Groundwater flow in a volcanic–sedimentary coastal aquifer: Telde area, Gran Canaria, Canary Islands, Spain

M. C. Cabrera · E. Custodio

Abstract Groundwater conditions in a 75-km^2 coastal area around the town of Telde in eastern Gran Canaria island have been studied. Pliocene to Recent volcanic materials are found, with an intercalated detrital formation (LPDF), which is a characteristic of the area. Groundwater development has become intensive since the 1950s, mostly for intensive agricultural irrigation and municipal water supply. The LPDF is one order of magnitude more transmissive and permeable than the underlying Phonolitic Formation when median values are compared (150 and 15 m^2 day^{-1}; 5 and 0.5 m day^{-1}, respectively). These two formations are highly heterogeneous and the ranges of expected well productivities partly overlap. The overlying recent basalts constituted a good aquifer several decades ago but now are mostly drained, except in the southern areas. Average values of drainable porosity (specific yield) seem to be about 0.03 to 0.04, or higher. Groundwater development has produced a conspicuous strip where the watertable has been drawn down as much as 40 m in 20 years, although the inland watertable elevation is much less affected. Groundwater reserve depletion contributes only about 5% of abstracted water, and more than 60% of this is transmitted from inland areas. Groundwater discharge into the sea may still be significant, perhaps 30% of total inflow to the area is discharged to the sea although this value is very uncertain.

Résumé Les conditions de gisement de l'eau souterraine d'une région de 75 km^2 de la côte Est de l'île de la Grande Canarie (archipel des Canaries), dans le secteur de Telde, ont été étudiées, en utilisant seulement les données fournies par les puits d'exploitation existants. Les matériaux volcaniques, d'âge Pliocène à sub-actuel, sont séparés par une formation détritique (FDLP), qui constitue la principale singularité de cette région. L'exploitation de l'eau souterraine est devenue intensive à partir de 1950, principalement pour des besoins d'irrigation (agriculture intensive) et d'alimentation en eau des zones urbaines. La comparaison des valeurs médianes montre que la FDLP est d'un ordre de grandeur plus transmissive et perméable que les formations volcaniques phonolitiques au-dessous (respectivement 150 et 15 m^2/jour ; 5 et 0,5 m/jour). Néanmoins, ces deux formations sont très hétérogènes et les deux gammes de valeurs de productivité des puits se recouvrent. Les Basaltes récents audessus qui constituaient, il y a encore quelques décades, un bon aquifère, sont presque entièrement desaturés à l'heure actuelle, a exception faite de la partie sud. Les valeurs moyennes de porosité drainable (efficace) sont de l'ordre de 0,03 à 0,04, voire localement plus élevées. L'exploitation des eaux souterraines a induit de forts rebattements au long d'une zone littorale (d'environ 40 m au cours des 20 dernières années), alors que la surface piézométrique est moins affectée en amont vers le centre de l'île. La diminution de la réserve des eaux souterraines dans la zone étudiée représente seulement 5% des volumes d'eau extraits. Plus de 60% proviennent du centre de l'île. Les écoulements vers la mer peuvent être significatifs, (environ 30% des entrées totales) bien que cette estimation soit sujeté à une très forte incertitude.

Resumen Se ha llevado a cabo un estudio detallado de una zona costera de 75 km^2 situada en la costa del Municipio de Telde, al Este de la isla de Gran Canaria, en el Archipiélago Canario. En ella se encuentran materiales volcánicos de edad Pliocena a Reciente, con una formación detrítica intercalada (FDLP), que constituye la máxima singularidad del área. La explotación de las aguas subterráneas ha sido intensiva a partir de la década de 1950, fundamentalmente para el riego de cultivos

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intensivos y para el suministro a la población. Comparando las medianas de los valores de transmisividad y permeabilidad entre la FDLP y la Formación Fonolítica que está debajo (140 a 15 m^2/día y 5 a 0,5 m/día respectivamente) se comprueba que la primera es un orden de magnitud más transmisiva y permeable que la segunda, aunque ambas formaciones son muy heterogéneas y los rangos de productividad esperables en los pozos se solapan entre sí. Los Basaltos Recientes que están encima fueron un buen acuífero hace algunas décadas, pero en la actualidad han sido drenados casi en su totalidad, excepto en el sector Sur. Los valores medios de la porosidad drenable (eficaz) parecen estar alrededor de 0,03 a 0,04, o más. La explotación de las aguas subterráneas ha producido una franja con un destacado descenso de los niveles piezométricos, que alcanza los 40 m en 20 años, aunque la superficie piezométrica hacia el centro de la isla está menos afectada. El descenso calculado en la reserva de aguas subterráneas alcanza solamente un 5% del agua extraída y más de un 60% se transmite desde las cumbres de la isla. La descarga al mar puede ser aún significativa, quizás el 30% de las entradas totales, aunque esta cifra es muy incierta.

Keywords Volcanic terrains · Intensive use · Groundwater flow · Hydraulic properties · Canary Islands

Introduction

On Volcanic Island Aquifers

Island volcanic rocks exhibit a very wide range of hydrogeological characteristics and circumstances, from almost impermeable to one of the most permeable rock formations, from a porous medium to fractured rock. Their behaviour depends on the type of eruption, distance to the source area, form of deposition, land slope, degree of weathering, post-depositional processes and regional and local tectonic disturbances, among other processes (Davis 1969; Custodio 1989, 2004a). They may be highly heterogeneous due to various processes and features that include dykes, intrusive bodies and baked palaeosoils. This means that properties vary locally over short distances. However, in order to define the regional hydrogeological behaviour of a volcanic island in regard to a complex groundwater system, it seems that, at the hectometric scale, average characteristics of the formations vary slowly. This implies that groundwater flow, variables and parameters can be defined, such as piezometric head, watertable, porosity and average permeabilites (Custodio 1978), in agreement with the concept of representative aquifer volume of Bear (1979). The study of small areas may require an accurate 3-D hydrogeological description in order to differentiate units to which averaged properties can be assigned. It may happen that some of these units are sedimentary in origin and were deposited during the inactive periods between major volcanic episodes in which erosive processes dominated.

There are local studies from many volcanic islands such as the archipelagos of Hawaii, the Canaries, Madeira and Azores, and the islands of Reunion, Mauritius, Guadelupe and Tahiti, among many others. A compilation of the results of these studies can be found in Falkland and Custodio (1991) and Peterson (1993).

Background on the Canary Islands

The Canary Islands comprise seven main islands and several islets which are situated in the Atlantic Ocean between latitude N27° and N30° and longitude W13° and W18° (Fig. 1). These islands are located on the passive margin of the African plate, on the oceanic floor that was formed in the first stages of the Atlantic Ocean spreading. The different island edifices have been built by the piling up of submarine and later of subaerial volcanic materials that have been emitted in several phases. Materials are predominantly basaltic but more acidic differentiates, such as phonolites and trachytes, are also common. Large landslides are a common feature. Long and intensive volcanic episodes are separated by quiet periods in which erosion predominates. The stage of evolution varies from relatively old islands (20 Ma) to recent ones (<1 Ma), relative to the oldest subaerial volcanics found.

