMULATION IN A VOLCANIC-SEDIMENTARY AQUIFER: LA ALDEA AQUIFER (GRAN CANARIA, CANARY ISLANDS)

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ABSTRACT

In this study, a groundwater flow model of this aquifer is developed. The model simulates an average steady-state condition for the year 1992, when an extensive field study was undertaken, in which 238 wells were visited in the study area. The model simulates groundwater flow over an area of about 44 km^2 with 190 rows, 201 columns and three layers. Based on the modelling results, the model reproduces the observed flow–field and the water balance components rather well. The model presents numeric stability problems due to the steep topography of the area that constitutes a determining factor.

Key words: Volcanic aquifer, conceptual model, numerical simulation, Gran Canaria.

INTRODUCTION

La Aldea Valley is located on the western side of Gran Canaria (Canary Islands, Spain) (Fig. 1). In the lower part of the La Aldea-Tejeda basin, the valley presents a flat bottom surrounded by high mountains with 1% to 10% slopes, where intensive agriculture of tomatoes and cucumbers under greenhouses exists. Irrigation water supply comes mainly from three dams situated upstream, although there are more than 370 large-diameter wells which provide the necessary water for the crops in dry seasons.

The hydrogeology of the area has been studied since 1992, with the development of several projects in order to improve the hydrogeology knowledge of the La Aldea aquifer, and a PhD thesis has been developed characterizing the aquifer behaviour (Muñoz, 2005). These works have been used to develop the mathematical model of the aquifer, based on a 3D conceptual model of hydrogeology flow which was later numerically implemented through the use of MODFLOW code. The main objective is to get better groundwater knowledge of the area and to develop a management tool for the future.

DESCRIPTION OF THE STUDY AREA

The study area is located on the western side of Gran Canaria, covering an area of 44 km^2, and it is limited in the north and south by high mountains (with heights varying from sea level to 1,415 m), in the east by the Atlantic Ocean and in the west by the waterproof materials of the intra-caldera area.

La Aldea Valley is composed by Miocene Basalts (14.5-14.1 My), consisting of a succession of basaltic and basanitic lava flows and fall pyroclasts. In the upper part of the valley, volcanic tuffs, ignimbrites and lava flows of Traquitic-rhyolitic Fm (14.1-13 My) crop out, in tectonic contact with the Miocene Basalts. Las Tabladas area is a complex structure located in the North-east (NE) of the study area; it is made up by sedimentary materials from Las Palmas Detritic Fm (Mio-Pliocene age) and volcanic materials of Pliocene (Roque Nublo group) and Plio-Quaternary age (Cabrera et al., 2007). The valley bed is formed by 15-20 m thick alluvial conglomerates (that can reach up to 30 m in some places) that overlay the Miocene Basalts. In the mountains slope, screes can be observed as a result of the land erosion. The superficial localization of the geological units can be observed in Fig. 1.

