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# Evolution of groundwater intensive development in the coastal aquifer of Telde (Gran Canaria, Canarian archipelago, Spain)

M. Carmen Cabrera
*Department of Physics (Geology). University of Las Palmas de Gran Canaria, Spain*
*mcabrera@dfis.ulpgc.es*

Emilio Custodio
*Geological Survey of Spain and Technical University of Catalonia, Spain*
*e.custodio@igme.es; emilio.custodio@upc.es*

## ABSTRACT

A 75 km$^2$, intensively developed coastal aquifer in eastern Gran Canaria island, Canarian Archipelago, around the town of Telde, has been surveyed and studied, using data from existing wells. The aquifer consists of Pliocene to Recent volcanic materials, with an intercalated detrital formation called Las Palmas Detritic Formation (LPDF). Groundwater development in the area started late in the 19th century by means of shaft wells fitted with horizontal water galleries and later on with horizontal drainage boreholes. Groundwater development became intensive since the 1950s, mostly for cash crop irrigation and town supply. First surveys are of the 1970s. Groundwater development conditions follow a quickly changing pattern. There is a conspicuous water table drawdown, up to 40 m in 20 years, following a strip parallel to the coast, although inland water table elevation is little affected. There is also a progressive water salinity increase with changes of the hydrochemical water type. Recent basalts were a good aquifer some decades ago but now are mostly drained. In spite of being considered the area as highly *overexploited*, groundwater reserve depletion contributes only about 5% of abstracted water, and more than 60% is transferred from inland areas. Discharge to the sea seems to be still significant, perhaps about 30% of total recharge.

Keywords: *Volcanic terrains, hydrogeology, groundwater flow, intensive use, hydraulic properties, Canary Islands.*

## 1 INTRODUCTION

The Canary Islands support an intensive exploitation of their groundwater resources, up to 300 Mm$^3$/yr, for a population close to 2 million inhabitants, especially in Gran Canaria and Tenerife. The general hydrogeological structure of the Canary Islands can be sketched as a *core* of low permeability old volcanic, intrusive bodies, and thermally metamorphosed rocks, with successive covers of younger, more permeable ones (Figure 1) (SPA-15, 1975; Custodio, 2003; Custodio y Cabrera, 2002). Groundwater flows from the central, high altitude areas, towards the coast, where it discharges mostly in diffuse form. A fraction of groundwater may discharge in inland areas, feeding springs and wet strips, and producing flow in some tracts of the gullies *(barrancos)*. These discharges depend on internal rock structure, and relief dissection by the gullies. Due to intensive groundwater exploitation these groundwater manifestations have

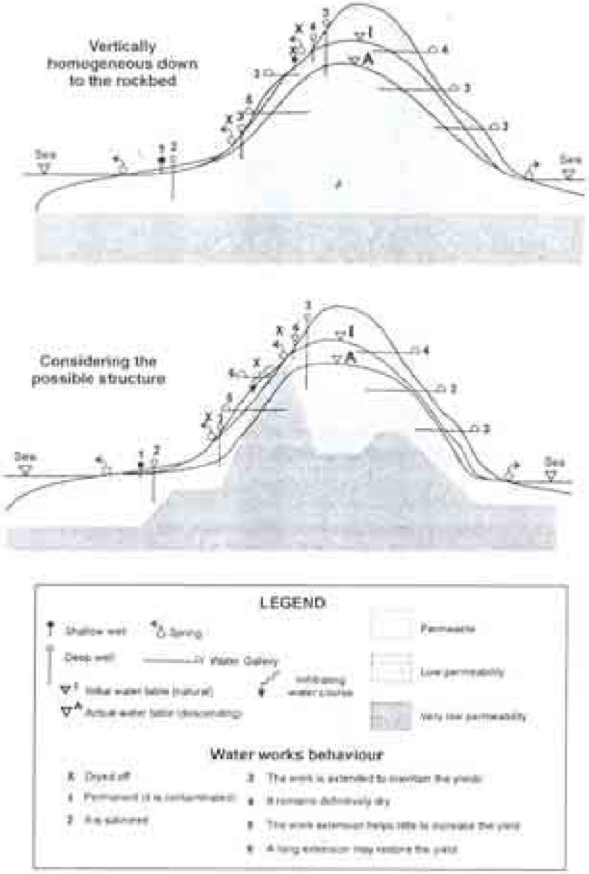


Figure 1. Schematic cross-sections to explain the hydrogeologic behaviour under natural and under intensive exploitation in Canary Islands, as inspired from Gran Canaria Island. The upper figure shows a low permeability core above a very low permeable bedrock, with young volcanic rocks or sediments in the periphery. The lower figure shows a central caldera partially slipped at one of the sides, and a young volcanics cover with intra- and extra-caldera areas. In both cases coastal water table gradients do not change significantly, at least at early times, from natural to intensive exploitation situations if groundwater development is mostly in the middle and high parts of the island (Custodio and Cabrera, 2002).

mostly disappeared and the water flows now through canals and pipes.