The Canary Islands are located in the Saharan dry belt. Thus, there is low rainfall, averaging 70 to 150 mm $year^{-1}$, especially in the eastern islands, but when the island altitude exceeds 1,200 m (see Fig. 1 for altitudes) the circulation of the northeasterly rain-bearing trade winds is intersected. Also the sporadic SW storms

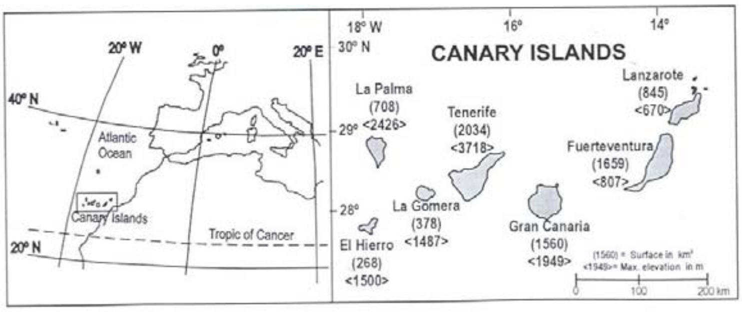

Fig. 1 General situation of the Canary Islands archipelago. Major islands' surface in km^2 and maximum elevations in metres are indicated

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produce a conspicuous increase in average rainfall in the areas facing prevailing winds. Average rainfall values up to about 1,000 mm $year^{-1}$ may be attained in some of these areas. This produces a groundwater recharge of up to a few hundred mm $year^{-1}$ on the areas with permeable volcanics. In the low rainfall areas, mostly near the coast, recharge amounts to only a few mm $year^{-1}$ of brackish water from evaporative concentration of rainfall, which has a relatively high content of airborne marine salts (Custodio 1990).

Storm runoff is very low except where low permeability materials crop out extensively, as is the case of the older eastern islands. Surface water flows only during, and shortly after, intense rainy periods, or downstream in groundwater drainage areas. Even in the last case the water may reinfiltrate downstream, flow entirely or partly through the alluvium or be evapotranspirated by vegetation patches, some of them with the abundant palm trees that characterise many landscapes of the islands.

The Canaries have been studied in detail, not only because of their very interesting volcanologic characteristics and wide range of rock exposures, but also because of the intensive exploitation of groundwater resources, up to 300 Mm^3 $year^{-1}$, for a population of close to 2 million inhabitants (Custodio and Cabrera 2002).

In broad terms, the general hydrogeological structure of the Canary Islands can be sketched as a "core" of low permeability old volcanics, intrusive bodies and thermally metamorphosed rocks, with successive covers of younger, more permeable materials which form an apron towards the sea coast (SPA-15 1975; Custodio 1985, 2004a; 2004b). These layers are often discontinuous both laterally and longitudinally. In some islands the "core" crops out extensively, and may include materials from the submarine stages and intrusive bodies, while in others only young volcanics are found at the surface. Formations can be defined from a lithological and volcanological point of view, but this may be of little hydrogeological value since distance to the eruption centres plays a dominant role in actual hydraulic properties.

Although there are conspicuous differences among the islands, in any case there is a well-defined regional watertable, which varies from shallow to several hundred metres in depth. In the Canaries, true perched aquifers are small if they exist at all, except during and shortly after very wet periods. Groundwater flows from the central, high altitude areas towards the coast, where it discharges mostly in diffuse form. A fraction of groundwater recharge may feed springs in inland areas, and sustain flow in some tracts of the gullies ("barrancos"). These discharges depend on rock structure and relief dissection in the gullies. The situation varies from island to island. Intensive groundwater development has produced the exhaustion of most of these springs; their water is now pumped or drained out from depth and flows to the water demand centres through channels and pipes. The evolution of groundwater development is explained in Custodio and Cabrera (2002).

Gran Canaria is an almost round island with a diameter of 40 km, and a height of ca. 2,000 m. It is radially dissected by deep gullies. Only subaerial volcanic materials crop out (Pérez-Torrado 2000), their ages ranging from 14.5 Ma to subhistoric residual volcanism. The island is essentially a basaltic volcano resting on the ocean floor at about 4,000 m depth, topped by a large shield volcano, with more recent series of more salic eruptions (mostly phonolites), extrusive sheets of breccias from highly explosive events (Roque Nublo group) and again predominantly basaltic flows (ITGE 1990). Between volcanically active stages occur long periods of calm dominated by intense erosion. There is evidence of large landslides. In the centre of the island, erosion has unearthed part of the deep dyke complexes and shallow magma chambers, but no outcrops of the submarine series are visible.

This paper deals mainly with the small area of Telde, in eastern Gran Canaria Island (Fig. 2), after the work of Cabrera (1995) under the tuition of the second author, and some recent new data. The work considers groundwater flow aspects, which is the object of the present paper; hydrogeochemical aspects were included in Cabrera (1995) and will be the subject of a paper in preparation.

Characteristics of The Study Area

General Characteristics

The Telde area is located in the eastern part of Gran Canaria. Its headwaters are outside of the area and extend up to the top highland of the island, with areas of up to 1,000 mm of average rainfall. The Barranco Real de Telde is the main gully (Fig. 2), and although it was one of the island's permanent streams in the past it no longer carries water. 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 km^2. It is a gently sloping lava platform, relatively smooth, bounded by east–west trending gullies to the north and south (Fig. 2), and dotted with small recent volcanic cones. Most of the coast consists of 10–30 m high cliffs cut on recent volcanics.

The average rainfall is 150 mm $year^{-1}$ and the average yearly temperature is 20 °C. The area lies at the southern boundary of the persistent northern cloud cover of the island which means a high sunshine exposure. It can be considered as an arid area, at the foot of relatively humid highlands.

Groundwater mining in the island was first developed in the Telde area, which has a sedimentary permeable formation interlayered with the volcanics, in the coastal area. This area has not been studied in detail before, with the exception of preliminary surveys carried out during the SPA-15 (1975) study. New data were added by the MAC-21 study (about 1980, unpublished), 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 Gran Canaria Water Plan (PHGC 1991). MAC stands for Macaronesia, the name of the

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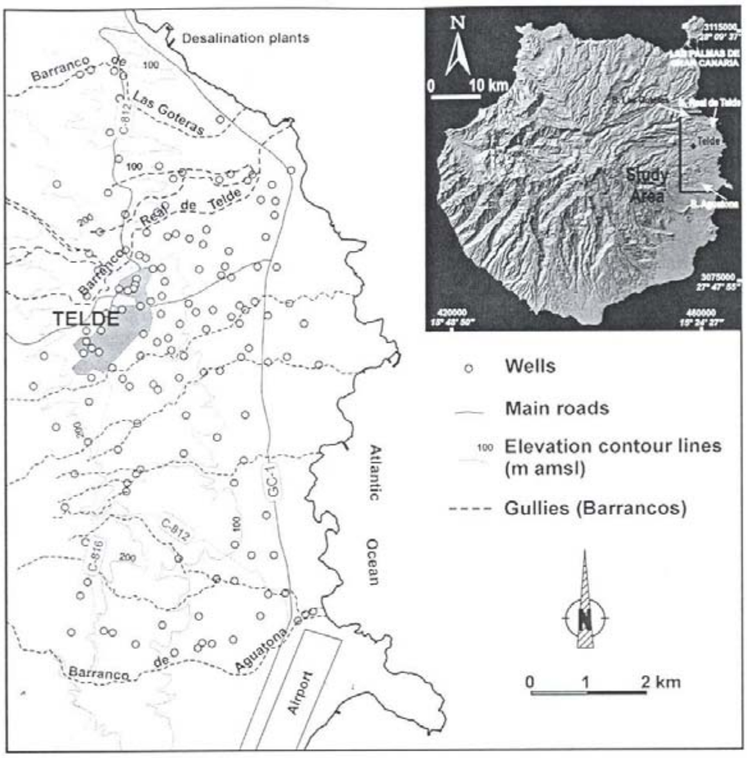

Fig. 2 Location of Telde area in Gran Canaria, Canary Islands (Spain), showing topography, main gullies (barrancos) and location of wells. The inset is the shaded zenithal view of Gran Canaria island (from works of GRAFCAN), with the study area indicated. Notice the main gullies (barrancos) and the relatively flat platform-like landscape of the study area which is due to recent lava flows

group of Atlantic volcanic archipelagos (Cape Verde, the Canaries, Salvagems, Madeira and Azores).