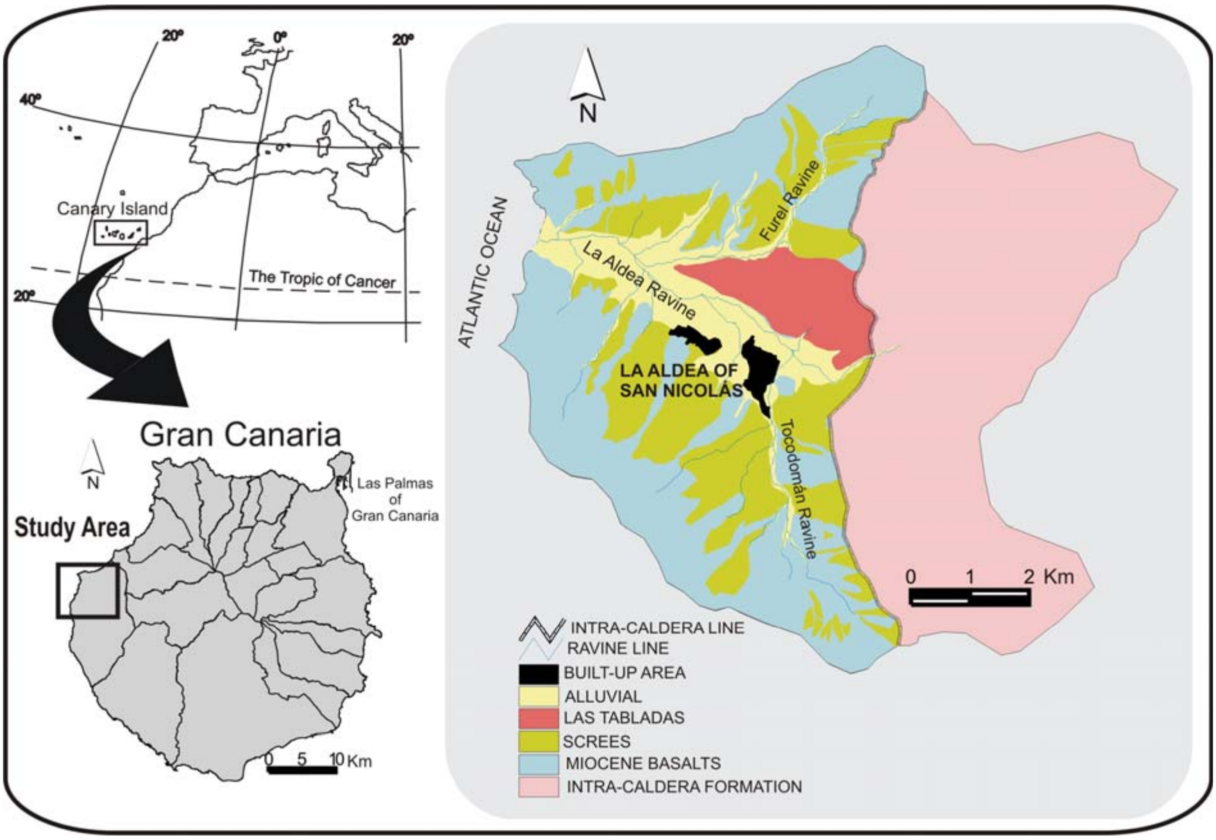

Fig. 1.- Location of study area and observation of different geological units.

The area enjoys a dry subtropical climate, with October and April as the rain period. The rain oscillates among 183 mm/year in the highest zones of the basin and 138 mm/year in the coastal zone with an average value of 161 mm/year. The maximum temperature is about 24º C during the summer months while the minimum temperature is about 17º C during the winter period.

HYDROGEOLOGIC FRAMEWORK

The insular aquifer has been conceptualized as a stratified, heterogeneous unique body of groundwater. The recharge takes place mainly at the top of the island, with groundwater circulating towards the coast. The discharge flows towards the sea and towards groundwater works (wells and groundwater galleries) (SPA-15, 1974; Custodio et al., 1989, Custodio and Cabrera, 2003). Within this framework, the study area represents a discharge area to the sea.

Based on the Geology, four hydrogeologic domains have been defined: Alluvial conglomerates, Screes, Las Tabladas and Miocene Basalts (Fig. 1), of which Alluvial and Miocene Basalt are the most significant hydrogeology domains in the study area.

The aquifer is unconfined, the alluvial and the basalt rocks can be considered as a single aquifer consisting of two sub-layers: the upper alluvial layer and the lower basalt layer. The limits of the study area are defined by the high mountain chains (North and South), the waterproof material of the intra-caldera area (East) and the coast line (West). The permeability of the alluvial conglomerates and the Basalts is 26-85 m/day and 0.03 m/day respectively, with specific yield values of 0.03-0.1 for the former and 0.005-0.01 for the latter. These hydraulic properties have been conducted through the analysis of 8 pumping test data, specific flow data and the study of the influence of tides for coastal wells.

The flow has a main Eastsoutheast-Westnorthwest (ESE-WNW) direction in the main ravine, a South-North (S-N) direction in Tocodomán ravine and heads North-South (N-S) in Furel ravine.