This paper deals mainly with the area of Telde (Cabrera *et al.*, 1992; Cabrera 1995; Cabrera and Custodio, 2003), in eastern Gran Canaria Island (Figure 2), which is the oldest of the intensively developed areas for local groundwater in the island. This area has not been studied in detail before, but for preliminary surveys during the SPA-15 (1975) study. Some new data has been added by the unpublished MAC-21 study (about 1980), and the twice-a-year monitoring network of the Geological Survey of Spain (IGME) from 1986 to 1990, on 42 wells, and the 12 wells surveyed by the Water Plan of Gran Canaria (PHGC) in 1991. Actually, a bigger area including Telde is being studying by the IGME in order to elaborate a plan to reorganise the groundwater exploitation in the east of Gran Canaria.

Telde is located in the eastern part of Gran Canaria. The headwaters of the area are outside it and extend up to the top of the island where average rainfall is close to 1,000 mm/yr. The *Barranco Real de Telde* is the main gully, which was one of the island permanent streams in the past. Now it is permanently dry. The study area is the coastal strip, up to an elevation of about 200 m, and extends along 10 km, with a total surface area of 75 km². It is a gently slopping lava platform, relatively flat, bounded by east-west trending gullies at the north and the south, and dotted with small recent volcanic cones. Most of the coast consists of 10 m to 30 m high cliffs on recent volcanics.

The Telde area is characterised by an average rainfall of 150 mm/yr with an average yearly temperature of 20°C. It is swept by frequent and relatively intense winds from the north. Besides it is at the boundary of the persistent northern cloud cover, which results in a high sunshine exposure. It can be considered an arid area, at the foot of the relatively rainy highlands.

The area has been traditionally used for irrigated agriculture, with changing dominant crops from the 15th century: sugarcane, vineyards, cereals, cochineal, banana and tomatoes. Banana trees have been cultivated from the end of 19th century to the 1970s. Afterwards, they were progressively replaced, first by pepper and cucumber cultivated under greenhouses in the





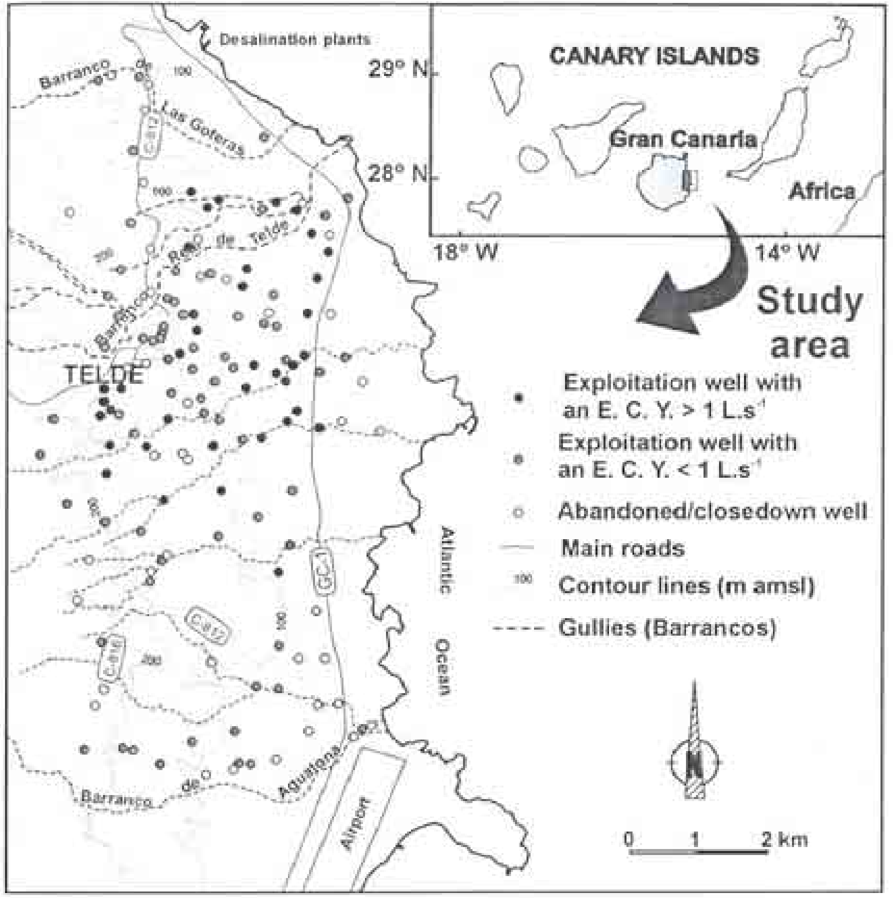


Figure 2. Location of Telde area in Gran Canaria, Canary Islands (Spain). It is shown the topography, main gullies (*barrancos*) and the location of wells with different exploitation regimes.

early 1970s, and later on by orange trees in the late 1970s. From 1980 the area has suffered an important urbanistic occupation, with the development of industrial and commercial parks and residential zones. The cultivated land has been reduced to some potato plots and fruit tree plantations for self-consumption. Currently about 80% of the study area is urban or commercial, or consists of abandoned plots of land that were previously used to cultivate tomatoes.