The land has been traditionally used for irrigated agriculture, with dominant crops changing from the 15th century: sugar cane, vineyards, cereals, cochineal, banana trees and tomatoes. Bananas have been cultivated since the end of the 14th century to the 1970s and were then progressively replaced, first by peppers and cucumbers in greenhouses in the early 1970s, and later by oranges in the late 1970s. From 1980 the development of industrial and commercial parks and residential zones has displaced former agricultural areas. Currently about 80% of the area has been urbanised and devoted to commerce, or consists of abandoned agricultural plots. The uplands are still largely rural, with irrigated plots, and reforested areas.

Until the end of the 19th century the 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 large diameter shaft wells, which are the oldest on the island. In the 1980s, half of the water required for irrigation and domestic supply came from the upper parts of the island and the other half was obtained from wells in the area. Currently, a large part of urban and domestic water supply comes from sea desalination plants, but local wells continue to be used, at a lower rate. Poor quality groundwater is often mixed with water from other sources.

Geology of the Study Area

In the study area the three main subaerial magmatic cycles of the island are represented: Cycle I or Old Volcanics (Miocene); Cycle II or Roque Nublo (Pliocene); and Cycle III or Recent (Plio-Quaternary). They are separated by inactive stages in which erosion was intense and detritic sedimentation dominated (ITGE 1990). The sedimentary deposits correspond to the Las Palmas Detritic Formation (LPDF) that is divided into Lower, Middle and Upper members, according to their characteristics and sedimentary environments. The contacts between the formations are erosive. Thick palaeosoils are only found inland and are discontinuous. Between volcanic flows and deposits some red layers can be found but in the Telde area these are incipient and patchy.

Figure 3 is a schematic representation of the geology of the study area, with detritic sediments interlayered between volcanic materials. From bottom to top, the stratigraphic column includes:

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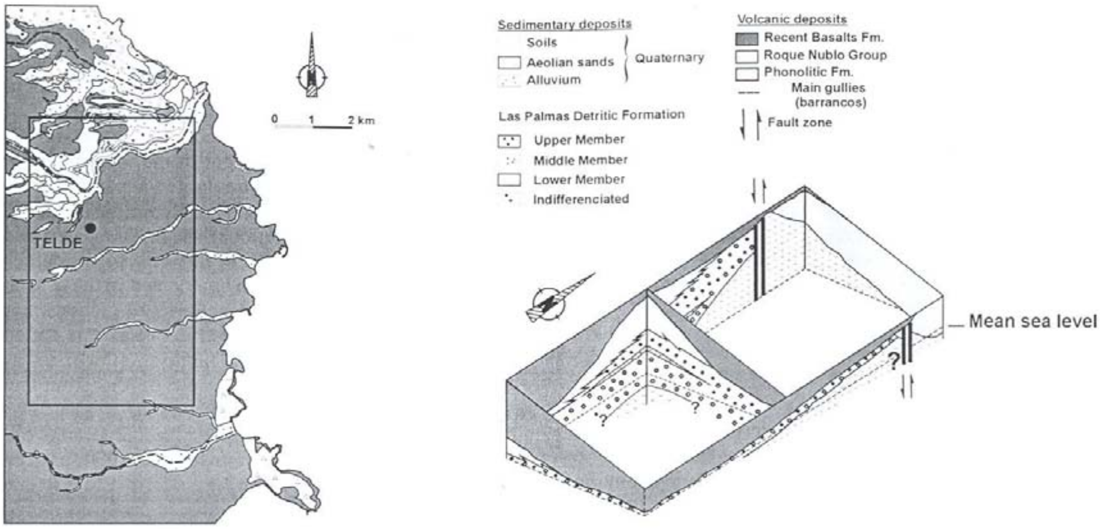

Fig. 3 Geology of the Telde area (modified from ITGE 1990) and interpretative diagram of geometry of the geological formations in the Telde area (modified from Cabrera 1995)

- Cycle I Phonolitic Formation: pyroclastic deposits, cineritic ash-flows, and block and ash flows, that may be interbedded with alluvial conglomerates from the LPDF Lower member. There is a minor proportion of greenish phonolitic lava flows, interbedded with ash and blocks, and ash flows.
- Las Palmas Detritic Formation (LPDF): three members have been found. The Lower member is formed by phonolitic alluvial conglomerates; the Middle member is formed by coastal sands of littoral origin (Gabaldón et al. 1989), and the Upper member is made up of basaltic and basanitic conglomerates, which show a gradual transition to the Roque Nublo volcanic breccias.
- Roque Nublo Group: pyroclastic facies, formed by breccias and pyroclastic flows, interbedded with the LPDF Upper member conglomerates.
- Recent Basalts Formation (Cycle III): massive basanitic lava flows alternating with thinner scoria layers. Locally, some strombolian volcanic cones of fall pyroclastic deposits may be covered by lava flows, up to 179 m thick to the south.

The spatial disposition of these materials in the subsoil was deduced from data from the large diameter shaft wells of the area, mostly by descending into them, but also by studying the voluminous rock waste dumps. The 3-D geological reconstruction (Fig. 3) has been based on 40 well descriptions, which are more or less uniformly distributed over the area (Cabrera et al. 1992; Cabrera 1995). No deep exploratory boreholes have been drilled in the area and thus the characteristics of the deeper formations are speculative.

The surface geology shows two different domains, separated by the Barranco Real de Telde. In the northern domain, materials from the three cycles crop out. The southern domain is covered almost exclusively by Cycle III basaltic and basanitic products; 5-m thick Upper member LPDF conglomerates can be found in the coastal cliff, under 15 m of Recent Cycle basalt lava flows. All these materials may be covered by thin Quaternary soils and anthropic materials.

Materials at depth, 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, being thicker in the south-west.

Groundwater Use

There are 145 wells in the area (Fig. 2), 30 of which were excavated before 1924. The oldest wells have an initial diameter of 6 m, to accommodate the old, bulky, blood-actioned pumping machinery (water wheels). The other traditional wells of the area, most of them built in the 1940s and the 1950s, are hand and explosive dug shaft wells in the rock, with a diameter of 2.5–3 m. They used to have secondary galleries at different depths and radial horizontal small diameter drains ("catas"), that were drilled at different stages as the water yield of the well decreased due to the general watertable level drawdown. Currently, most of these secondary galleries are now useless because they lie above the watertable. Four of these wells were reported to be deepened in the 1980s by

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drilling a vertical borehole inside them. Well depths range from 15 to 313 m, with an average of 102 m. A total of 12 boreholes, 350–400 mm in diameter, were drilled in the 1980s. They are deeper than the shaft wells, with an average depth of 165 m. They are uncased or the casing consists of a simple slotted tube to protect the pump from falling stones.

Most irrigation wells are pumped several hours each day, resting 1 or 2 months a year. Pumping rates range from 3 to 50 L s^{-1}, with an average value of 12 L s^{-1}. Since the pumps do not work continuously, an equivalent continuous yield is calculated from data obtained during field surveys (Cabrera 1995; Cabrera and Custodio 2001).

Groundwater Flow Results

Groundwater under natural conditions in the Telde area originates mostly in inland areas and is discharged along the coast. No references to discrete coastal and submarine freshwater outflows are available nor were they identified in an airborne thermographic survey (SPA-15 1975).

Figure 4 is a schematic representation of regional groundwater flow based on a detailed survey of eight selected wells along a radial cross-section that is assumed to follow a regional flow line. Recent data were used from an ongoing study of the eastern part of Gran Canaria by the Geological Survey of Spain (IGME). Groundwater is transferred from the Phonolitic Formation, with its relatively low transmissivity to the more transmissive and wide detrital (LPDF) materials near the coast. Consequently the watertable slope decreases from about 0.04 to about 0.002.