MODEL DESCRIPTION

A three-dimensional flow model of groundwater has been developed, assumed to have an anisotropic and heterogeneous environment and constant density. The finite-difference computer code MODFLOW (McDonald, M.G. y Harbaugh, A.W., 1988) was used to simulate the groundwater flow in the study area. The pre- and postprocessor, developed by the US Geological Survey and compiled in the commercial adaptation by Waterloo Hydrogeologic Inc., Visual MODFLOW (Waterloo Hydrogeologic, 2005), was used to give input data and process the model output.

The geometry of the model is conditioned by the geology and the topography of the study area. The modelling area was tridimensionally discretized as cells of 50 x 50 m; 114,570 cells were divided into 190 rows and 201 columns and vertically into 3 layers (Fig. 2). The superficial layer (layer 1) comprises the sedimentary material (alluvial and screes) and some metres of the altered basalts located below, while the other two layers are Basalts, divided into two layers due to the existence of red ochre “almagre” (impermeable layer formed by the circulation of lava flows over previous soils) between them (layers 2 and 3).

The hydraulic conductivities have been divided into 15 zones based on hydrogeological reasoning (Fig. 3). The hydraulic conductivity of layer 1 is heterogeneous depending on the alluvial thickness, and the existence of screes or Las Tabladas materials. The hydraulic conductivity of layers 2 and 3 has been considered as homogeneous. An anisotropy ratio (k_h/k_v) of 100 was selected to be representative of the basalts and screes, and a ratio of 50 was chosen for the alluvial (Table 1), following the previous works on Gran Canaria (INTECSA, 1981; SPA 15, 1975).

Recharge is a result of rainfall, irrigation returns, supply network leaks and inflow from the intra-caldera zone. The rainfall data have been obtained through the Easy-bal program developed by the Technical University of Catalonia, while the irrigation return flow data have been estimated following indications from the agrarian service of Cabildo Insular of Gran Canaria and the supply network leaks have been estimated by the authorities concerned. The recharge by inflow from the intra-caldera zone has been estimated in the different model calibrations and is located in the eastern area.. Rainfall and irrigation returns are the principal sources of groundwater recharge. The study area was divided into three rainfall recharge areas based on the annual average isohyets of 150, 170 and 190 mm/year for the period 1980-2003 and into two irrigation returns recharge areas based on is the existence of greenhouses. The combination of these factors has allowed the division of the study area into 10 recharge zones. The recharge values incorporated in the model for each zone are shown in Fig. 4.

Discharge takes place by pumping wells and flows towards the sea. The pumping wells located in the central part of the aquifer mainly perforate the alluvial conglomerates, and some of them reach the Miocene Basalts below, exploiting the groundwater from both materials (Fig. 2). The pumping wells data have been obtained through several field inventories conducted in the study area.

The boundary conditions used on the model correspond to the real physical boundaries of the aquifer. The limits of the northern and southern areas have been defined as null flow boundary conditions (waterproof edge). In the western area, the coast line has been defined as constant level (elevation: 0 m). The eastern limit (marked by the volcanic caldera) has been considered like a constant flow along the contact line. In the ravine bed, a section has been defined as a constant flow too, representing the contribution from the high part of the island towards the study area through the alluvial conglomerates. The bottom surface is defined as a null flow condition in the limit between the alterated Basalts and the Basalts without alteration (Layers 2 and 3). A drain condition has been imposed in the ravine (Fig. 2).