Water supply for irrigation was initially spring water coming from higher lands, and uptakes from the *Barranco Real de Telde*. After the 1880s the growing irrigation needs fostered the use of local groundwater by means of shaft wells, which are the oldest in the island. In 1980s, half of irrigation water as well as domestic water supply came from upper parts of the island and the other half was from wells in the Telde area. Now, urban and domestic water supply include desalinated sea water. Wells continue to be exploited for local needs, although less intensively, and the water is party mixed with desalinated water. Groundwater exploitation has followed the same scheme: from 1900 to 1950 many wells were excavated; later on water needs for irrigation caused an abstraction increase which was accompanied by the deepening of wells until the 1980s, when water exploitation has decreased due to salinity increase and land use changes.

From bottom to top, the stratigraphic column includes: Cycle I phonolitic lava flows and ash-flows (Miocene); Las Palmas Detritic Formation (LPDF) sediments; Cycle II basanitic and basaltic lava flows and volcanic breccias (Pliocene); and Cycle III basanitic lava flows and fall pyroclastic deposits (Plio-Quaternary). The sedimentary deposits correspond to the LPDF, that is divided in Lower, Middle and Upper members, according to their characteristics and sedimentary environments. The spatial disposition of these materials in the subsoil is deduced from visits to the shaft wells of the area, mainly descending into them, but also by studying the voluminous tips. Materials at about sea level change from north to south: they are mostly lava flows and pyroclastic deposits of phonolitic composition at the northern part of the area, and LPDF in the central and southern area. Recent basalts with Roque Nublo Formation represent the non-saturated zone in most of the area; they are thicker in the south-west.

There are 145 wells in the area, 30 of which were excavated before 1924. The oldest wells have a diameter of 6 m in the first metres to hold the old, bulky, animal powered pumping machinery (water wheel). The younger traditional wells of the area, most of them built on the 1940s and the 1950s, are hand and explosive dug shafts wells in the rock, 2.5–3 m of diameter. Some parts of the shaft are lined with concrete or holds a reinforced annulus when rock is unstable; 4 of them have small diameter vertical boreholes at the bottom, built in the 1980s. They use to have secondary works like galleries at different depths and horizontal, small-diameter drains (*catas*), that have been drilled in different stages as well water yield decreased due to the general water table level drawdown. Then, it is very common that these old secondary galleries are now useless because they are above the water table. Well depths range from 15 m to 313 m, with an average of 102 m, without significant differences between large diameter wells and wells with bottom drains. A total of 12 (350–400 mm diameter) boreholes were drilled in 1980s. They are deeper than the shaft wells, with an average depth of 165 m, and generally uncased or with only a slotted tube to protect the pump from falling stones.

The exploitation regime is very variable, from automatized to manually operated wells. Most irrigation wells work several hours a day, resting one or two months a year. Pumping rates range from 3 L/s to 50 L/s, with an average value of 12 L/s. Since the pumps do not work continuously, an equivalent continuous yield is calculated after interpreting the data obtained during field surveys (Cabrera, 1995; Cabrera and Custodio, 2001).

## 2 GROUNDWATER EXISTENCE AND EXPLOITATION

Groundwater in the Telde area originates mostly in inland areas. Under natural conditions this water discharged in diffuse form along the coast. There are neither references about discrete coastal and submarine freshwater outflows nor they were not identified in an airborne thermographic survey (SPA-15, 1975). They were not observed during the detailed surveys along the coast carried out for recent studies (Cabrera, 1995).

The time evolution of potentiometric levels in the study area comes from data from different times and origins: 1970–1971 for the SPA-15 study, 1980–1981 for the MAC-21 study, 1986–1989 for the operation of the IGME network, and 1991–1992 for the technical reports for the Island's Water Register, plus the 1988 data from the exhaustive inventory carried out by the first author. The analysis has been made considering potentiometric levels, well depth and exploitation data expressed as equivalent continuous yield. Levels go down in 38 wells out of the 50 wells with data, even in the case of abandoned wells. The water table drawdown range from 1 m to 30 m in wells that have not changed their depth, most of them located in the central part of the study area. In wells that have been extended, groundwater levels use to go down in parallel with well depth as a result of increased abstraction. This makes deeper the local drawdown cones around wells. In spite of abstraction decrease, only in four wells a water level stabilization or recovery has been observed.

Figure 3 shows an example of the evolution of three wells with the typical behaviour of different zones. Well A, located at the north of the area, is out of use and show a level drawdown close to 14 m. Well B is located at the central part of the area, where the exploitation is more important. This well has been deepened about 90 m by drilling a borehole in the bottom of the shaft well; this allows an increase of abstraction (until almost 20 L/s of equivalent continuous yield) and has produced a piezometric level decrease of 10 m. Well C shows the behaviour of the wells at the southern part of the area, where there is a progressive closedown of wells due to groundwater salinization.