The time evolution of potentiometric levels in the study area comes from data from different times and origins: 1970–71 for the SPA-15 study, 1980–81 for the MAC-21, 1986–89 for the operation of the IGME network, and 1991–92 for the technical reports for the Insular 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. The effect of pumping conditions or of residual drawdowns has been duly considered. Out-of-use wells have been given more weight in the interpretation. Well depth increases may cause larger apparent drawdown. Levels dropped in 38 of the 50 wells with data, even in the case of non-operational wells. The watertable drawdown ranges from 1 to 30 m in wells where depths have not changed, most of which are located in the central part of the study area. In deepened wells, groundwater levels dropped in parallel with well depth as a result of increased extraction. Water level stabilisation or rise was observed in four wells as the result of discontinuing groundwater abstraction in the nearby area.

The sparse data from the wells of the IGME network show water level drawdowns from 1985 to 1990, as seen in Fig. 5. An average increase in levels from 1 to 3 m can be noted in the period 1988–90, which is partly attributed to an increase in precipitation in 1987–89. This, besides increasing recharge in the catchment, reduced dynamic drawdown by reducing the groundwater abstraction rate for irrigation. Groundwater levels, groundwater exploitation rate and well deepening all correlate to some extent.

Watertable elevation maps have been drawn for three different times: 1970–1971 (SPA-15 data), 1980–1981 (MAC-21 data) and 1988–1991 (authors' and insular water register data) as shown in Fig. 6. Several empty zones exist where there are no wells, especially near the coast. Altitude errors may be up to 5 m in some cases and water depths may occasionally reflect residual or active dynamic effects. In Fig. 6, low points that represent the local effect of a well or a close-by cluster of wells have been deleted, while the more extensive depressed areas are shown.

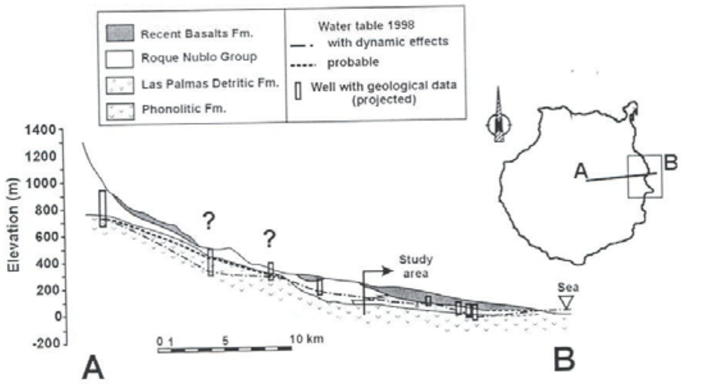

Fig. 4 Hydrogeologic cross-section of Telde and inland areas, based on a detailed survey of 1988 and confirmed by recent data. The wells marked with the ? sign indicate that the water level may show some dynamic drawdown or are affected by the projection in the cross-section. The headwaters and central island "caldera" are not included due to their geological complexity and the effect of intrusions and densely dike-injected formations that greatly modify hydraulic properties

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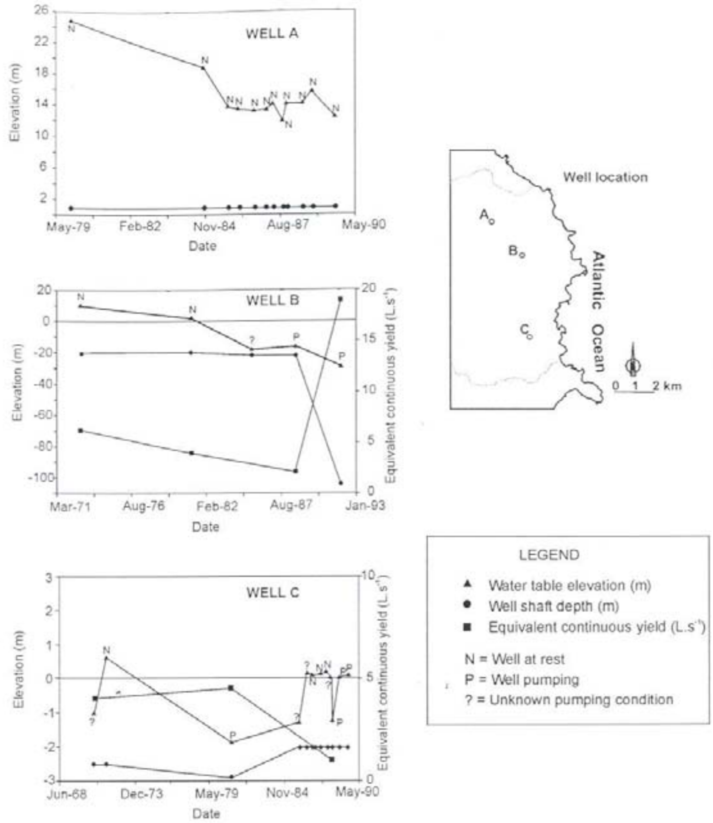

Fig. 5 Time evolution of watertable elevation, well shaft depth and abstraction (expressed in equivalent continuous yield) in three wells of the study area, after IGME surveys. Well A, at an elevation of 110 m, is out of use and its depth is constant; it reflects watertable evolution, with small measurement errors. Well B is located in the central part of the area, where exploitation is more intensive; the well was deepened, to increase the yield, which implies a lower exploitation level. Well C is skimming the watertable, possibly to reduce salinity; the slight decrease in depth is possibly due to progressive upfilling with sediments or rock falls

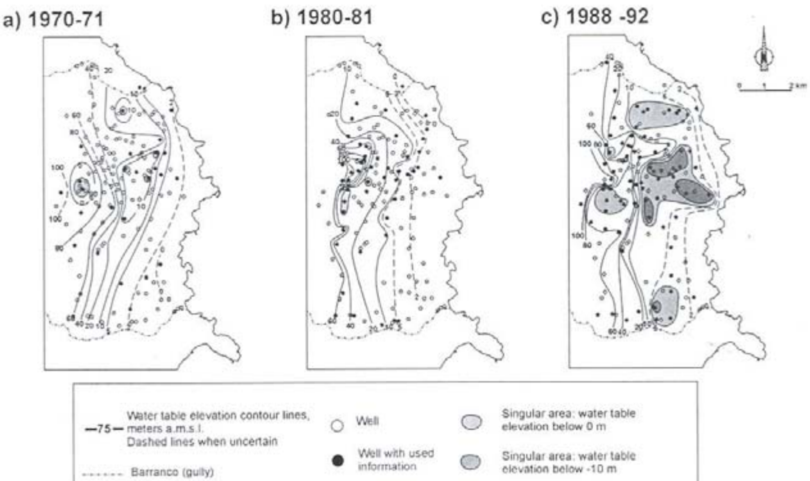

Fig. 6a–c Water-table elevation contour lines at three different times: **a** 1970–1971; **b** 1980–1981; **c** 1988–1991. Singular areas where coalescent drawdown pumping cones have been identified

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Regarding the hydraulic properties of the formations, as presented below, simple calculations show that the drawdown cone around a pumping well is presumably rather small and deep, especially for the Phonolitic formation; for a borehole it may be about 150 m in diameter and 100 m deep.

Hydraulic Characteristics of Wells

No classical pumping tests have been carried out in the area. Neither observation boreholes nor groundwater level recorders have been emplaced. Wells have a high water storage capacity, the horizontal galleries or drains ("catas") at the bottom complicate pumping tests interpretation, and wells are not available for long pumping and recovery times. Despite this, the legal registration of the well and its discharge rate now requires a mandatory technical report signed by a professional that includes an elementary pumping test with water level measurements until "stabilisation" at least during 24 hours for a constant pumping rate. True data present a series of deficiencies, from starting the pumping with a non-stable water level in the well to progressively decreasing well discharge to force stabilisation. Faked results are not infrequent. Well owners tend to declare exaggerated discharge rates to secure the right to deepen the well in case the need for more water should arise. During pumping, galleries and "catas" may become perched or water may enter from upper parts of the well. Level recovery may be disturbed by improper functioning of the pump foot valve which allows water to return to the well from the rising tube and other pipes.