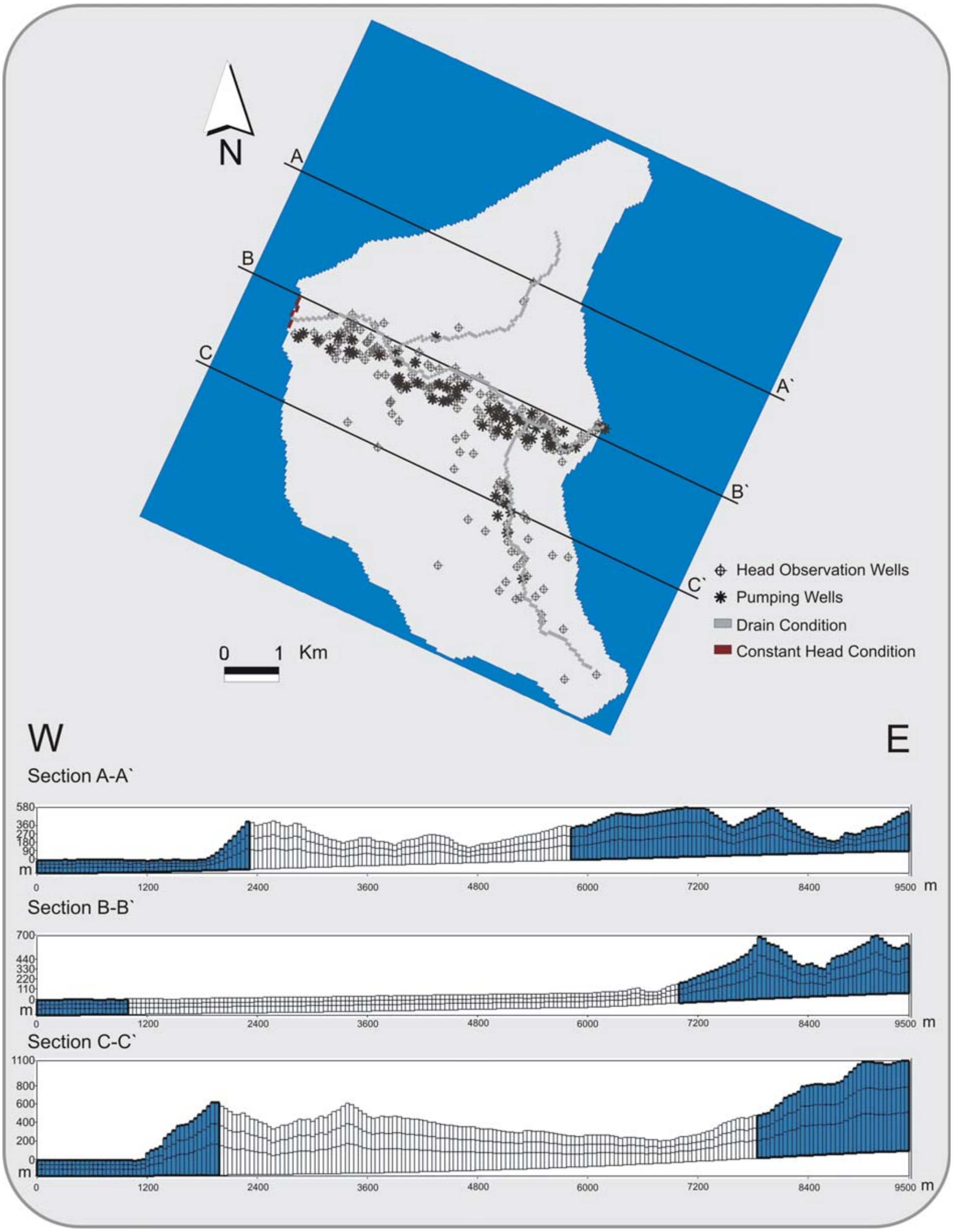

Fig 2.- Cross section and vertical discretization of the study area. Observation and pumping wells and boundary conditions for the groundwater flow model.