The water table elevation has been drawn in three different times: 1970–1971 (SPA-15 data), 1980–1981 (MAC-21 data) and 1988–1992

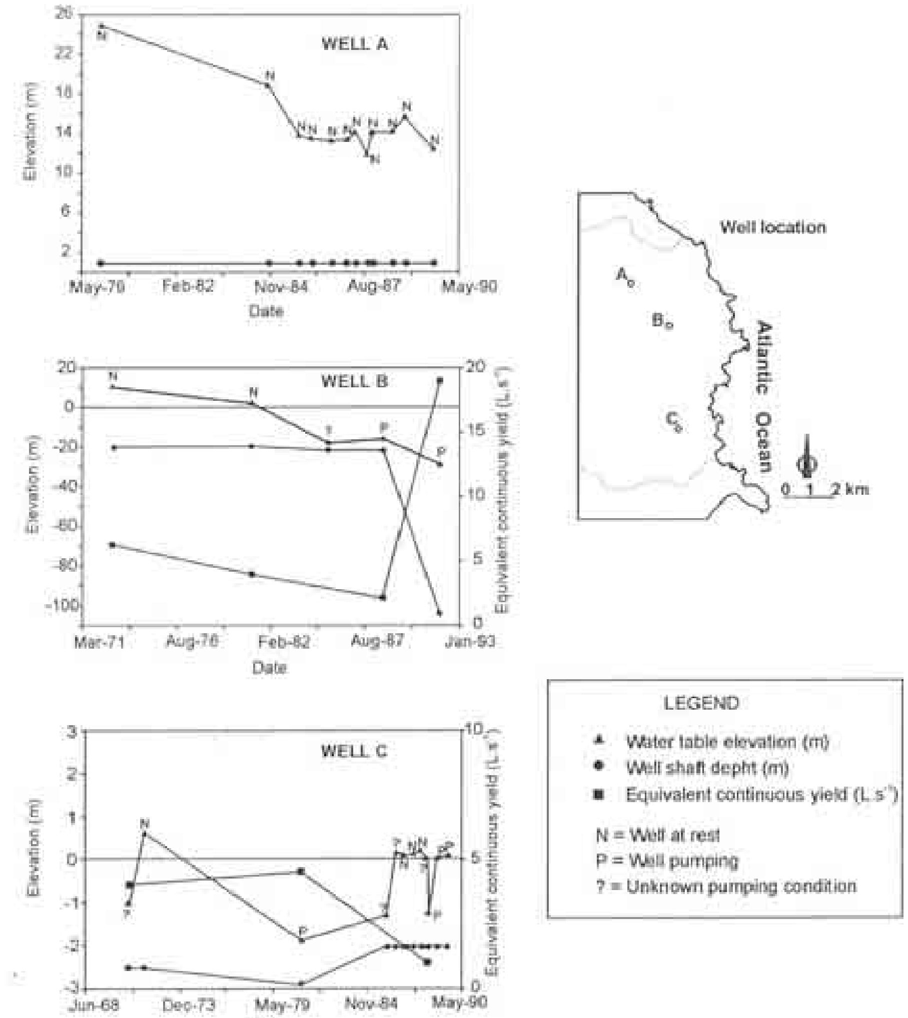


Figure 3. Time evolution of water table elevation, well shaft depth and abstraction (expressed in equivalent continuous yield) in three wells of the study area. Well A is out of use. Well B is located in the central part of the area, where exploitation is more intensive. Well C presents a slight depth decrease, possibly due to up filling with sediments or rock falls.

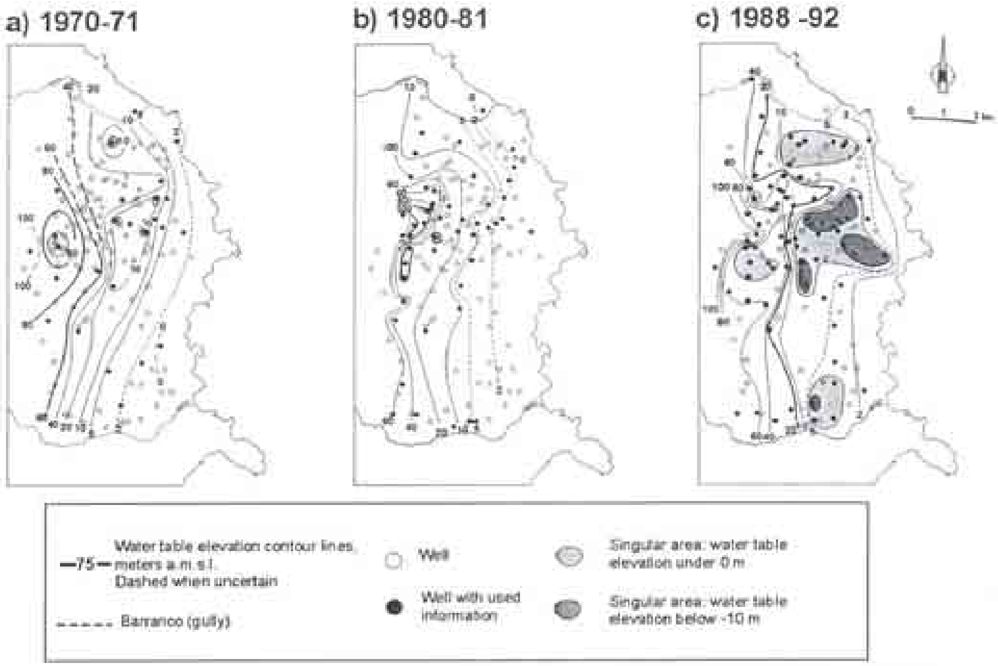


Figure 4. Water table elevation contour lines in three different times: a) 1970–1971; b) 1980–1981 and c) 1988–1992. Singular areas with coalescent drawdown pumping cones have been identified (Cabrera and Custodio, 2003).