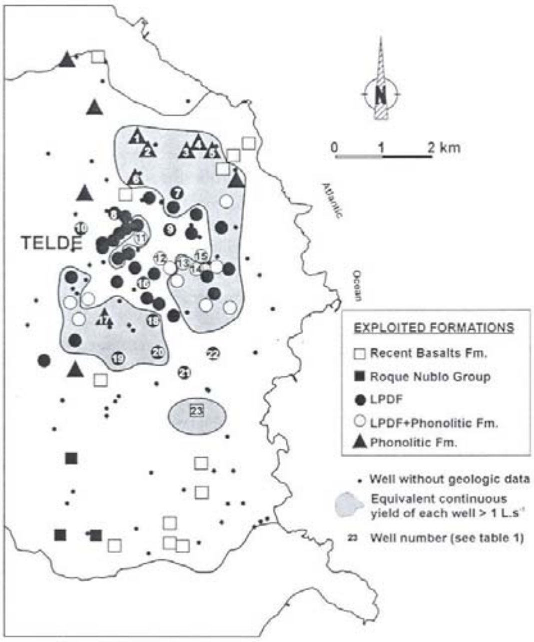

Fig. 7 Wells with data on the exploited formation. Three main zones are distinguished. Wells with an equivalent continuous yield higher than 1 L s^{-1}. Numbers indicate the location of the wells with an available elementary pumping test

Many data sets have been interpreted, corrections being made or different weight being given to the drawdown values, obtained both by manual (see Custodio and Llamas 1983) and by automatic methods (EPHEBO program, developed by the Hydrogeology Group of the Geotechnical Engineering Department, Technical University of Catalonia, with a friendly interface for the MariaJ inverse problem formulation Program, Carbonell 1989).

Well emplacement is shown in Fig. 7, in which the geological formation exploited by each well is also included. The description of calculations and results, which are given in Table 1, can be found in Cabrera (1995) and Cabrera et al. (2001). Figure 8 shows a sample of the plots for pumping and recovery, and the adjusted lines.

Discussion

Geological Conditions

Rocks observed in the wells show a geological discontinuity that is interpreted as a main fault in the island (Fig. 3). The fault may affect the present position of the Barranco Real de Telde and produces the outcrop of the formations placed below in the stratigraphic position along the northern boundary of the study area (Phonolitic Formation; Roque Nublo Group materials and LPDF). This fault has not been identified in geological surface surveys because it is buried by the Recent Basalts. This implies that the age of the fault must be Pliocene. The existence of the fault is supported by the lower elevation of the LPDF inside the wells south of the Barranco Real de Telde, with respect to the same materials placed in the North. The observed difference between the elevation of the Middle Member (deposited at the same depth in a littoral environment) in the outcrops in the North (80–100 m) and in the wells (20–43 m) is explained by faulting. The hypothesis of erosion of the phonolites and back filling with the LPDF has to be rejected because this would not produce the elevation of the different members observed inside the well shafts. Similar fault systems have been recently deduced in LPDF outcrops in the Las Palmas de Gran Canaria area by means of precise topographic methods (Pérez-Torrado et al. 2004). Such systems are important since deep faults may allow the discharge of deep groundwater and volcanic gas. Discharges of this nature have been identified in the south of the study area, and manifestations are present upstream in Valle de San Roque, near the Barranco Real de Telde middle reaches, before the watertable was depleted by local intensive aquifer development.

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Table 1 Results from aquifer tests interpretation, with indication of the exploited formations. T and S values are the results of the best adjustment to the Jacob and Theis models, taking into account well capacity effects, backwater flow disturbance and effective diameter

Well number	Type	Exploited formation	T (m^2 day^{-1})	S
23	Shaftwell	Recent Basalts Formation	500	0.05–0.2
7	Shaftwell	LPDF	140	0.06
8	Shaftwell	LPDF	50	–
10	Shaftwell	LPDF	25	(0.25)
18	Shaftwell	LPDF	100	0.04
19	Shaftwell	LPDF	160	(0.03)
20	Shaftwell	LPDF	150	0.04
22	Shaftwell	LPDF	160	0.05
9	Shaftwell	LPDF–Phonolitic Formation	(70)	–
11	Shaftwell	LPDF–Phonolitic Formation	(10)	(0.02)
12	Shaftwell	LPDF–Phonolitic Formation	240	0.16
13	Shaftwell	LPDF–Phonolitic Formation	(50)	–
15	Shaftwell	LPDF–Phonolitic Formation	55	–
1	Borehole	Phonolitic Formation	18	0.05
2	Borehole	Phonolitic Formation	10	0.04
3	Borehole	Phonolitic Formation	10	0.03
4	Borehole	Phonolitic Formation	7	0.02
5	Borehole	Phonolitic Formation	15	0.04
6	Borehole	Phonolitic Formation	(600)	–
17	Borehole	Phonolitic Formation	8	0.03

Notes:
(XX)=uncertain value
Pumping is cyclic in many wells
True level stabilization takes place only in two wells; in the others stabilization may be due to preceding partial recoveries. The check valve is also often closed progressively to force results
Wells 8, 9, 11, 12, 13 and 15 have a vertical borehole at the bottom and two pumps; only recovery data are considered; there is a bottom gallery
Well 10 presents a layer of phonolitic ashflow
Well 20 has several pumping rate changes
Wells 1, 2, 3, 4, 5, 6 and 17 show a fast recovery

Figure 7 shows that the wells in the southern zone exploiting the dominant Roque Nublo Group volcanic breccias and Recent Basalts formation have a low yield. The remaining formations may yield more than 1 L s^{-1} per well in areas having a cluster of several wells. The correspondence between clusters and the geological formations is not clear because this depends on several factors, such us well penetration relative to watertable depth, and the effect of the horizontal borehole drainage. The most productive cluster lies east of the town of Telde, where the LPDF and/or the Phonolitic Formation are exploited, although most of the well productivity is probably due to the LPDF, directly or by leaking into fractures in the phonolites below. How this extends coastward is poorly known.

Hydrogeological Properties of Rocks

Of the different formations involved only the LPDF approaches a typical porous one, although it is heterogeneous and with low permeability interlayers. The remaining formations are rocks with fissures and porous-like blocks, as occurs in most subaerial volcanic formations. In detail they are fissured lava flows with potentially more permeable top and bottom breccias which form preferential horizontal permeable layers; pyroclastic and ash fall deposits are expected to behave irregularly. The role of red layers and palaeosoils seems minor, although they may enhance anisotropy. In some areas thermally altered and volcanic CO_2 weathered rock have a reduced permeability, as expected in the south of the study area. The local role of the above-mentioned main fault is currently unknown as well as that of other possible faults in the area.

The frequent fissures in the rock mass allow groundwater to flow in a 3-D pattern, as occurs in other volcanic areas and can be seen in outcrops. In this case the fissures are rarely related to dykes, which are not an important feature of the area. How properties change at depth is not known here since there are no deep exploratory boreholes. The bulk behaviour of the volcanic formations is probably different from that in the vicinity of the wells, where horizontal stratification may play an important role. This implies that if a major fracture is not intersected most of the flow to the well comes radially from the saturated formation that has been penetrated, even when there are several horizontal boreholes. By direct observations in the dewatered zone inside pumping wells, groundwater flows out along the entire seepage face of the LPDF, but in the volcanic materials visible outflows correspond to contacts between lava flows or to scoria and breccia layers. Phonolitic ash-flow layers seem to be dry with the exception of the contacts between different formations.