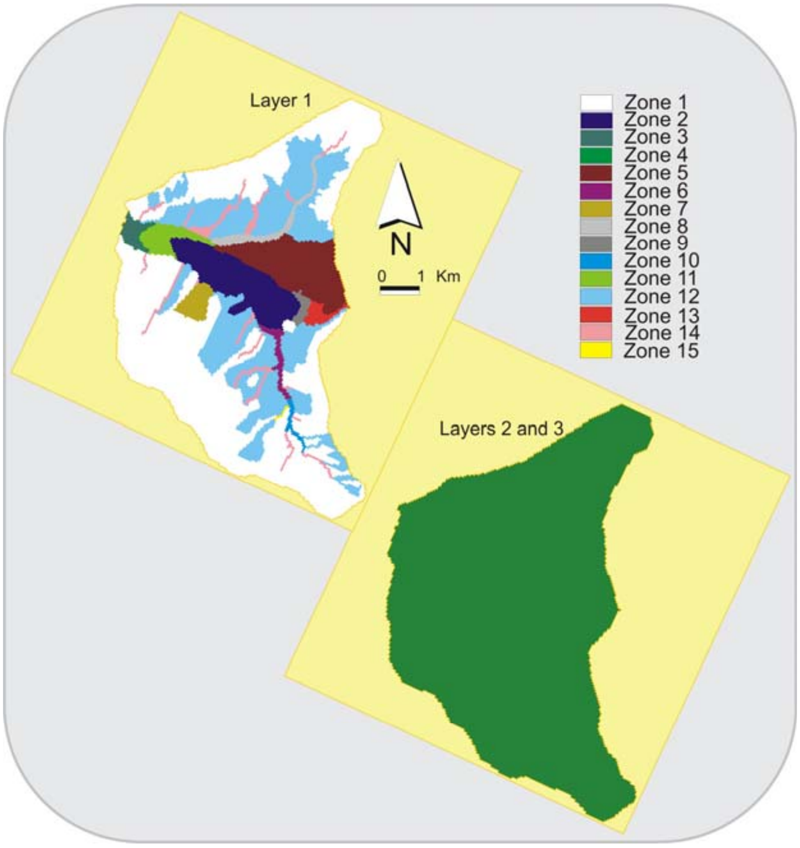

Fig. 3.- Map of surface distribution of horizontal hydraulic conductivity in the study area.

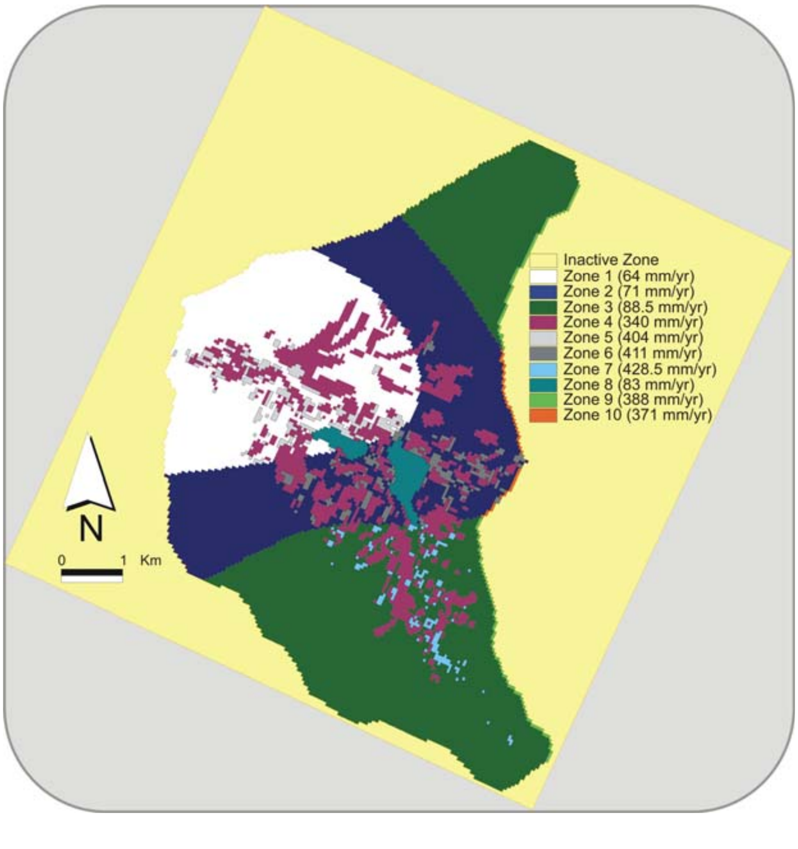

Fig. 4.- Recharge zones and amount of recharge in the study area.

MODEL CALIBRATION

A steady-state model calibration was carried out to minimize the difference between the computed and the field water-level using MODFLOW-2000. The water-level data used come from the established wells monitory network (July and August 1992), which consists of 198 wells with static level distributed in the study zone. There are many wells in the alluvial of main ravine and the alluvial of Tocodomán ravine and few in the alluvial of Furel ravine as seen in Fig. 2. The differences between the measured and simulated values are residuals.