(authors' and island water register data) as shown in Figure 4. The area is not uniformly covered with information. There are several zones where there are no wells, especially near the coast. In some cases altitude errors may be up to 5 m and water level depths may reflect residual or active dynamic effects. In the figure, low values that represent the local effect of a well or a close-by cluster of wells have been deleted, but the more extensive depressed areas are shown.

The materials through which groundwater flows and is abstracted are different from what shows the surface geology due to the depth of the water table (often more than 100 m) and the horizontal and vertical complexity of the area. The possibility to directly observe the penetrated materials by descending into the wells is a rare opportunity when a trustable, detailed geological description is not available. The emplacement of wells and the geological formation exploited by each one are shown in Figure 5. Wells in the southern zone exploiting the dominant Roque Nublo Group volcanic breccias and Recent Basalts formation have a low yield. The other formations may yield more than 1 L/s per well in areas that cluster several wells. The correspondence between well yield and the geological formations is not clear; there are several factors which intervene, that include well penetration and the effective functioning of the drainage horizontal boreholes at the study time. The most productive area is at the east of the town of Telde, where the LPDF and/or the Phonolitic Formation are developed, although most of the well productivity is probably due to the LPDF contribution, directly or by leaking water into fractures in the phonolites below. The coastward extension is poorly known.

Of the different formations involved only the LPDF is a typical porous one. The other formations are rocks with fissures and porous-like blocks, as happens to most subaerial volcanic





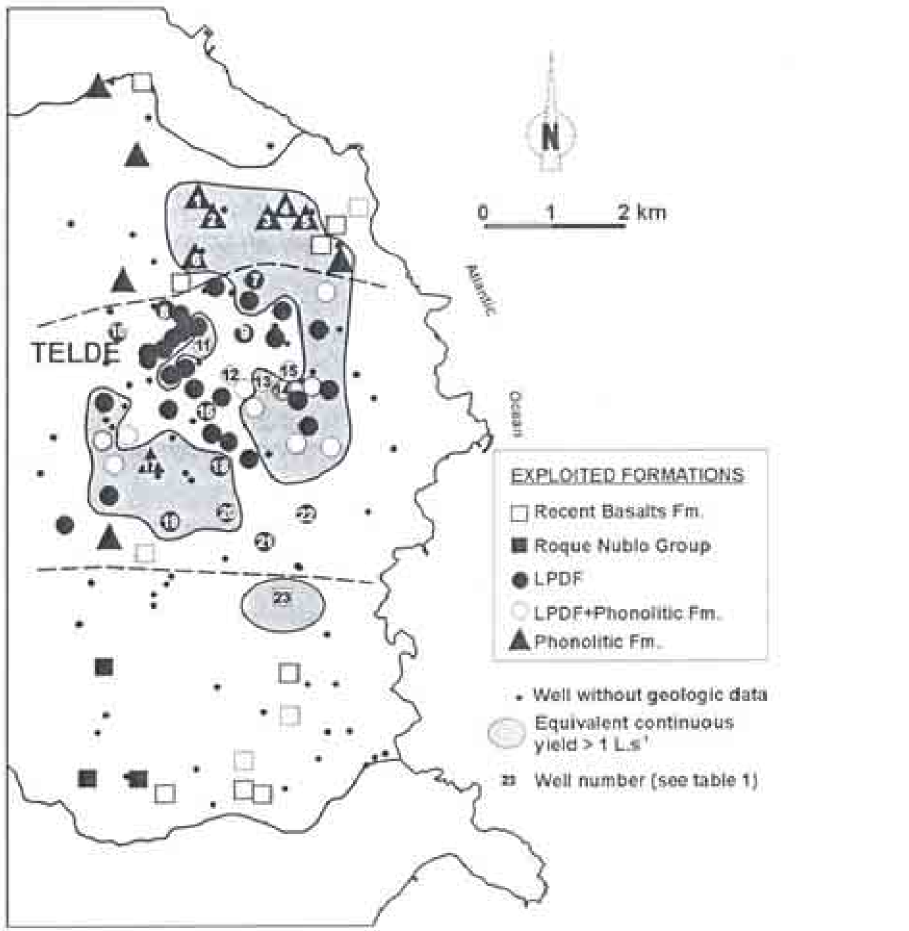


Figure 5. Wells with data on the exploited formation. Three main zones are distinguished. Wells with an equivalent continuous yield higher than 1 L/s are indicated (modified from Cabrera and Custodio, 2003).

formations (Custodio, 2003). Calculated aquifer hydraulic properties refer to bulk rock properties (Cabrera and Custodio, 2003).

## 3 GROUNDWATER QUALITY

Groundwater in the area is divided in several water families depending on the water-rock interaction with the different materials. Interaction is enhanced by volcanic $CO_2$ contributions and mixing with other waters. Typical groundwater from the zone is of the Mg-$CO_3$H type when basaltic and basanitic materials from Cycles II and III are exploited. They are located at the south of the study area, above 100 m elevation, in an area where deep $CO_2$ contributions are important. Water coming from Cycle I phonolitic lava flows and from sedimentary LPDF is of the Na-Cl type and are located in the north and centre of the area. Na-Cl-$SO_4$ type water is found in the coastal strip, pointing to the mixing with sea water which is intruding as a result of freshwater abstraction. This is accompanied by cation exchange processes in the mixing front, even with possible local gypsum precipitation due to water hardening, and later redissolution by the intruding seawater. There are no enough monitoring wells to check this behaviour, but it shows up more to the south of the study area (unpublished). Mg-Cl type water at the south indicates the existence of saline recharge and mineralization from the rocks in a $CO_2$ rich media. Groundwater in the central part of the zone is of the $Na\text{-}SO_4$ or $Na\text{-}CO_3H\text{-}Cl$ types, with high nitrate contents (up to 300 mg/L), that points to the mixing with irrigation return flows, or urban waste water, which have already penetrated the thick unsaturated zone.