The application of unsteady flow solutions to interpret pumping tests in partially penetrating wells in layered aquifers is not strictly valid, but a linear relation of drawdown versus the logarithm of time can be adjusted, which can be described by two values, T^* and S^*, playing the role of transmissivity (T) and storage coefficient (S) of

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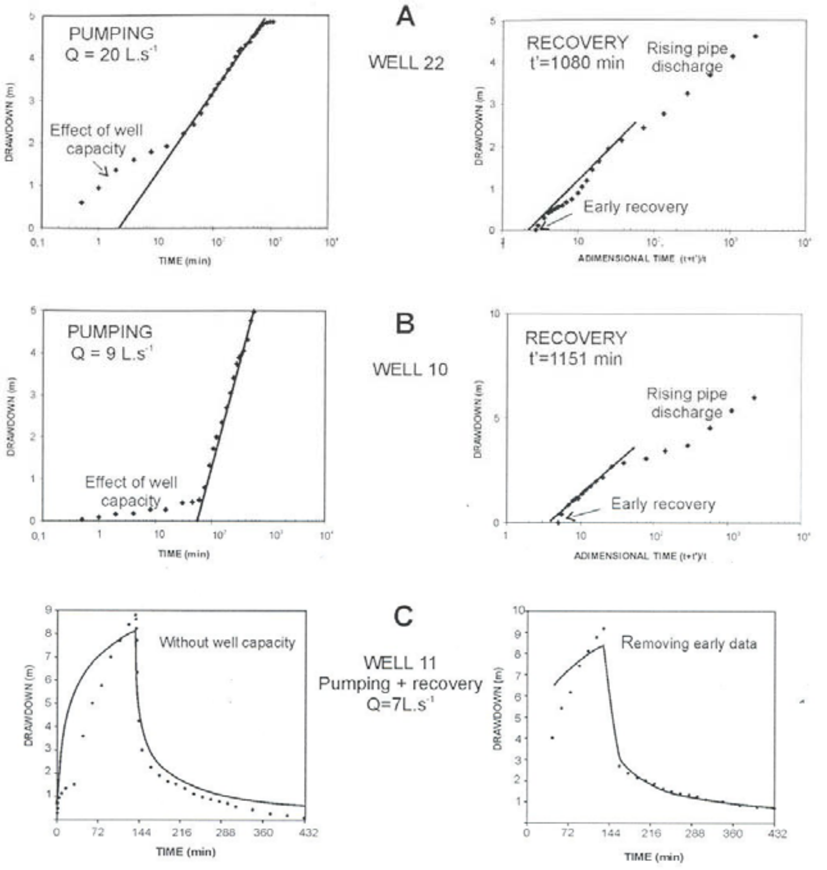

Fig. 8A–C Pumping and recovery plots for the pumping tests in three wells. Pumping rates (Q) are indicated as well as the effect of well capacity and backwater during recovery. **A** and **B** are manually interpreted; the early recovery is probably due to the upward trend of groundwater levels; **C** is the result of automatic interpretation with the EPHEBO program with all data and without considering well capacity (*left hand*), and adding 0.5 m to drawdown data to compensate for rising static level and removing some early pumping data to avoid capacity effects (*right hand*). t' in the recovery plots is the duration of previous pumping

homogeneous, horizontal aquifers, fully penetrated by the wells.

Meier et al. (1998) and Sánchez-Vila et al. (1999) have considered the results of applying the Jacob's model to randomly heterogeneous formations, and have pointed out that T^* is an estimation of the transmissivity properties of the medium for horizontal flow. Therefore, T^* is an estimation of the average transmissivity of the penetrated saturated materials by the shaft wells or the uncased boreholes, provided horizontal permeability dominates and the slope corresponds to the late stages of pumping, once well capacity effects fade out.

The interpretation of S^* is less clear since many variables are involved. For a borehole, well head loss may dominate S^*. For a small penetration shaft well pumped at low rate water head losses may be assumed to be small, especially if horizontal drains are present. Then S^* may approach the average local specific yield of the saturated zone if an effective equivalent well diameter is used and time is sufficiently long for transient effects of vertical flows between layers to fade out. The effect of local inflow from the blocks to the most permeable features may appear as an early recovery of water levels, but this may be due mostly to an ascending watertable trend when pumping starts, be it regional or local as a consequence of a too short previous rest period of the well. In what follows the asterisk will be dropped, and T and S are taken as estimations of penetrated aquifer transitivity and specific yield, when appropriate. Specific yield tends to the value of porosity that can be drained by gravity (drainable porosity).

The LPDF tends to be one order of magnitude more transmissive (30–150 m^2 day^{-1}) than the Phonolitic Formation (5–20 m^2 day^{-1}), with little overlapping. Recent Basalts Formation is only represented by one well, with a corresponding transmissivity of 360–500 m^2 day^{-1}; this is larger than the 40–200 m^2 day^{-1} estimated in the SPA-15 (1975) project for the island. All the shaft wells that penetrate the Phonolitic Formation + LPDF have currently bottom vertical boreholes; it seems that water now comes mostly from the Phonolitic Formation. The Phonolitic Formation transmissivity values are lower than those estimated for this formation in the Amurga Massif, in SE Gran Canaria, which varies from

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Table 2 Statistical data of equivalent continuous well yield, well specific yield (well yield/drawdown) and well productivity (specific yield/effective penetration) after the different exploited formations in the Telde area. *N* is the number of wells of the sample, *M* is the median value and *R* represents the range defined by the 10–90% percentiles

Formation	Equivalent continuous well yield ($L\ s^{-1}$)			Well specific yield ($L\ s^{-1}\ m^{-1}$)			Well productivity ($L\ s^{-1}\ m^{-2}$)		
	N	*M*	*R*	*N*	*M*	*R*	*N*	*M*	*R*
LPDF	35	1.18	0.27–6.20	12	4.55	0.67–10.60	12	0.95	0.06–9.34
LPDF–Phonolitic Formation	14	3.47	0.38–12.75	9	1.02	0.31–14.17	9	0.06	0.02–3.63
Phonolitic Formation									
Shaftwells	6	2.30	0.64–11.46	7	0.34	0.21–2.59	7	0.02	0.003–0.37
Borewells	12	6.63	1.05–14.62						
Recent Basalts	13	1.16	0.16–7.69	3	3.69	(1.06–7.48)	3	1.47	(0.40–2.54)

50 to 800 $m^2\ day^{-1}$ when considering only the productive boreholes (Manzano et al. 2001), but there are many failed boreholes ($T \leq 1\ m^2\ day^{-1}$). In the Amurga Massif, the average value that accounts for the regional flow pattern is estimated to be an order of magnitude less than that derived from pumping tests in operating wells, in agreement with what occurs in the Telde area and the 10–25 $m^2\ day^{-1}$ estimated in the SPA-15 (1975) project for phonolitic materials in selected areas of the island.

The formations permeability (*k*) has been calculated using the transmissivity estimated from the pumping tests and the penetrated saturated thickness of the different formations in each well. For the Phonolitic Formation, *k* ranges from 0.2 to 2.5 m day^{-1} and for the LPDF from 2.3 to 17 m day^{-1}. There is some overlapping. The higher *k* of the LPDF explains the original concentration of wells in the central part of the area, where the main aquifer is situated. Permeability values for the Phonolitic Formation and the LPDF in the Telde area are higher than those calculated in the SPA-15 (1975) for the whole island: 0.1–0.5 m $day^{-1}$for the Phonolitic Formation and 1.5–8 m day^{-1} for the LPDF.

The transmissivity values from the pumping tests can be used to find the correlation with well specific yield and to try to interpret the more numerous data of the other wells of the area. The regression coefficient between transmissivity from pumping tests and the corresponding well specific yield (pumping/drawdown) is 1.69 after homogenising the data to consider the different diameters of shaft wells and boreholes (Cabrera 1995). To summarise the information, in Table 2 are given the median value and the 10 to 90% range of the values of the equivalent well continuous yield, the well specific yield and the well productivity (well specific yield/effective penetration), grouped by formations. The well specific yield is related to penetrated aquifer transmissivity and well productivity to average permeability of the exploited formations (Cabrera et al. 2001).