During the trial and error calibration, different spatial configuration and values for the hydraulic conductivity were proved. The preliminary zoning formed by alluvial, screes, Las Tabladas and basalts zones was modified to improve the calibration, obtaining 15 final zones of hydraulic conductivity (Fig. 3).

The sensibility analysis of the model to input parameters was tested varying only the parameter of interest over a range of values, and monitoring the response of the model determining the root mean square error of the simulated heads compared to the measured heads. The model is highly sensitive to the hydraulic conductivity and the recharge and particularly to basalts hydraulic conductivity.

The comparison between the observed and the simulated groundwater heads for steady-state models is shown in Fig. 5. Maximum residual value is localized in Tocodomán Ravine and the minimum residuals are localized in the main ravine. The root mean squared value of the remainder is 2 m.

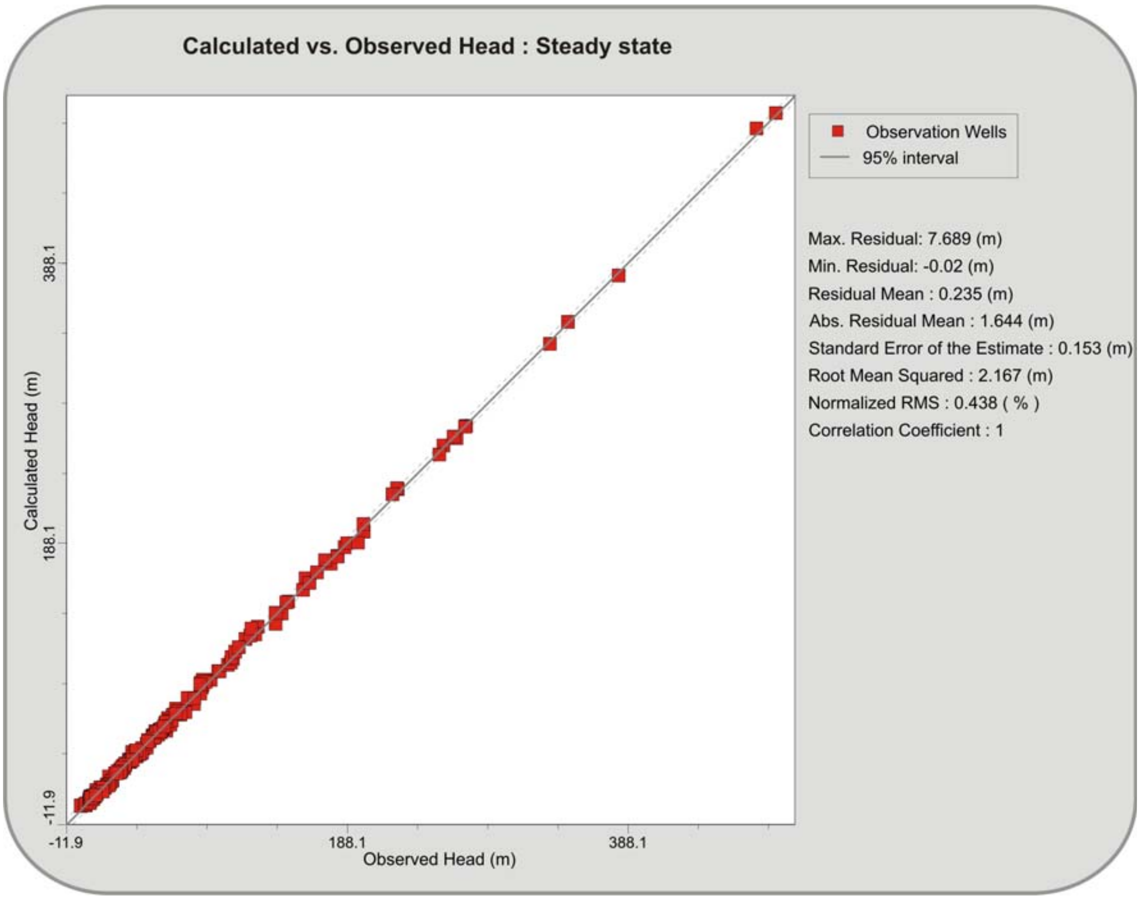

Fig. 5.- Comparison between calculated and observed groundwater heads (m) under steady-state calibration.