The analysis of the hydrochemical evolution from 1970s to 1992 shows a generalised salinity increase (Figure 6), which follows the groundwater level drawdown. In the coastal-central part of the area the pumped water temperature also increases as well depth increases, but other wells located at the southern and northern part can yield high temperature water associated with deep $CO_2$ contributions. The salinity and temperature increase in the coastal-central part of the area goes along with a change of the water type when the wells are deepened, from the $Na\text{-}Cl\text{-}SO_4$ or $Na\text{-}SO_4$ types to the $Na\text{-}CO_3H\text{-}Cl$ type, with an important nitrate content decrease. This is due to the abstraction from deeper formations (mainly phonolitic lava flows), with a lower proportion of irrigation return flows. In other wells that have not been deepened, groundwater evolves to $Na\text{-}Cl\text{-}SO_4$ type, showing a salinity increase due to increasing irrigation return flows effect.

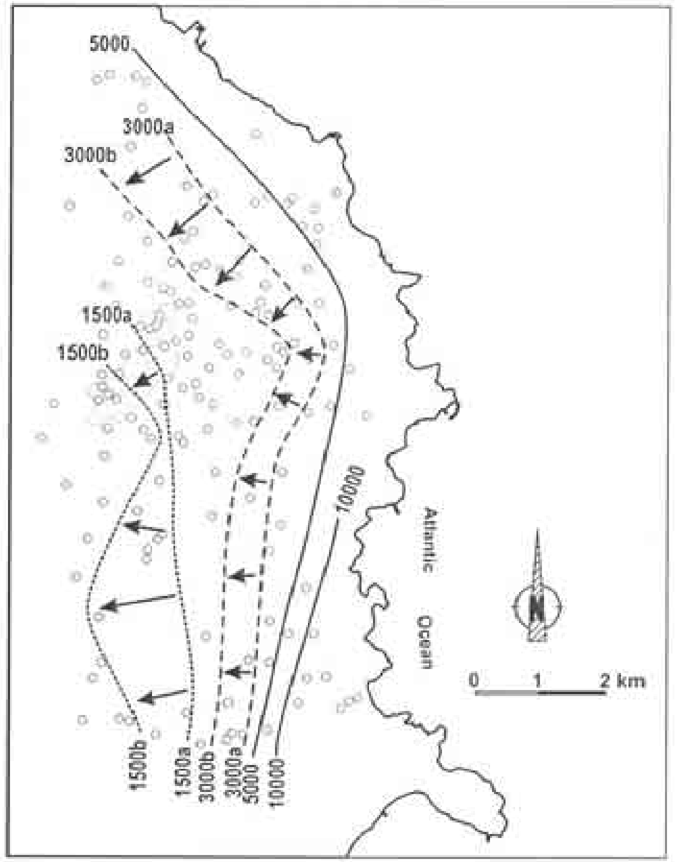


Figure 6. Spatial distribution and time evolution of electrical conductivity of groundwater from 1972 (a) to 1992 (b) in the study area. Arrows show the movement of isolines.





## 4 RESULTS OF INTENSIVE EXPLOITATION

Information about the aquifer in the Telde area starts when it was already intensively exploited, so the natural situation cannot be known, but for some scattered data. It seems that the *Barranco Real de Telde*, and perhaps some of the other gullies, were draining groundwater from the aquifer in the headwater areas, but not in the lower reaches in the study area. Here the water-table was below the gully channel, and now it is very deep below it. There were recharge areas in which possible surface flows infiltrated, and perhaps continue to infiltrate today when sporadic storm runoff is produced. In practice it seems that this recharge can be currently considered a small groundwater balance term, and little affects the water table. It can be safely assumed that in 1970, the date of the first water-table map, there were already some clear drawdown in the area.

Figure 4 shows that in the intensively groundwater developed area of Telde:

- along the coast there are no water-table elevations below sea level, except locally.
- below sea level water-table elevations have been developed along a central strip and they have progressed toward the coastal area.
- the central strip roughly corresponds to the most permeable areas shown in Figure 5, where groundwater abstraction concentrates.
- at the western boundary the water table elevation is little unchanged.
- groundwater flow presents an average slope of about 20‰ to 40‰ at the inner boundary, and flattens to 3‰ to 5‰ near the coastal line, but there are local disturbances created by the exploitation well clusters.
- an area of small drawdown and high water table goes W-E through the town of Telde; it may be the result of preferential recharge by leakage from the urban water supply network, sewage system and irrigated areas at the time.
- no clear relationship shows up between water table position and lithology.