It appears that the LPDF, which is exploited directly or drained through the Phonolitic Formation below, is more transmissive than the Phonolitic Formation. The Recent Basalts are in an intermediate position, but close to that of the LPDF. When considering well productivity only two groups appear since the deeper penetration of wells in the

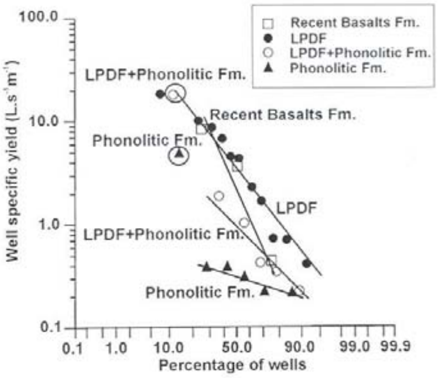

Fig. 9 Probabilistic plot of the log of well specific yield of the Telde area wells, with frequencies calculated separately for the different formations. Encircled values are offset points due to changing conditions

Phonolitic Formation, with or without the LPDF, reduces the value. They are boreholes or shaft wells with bottom vertical boreholes. The frequency distribution of results is shown in Fig. 9 for well specific yield and in Fig. 10 for well productivity. There is a conspicuous variability in any of the formations. The small variation for the poorest Phonolitic Formation is due to the fact that five of the values are from closely located similar boreholes; the other is for a shaft well for which the point plot is offset. Two different behaviours can be deduced from Fig. 10: wells exploiting LPDF and Recent Basalts Formation, and wells exploiting the Phonolitic Formation, alone or with LPDF, that show a lower well productivity. In the first group two wells exploiting the LPDF + Phonolitic Formation are included, since the main contribution to the well productivity is from the LPDF.

The median value of *S*, taken as a lower boundary of specific yield (average drainable porosity) is about 0.04. Excluding some suspiciously extreme values, the range is 0.015–0.06.

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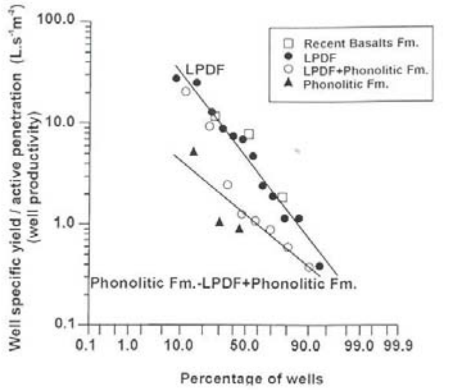


Fig. 10 Probabilistic plot of log of well productivity (well specific yield/effective penetration) of the Telde area wells, with frequencies calculated separately for the different formations

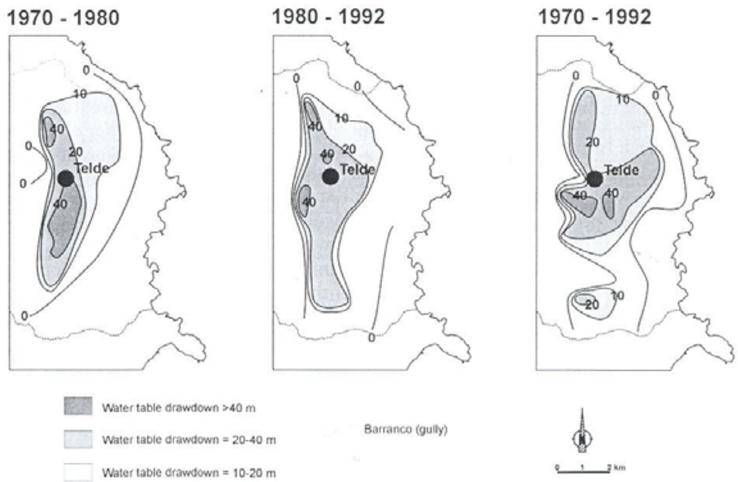
Groundwater Flow

Information became available when the aquifer was already intensively exploited, and therefore the natural situation is unknown, except for some scattered data. It seems that the Barranco Real de Telde was draining groundwater in the headwater areas, but not in the lower reaches of the study area. Here the watertable was below the gully channel, and it now lies deep under it. The lower reaches were recharge areas in which surface flows infiltrated, and perhaps continue to infiltrate today when sporadic storm runoff is produced. It seems that this recharge can be currently considered to be small as a groundwater balance term and only slightly affects the watertable position. It can be safely assumed that in 1970, the date of the first watertable map, watertable drawdown had clearly already, ocurred in the Telde area. Figure 11 shows the drawdown of the watertable position for the periods 1970–1980; 1980–1992 and 1970–1992, deduced from Fig. 6. Both figures show that:

- Along the coast there are no watertable elevations below sea level, except locally.
- Low and negative (below sea level) watertable elevations have been developed along a central strip, and have progressed towards the coastal area.
- At the western boundary the watertable elevation is relatively unchanged.
- The central strip roughly corresponds to the most permeable areas shown in Fig. 7, where groundwater abstraction is concentrated.
- Groundwater flow presents an average slope of about 0.02–0.04 at the inner boundary, which flattens to 0.003–0.004 near the coastal line; exploitation well clusters produce local disturbances.
- An area of small drawdown and high watertable runs W–E through the town of Telde; which may be the result of preferential recharge by leakage from the urban water supply network, sewage system and irrigated areas at the time (Cabrera 1995). This will be discussed in future papers dealing with hydrogeochemistry.

Figure 12 is an attempt to reconstruct the relatively undisturbed watertable before 1970, with a representative cross-section through Telde, in which the watertable was in the Recent Basalt Formation, which is currently mostly drained. This reconstruction has been made with the help of some previous well data from this area and the depth of the first drainage works excavated in the wells. Figure 13 is an attempt to show the current situation by extrapolating 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 is

Fig. 11 Indicative drawdown of the watertable for the periods 1970–1980, 1980–1992 and 1970–1992. There are several inconsistencies due to uncertainty in the areas



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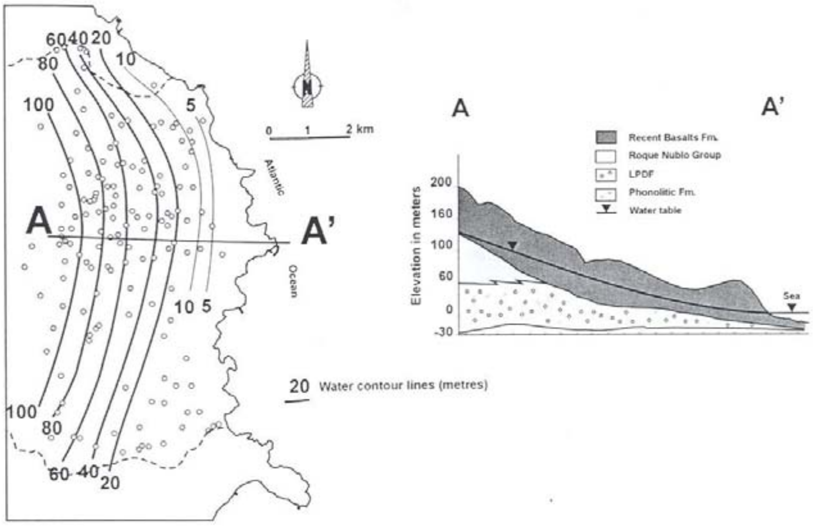

Fig. 12 Assumed watertable map and hydrogeologic cross section for Telde area before 1970, with low groundwater abstraction