RESULTS

The model was simulated in steady-state conditions for the year 1992. There was good adjustment between the computed and observed heads (Fig. 5). The simulated groundwater head reflects the topography. The highest heads are found on the northern and southern side of the study area.

The estimated values of the hydraulic conductivities (Table 1) show relatively good correspondence with the values measured for the alluvial domain, but the values are smaller for the basalts. A low permeability zone (Zone 9, Fig. 3) can be observed in the alluvial domain attributed to a decrease of the thickness of the layer in that zone. The screes hydraulic conductivity values are only estimations, because the thickness is variable (between 5 and 20 m can been observed in the field).

Table 1.- Hydraulic conductivities obtained for the hydrogeological units defined in this model.

	Average thickness (m)	k_h (m/d)	K_v (m/d)	k_h/k_v	Alluvial and Screes average thickness (m)	Basalt average thickness (m)	k_h Alluvial or Screes (m/d)	k_h Basalts (m/d)
Zone 1	175	0.005	0.00005	100		175		0.005
Zone 2	50	12.5	0.25	50	20	30	31.24	0.005
Zone 3	200	0.0048	0.000048	100		200		0.0048
Zone 4	50	52	1.04	50	30	20	86.66	0.005
Zone 5	100	0.015	0.00015	100				
Zone 6	75	9.5	0.19	50	20	55	35.61	0.005
Zone 7	75	0.25	0.0025	100	5	70	3.68	0.005
Zone 8	50	7.5	0.15	50	15	35	24.99	0.005
Zone 9	50	1.2	0.024	50	20	30	2.99	0.005
Zone 10	100	2.5	0.05	50	10	90	24.96	0.005
Zone 11	50	28	0.56	50	20	30	69.99	0.005
Zone 12	75	0.05	0.0005	100	5	70	0.68	0.005
Zone 13	50	10	0.2	50	15	35	33.32	0.005
Zone 14	75	1.3	0.013	100	5	70	19.43	0.005
Zone 15	75	1	0.01	100	5	70	14.93	0.005

Fig. 6 shows the levels for the stationary state simulation for the year 1992. Groundwater flows from different materials (Basalts, screes and Las Tabladas Units) to the alluvial, while within the alluvial it flows westward in agreement with the conceptual water table elevation map. In the Basalts unit, where the groundwater flow is governed by the less conductive, the equipotential lines are spaced very close to each other.

The simulated water balance for the year 1992 is presented in Table 2. The total water balance over the entire aquifer shows a perfect balance between inflows and outflows of groundwater, which is consistent with the steady state modelling hypothesis. The inflow is due to the recharge from the rainfall (2.99 hm^3/year), irrigation returns (1.98 hm^3/year), supply network leaks (0.07 hm^3/year) and inflow from the intra-caldera zone (0.46 hm^3/year). The outflow is due to the pumping wells and the flow to the sea. The range of inflow and outflow is 6 hm^3/year.

Table 2.- Water balance obtained in the model for the year 1992.

IN:
Inflow from the upper part of the ravine = 0.62 [hm^3/year]
Recharge = 5.52 [hm^3/year]
Total IN = 6.14 [hm^3/year]
OUT:
Outflow to the sea = 2.63 [m^3/day]
Wells = 2.84 [m^3/day]
Drains = 0.68 [m^3/day]
Total OUT = 6.15 [m^3/day]
Discrepancy = -0.01