Figure 7 is an attempt to reconstruct the little disturbed water table before 1970; it also shows a representative cross-section though Telde, in which the water table was inside the Recent Basalt Formation; it is currently mostly drained.

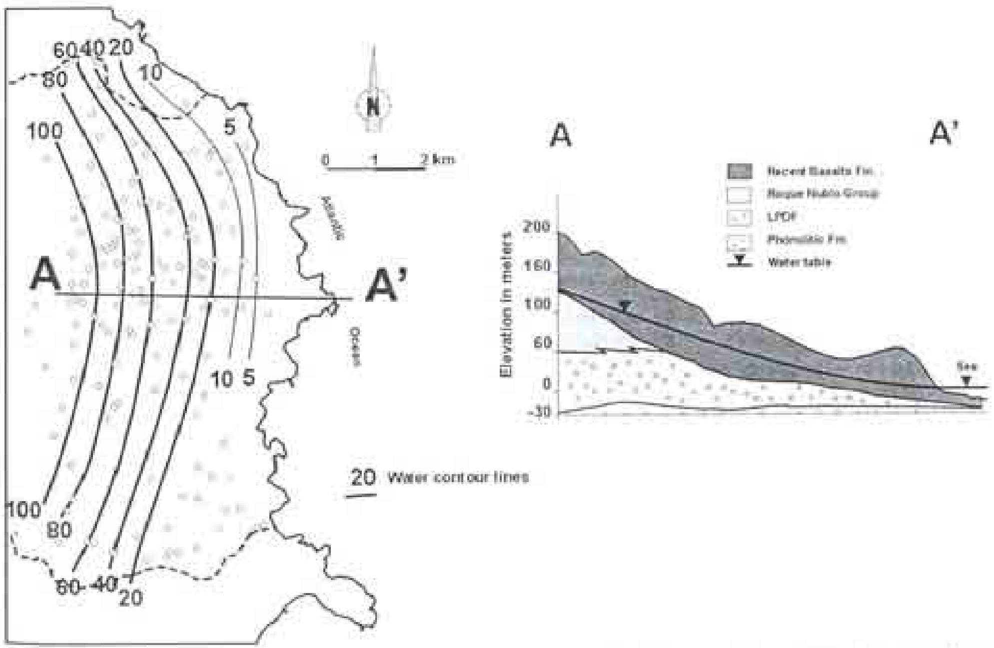


Figure 7. Assumed water table map and hydrogeologic cross-section for Telde area before 1970, when groundwater abstraction was small (Cabrera and Custodio, 2003).

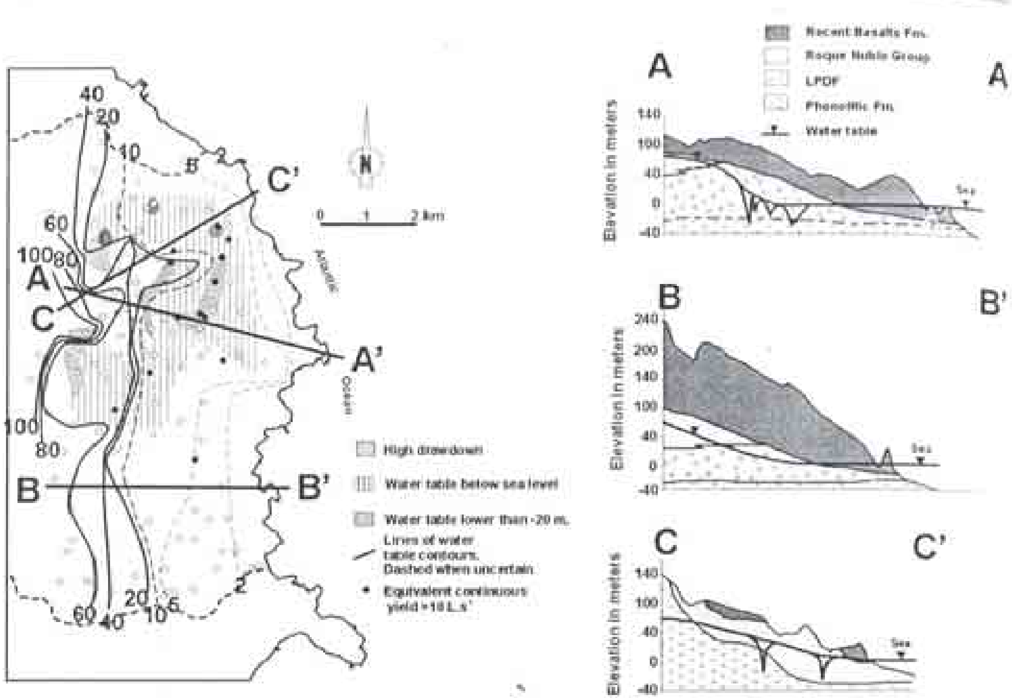


Figure 8. Smoothed water table map and hydrogeologic cross-section of the 1988 situation in Telde area. Local pumping cones are not considered in the map. In the cross-sections they are depleted only for illustration, and do not necessarily correspond to real wells (Cabrera and Custodio, 2003).