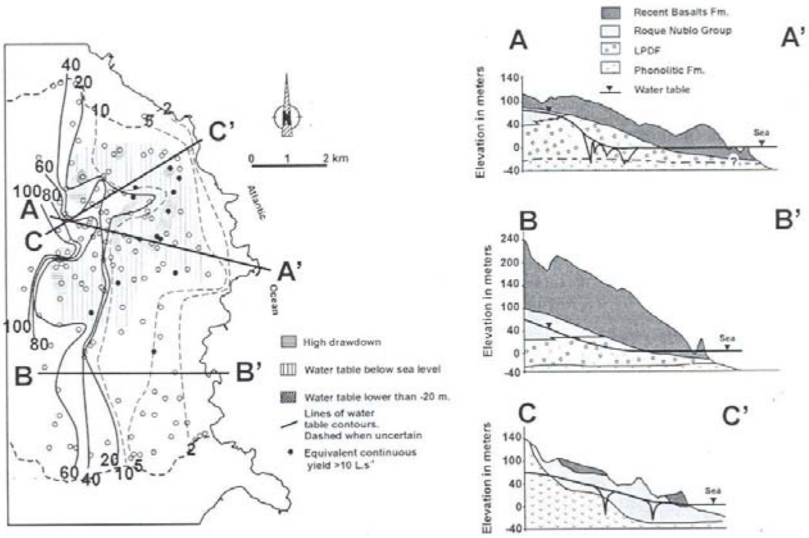

Fig. 13 Smoothed watertable map and hydrogeologic cross section of the 1988 situation in Telde area. Local pumping cones are not considered in the map. In the cross sections they are indicated solely for information, and do not necessarily correspond to real wells

recharge as previously explained. The three cross-sections show that currently the watertable is mostly in the LPDF, except to the north of the town of Telde, where static levels are in the Roque Nublo Group breccias and the 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 current situation. Groundwater came initially from LPDF. When the watertable descended, the Phonolitic Formation started to be exploited, compensating its low mean permeability with greater penetration of boreholes. Generally the shaft wells do not have horizontal drains ("catas") in the phonolites since they were the last to be penetrated.

Along the coastal strip, wells are scarce and reliable information is currently unavailable. This only allows for rough hydrodynamic considerations. Under no flow conditions of saline ground water, according to the Badon Ghyben–Herzberg formula (Custodio and Llamas 1983; Custodio and Bruggeman 1987), the depth of the theoretical sharp salt water–fresh water interface is about 40 times the fresh-water head above mean sea level. In the

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Table 3 Approximate groundwater balance of the study area of Telde (75 km^2) for conditions in the 1990s. Inflow and outflow from the N and S boundaries are assumed not significant

	Mm^3 year^{-1}	Comments on calculation
Inflow terms		
Lateral inflow from the western boundary	7.4 (4.0–14)	Darcy's law
Infiltration from Barranco Real de Telde	0.5 (0.0–1.0)	SPA-15 (1975) data
Local rainfall recharge	1.8 (1.5–2.3)	Chloride balance (Cabrera 1995)
Irrigation return flows	1.7 (1.4–2.0)	Uncertain (by surface area)
Leakage from supply network	0.7 (0.5–1.0)	Municipality data
Groundwater storage depletion	0.7 (0.5–1.0)	Over 25 km^2 with 0.06 porosity
Seawater intrusion	≈0	Aquifer discharge into the sea
Total	12.8 (7.7–21.3)	
Outflow terms		
Well abstraction	9 (8.0–10.0)	Survey
Discharge into the sea	3.8 (0.8–4.1)	Darcy's law, very uncertain
Total	12.8 (8.8–14.1)	

study area, this means that under natural conditions (head higher than 2 m) the salt-water wedge was restricted to a narrow coastal strip in the Phonolitic Formation, the LPDF being almost free of saline water. Under the current groundwater exploitation pattern similar conditions seem to prevail in many coastal tracts, but locally the LPDF may be a fast flow path for seawater penetration towards some wells when the drawdown cones approach the shoreline. This may happen in three pumping areas that are north-facing and south of Telde (Fig.6c). But since the LPDF may be drained out, the salinity front must advance through the Phonolitic Formation in an unknown manner, but probably progressing slowly and randomly through fractures.

A similar process is observed in the Amurga phonolitic massif, in SE Gran Canaria, where only one of the wells at about 2 km from the shore has been directly affected by seawater intrusion after 10 years of use. No clear saline water upconing problems have been observed in this case due to the low transmissivity of the phonolitic formation.

Recharge mechanisms have not been studied in detail. The Recent Basalts and the thin soil cover in some areas allow downward vertical water transfer or recharge without the formation of permanent or temporal perched aquifers, or at least they have not been seen during the descents into the wells. The only falling water that was observed was very shallow and related to local pipe 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 (Table 3). No attempt has been made up to now to carry out a detailed numerical model, apart from a general one for the island during the MAC-21 study. Balance terms of Table 3 are average values in the 1990s, in million m^3 per year (Mm^3 year^{-1}).

In this intensively exploited area, with conspicuous watertable depletion, lateral inflow plus local recharge and other sources of recharge may still exceed actual groundwater exploitation. The recent changes transforming cultivated areas into urbanised land caused 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 (Table 3) are decreasing, even though lateral inflow is maintained. But also well abstraction is decreasing, according to new data for the area.

Groundwater storage depletion is a minor term and may mostly reflect the transient evolution of the system. It may continue to increase if well abstraction is not noticeably decreased. It seems that this is happening as expected as irrigation land becomes urban. A major drawback is progressive quality impairment by saline water intrusion in some areas, but this is still a poorly known process in the area.

Conclusions

The study area is volcanic, mostly of distal conditions, with a complex disposition of materials and a relatively deep (40–100 m) watertable. The materials through which groundwater flows and is abstracted are different from what is shown by the surface geology due to the depth of the watertable (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 reliably, detailed geological description is not available. Groundwater flow is variable depending on the zone. Important changes take place in the watertable position over time due to variable exploitation. The existence of an intercalated detritic formation (LPDF) plays a major hydrogeological role, both direct or by leaking water to other formations; it produces a decrease in groundwater flow gradient, from around 0.04 to about 0.003. The area shows a central strip of watertable depletion due to abstraction, up to 40 m of drawdown between 1970 and 1992, and a complex temporal evolution. But 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 roughly about 30% may be still discharged, which is much more than reserve depletion, in

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spite of the persisting drawdown trend and the risk of local seawater intrusion.

Detailed geological surveys inside the large diameter shaft wells point to the existence of a regional Pliocene fault crossing the north of the area, which does not induce known hydraulic anomalies.

The two main saturated formations under current conditions are the detritic (LPDP) and the Phonolitic (Ph) formations. Both present a similar average drainable porosity (specific yield) of approximately 0.03 to 0.04, but their hydrodynamic properties are quite different. Considering the median value and the 10–90% range, the local LPDF is characterised by a well yield of 1.2 (0.3–6) L s^{-1} m^{-2}, or a permeability of 2.3–17 m day^{-1}. The Phonolitic formation values are about one order of magnitude less: well specific yield is roughly 5 L s^{-1} (0.6–15) since they operate with a larger drawdown, a well specific yield of 0.3 (0.2–2.6) L s^{-1} m^{-1}, or a transmissivity of 15 (5–20) L s^{-1} m^{-2}, and a well productivity of 0.02 (0.003–0.4) L s^{-1} m^{-2}, or a permeability of 0.2–2.5 m day^{-1}. The data from a few wells obtaining water from the Recent Basalt Formation point to values similar to those of the LPDF: well yield of about 1.2 L s^{-1}, well specific yield of about 4 L s^{-1} (T about 400 m^2 day^{-1}) and well productivity of about 1.5 L s^{-1} m^{-2}.

Despite the intensive groundwater exploitation of the area of Telde and the continuous drawdown, the area may be managed to attain a sustainable use if abstraction is reduced and the spatial distribution of exploited wells is corrected to avoid saline water problems. The creation of a groundwater users' association is recommended, which must include inland water stakeholders, and a monitoring network to produce informed decisions.

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