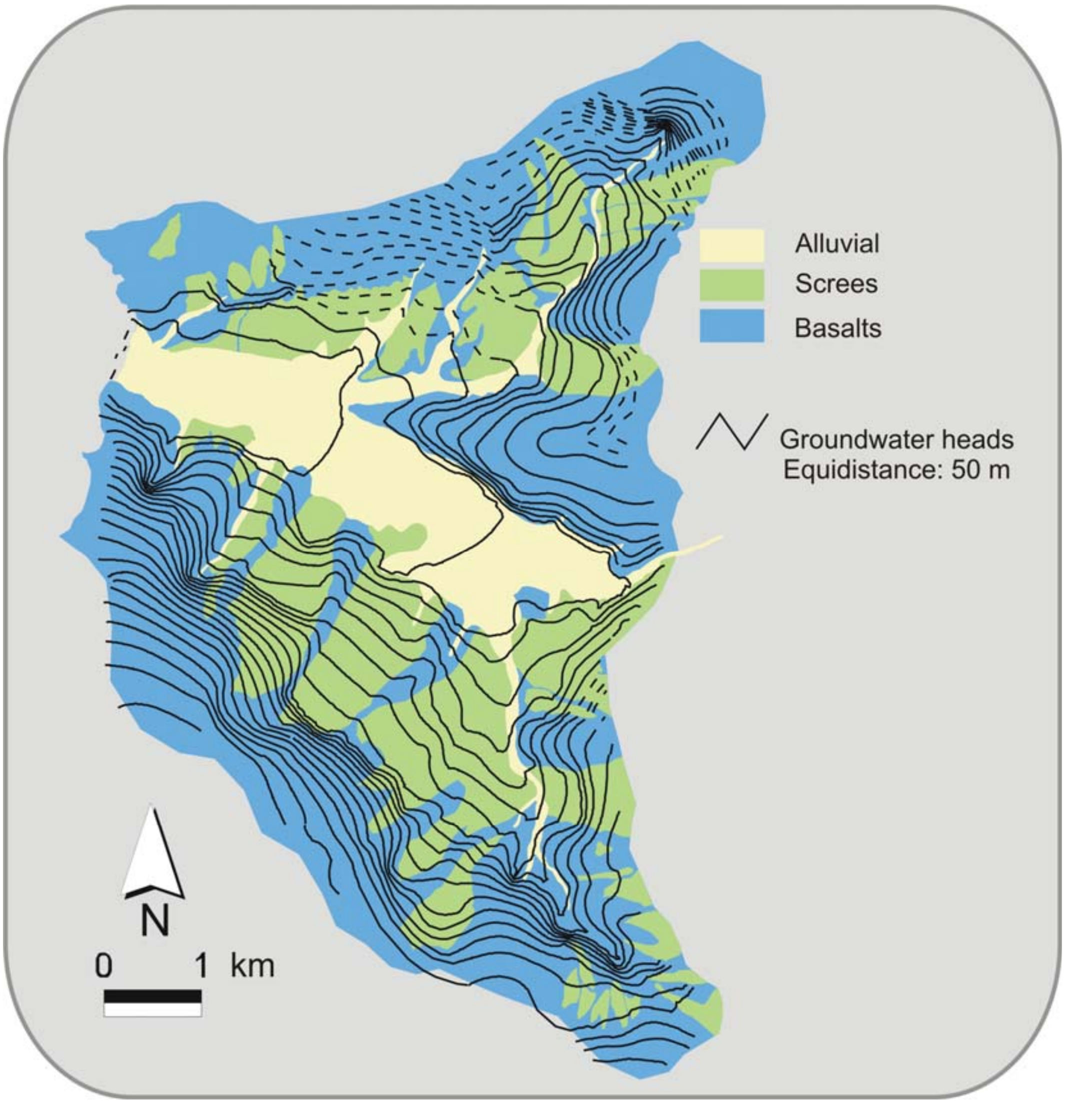

Fig. 6.- Simulated groundwater head for steady-state condition in the year 1992.

CONCLUSION

La Aldea ravine constitutes a productive agricultural area in Gran Canaria. The groundwater flow is modelled using MODFLOW in the Visual MODFLOW environment. A three-layer steady-state flow model was used to simulate the groundwater head in the La Aldea aquifer for the year 1992 in order to acquire a better understanding of the aquifer system. The model results correspond closely to what is observed in the field. The simulated results indicate the importance of the topography and the geology in the distribution of the groundwater heads in the study zone. The consideration of the domain of the screes and secondary alluvials has become very important factors to obtain a good adjustment in the model.

The water is provided by the different hydrogeologic domains to the alluvial unit and circulates through the alluvial from East to West. The main inputs to the study area are rainfall and irrigation returns and the main outputs are the pumping wells and the flow to the sea.

The model and the obtained results are an important tool for to get better groundwater knowledge of the area and can be taken as starting point by transient model.

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