Figure 8 is an attempt to show the current situation by extrapolating the presented results with new available information, which shows the depletion of groundwater in a central N-S strip, except around the town of Telde, where there are the recharge circumstances explained before. The three cross-sections show that now the water table is mostly inside the LPDF except to the north of the town of Telde, where static levels are in the Roque Nublo Group breccias and depleted water levels are in the Phonolitic Formation below.

Drawdown has produced the evolution from a situation where presumably the Recent Basalts Formation was the most productive unit, sometimes draining water from the LPDF emplaced below, to the actual situation. The evolution was that water came first from LPDF, and when the water table went down it was the Phonolitic Formation which started to be exploited, compensating its low permeability with the greater penetration of the recent boreholes.

As a secondary effects of drawdown, the groundwater chemistry shows a generalized salinity increase (Figure 6) and changes in the chemistry water type. The abstraction of water from the Recent Basalts Formation and FDLP produces groundwater of the Na-Cl-$SO_4$ or Na-$SO_4$ types, with a high content in nitrates due to irrigation return flows. When wells are deepened and groundwater come from the phonolitic lava flows, water changes to the Na-$CO_3$H-Cl type, with an important nitrate content decrease. This can be due to the dilution of the irrigation return flows and/or to a decrease of the agriculture in the area from 1980s. Nevertheless, certain wells that have not been deepened show an increase in the salinity, which may be due to the increase in the recharge from irrigation return flows.

Recharge mechanisms have not been studied in detail. The Recent Basalts and the thin soil cover in some areas allow the downward vertical transfer or recharge water without the formation





Table 1. Indicative groundwater balance of the 75 km² of the Telde area for the situation in the 1990s. Average values are given. Uncertainty may be large.

| *Inflow terms* | Mm³/yr | *Comments* |
|---|---|---|
| Lateral, from the W boundary | 7.4 | Applying Darcy's law |
| Infiltration from Bco. Real Telde | 0.5 | Data from SPA-15 (1975) |
| Recharge from local rainfall | 1.8 | Chloride balance |
| Return flows from irrigation | 1.7 | Uncertain |
| Leakage from supply network | 0.7 | Municipal data |
| Depletion of groundwater storage | 0.7 | 25 km²; 0.06 drainable porosity |
| TOTAL | 12.8 | Uncertainty ± 5 Mm³/yr |
| *Outflow terms* | Mm³/yr | *Comments* |
| Abstraction from wells | 9.0 | After the survey |
| Discharge to the sea | 3.8 | Applying Darcy's law; uncertain |
| Outflow to water courses | 0.0 | No drainage |
| Direct evaporation | 0.0 | Deep water table |
| TOTAL | 12.8 | Uncertainty ± 3 Mm³/yr |

of permanent or temporal perched aquifers, or at least they have not been seen during the descents into the wells. The only falling in water that was observed was very shallow and related to leakages and irrigation.

A groundwater balance in the study area of Telde is a crude exercise but shows the relative values of the different terms. Balance terms of table 1 are average values in the 1990s, in million $m^3$ per year ($Mm^3$/yr).

In such an intensively exploited area, with conspicuous water table depletion, lateral inflow plus local recharge and other sources of recharge may still exceed actual groundwater exploitation. The recent evolution of the area to transform the cultivated areas into urbanised land causes the progressive decrease of local recharge and irrigation return flows. Also the leakage from the water supply network has been greatly reduced after major investments and repairs to save water. So, the inflow terms are decreasing, even if lateral inflow is maintained. But also well abstraction is decreasing, according to new data on the area.

Groundwater storage depletion is a minor term and may mostly reflect the transient evolution of the system, but it may continue to increase if well abstraction does not sharply decrease. This seems to be happening as expected if irrigation land becomes urban. A major drawback is progressive groundwater quality impairment by saline intrusion, but this is still a too poorly known process in the area, especially due to the lack of observation points in the critical areas.

## 5 CONCLUSIONS

The study area has a complex disposition of materials and a relatively deep (40 m to 100 m) water table. Groundwater flow is variable areally and also along time, as the water table position changes due to exploitation. Exploitation causes also an increment in water salinity and changes in the hydrochemical water type, when water flows through deeper formations. The existence of an intercalated detritic formation (LPDF) plays a major hydrogeological role as a preferential pathway for groundwater. The area shows a central strip of groundwater reserve depletion due to abstraction, up to 40 m of drawdown between 1970 and 1992, where salinity increase is higher than in other areas.

Groundwater reserve depletion contributes only about 5% to input balance terms while groundwater transfer from inland areas is more than 60%. Recharge was almost entirely discharged into the sea in dispersed form along the shoreline; currently about 30% may be still discharged, much more than reserve depletion, in spite of persisting the drawdown trend, and the existence of local seawater intrusion.

In spite of the intensive groundwater exploitation of the area of Telde and the continuous drawdown, the area may be managed to get a sustainable use if abstraction is reduced and the spatial distribution of wells is corrected to avoid saline water problems. This means a groundwater users' association, which must include inland stakeholders and a monitoring network.

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*With the collaboration of*
R. Aliaga[1],[5]

[1] *Technical University of Valencia, Spain*
[2] *Marcelino Botín Foundation, Santander, Spain*
[3] *Spanish Association of Groundwater Users, Madrid, Spain*
[4] *Technical University of Catalonia, Barcelona, Spain*
[5] *Geological Survey of Spain, Madrid, Spain*

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