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HYDROGEOLOGICAL EXCURSION TO THE SIERRA GORDA KARSTIC AQUIFER

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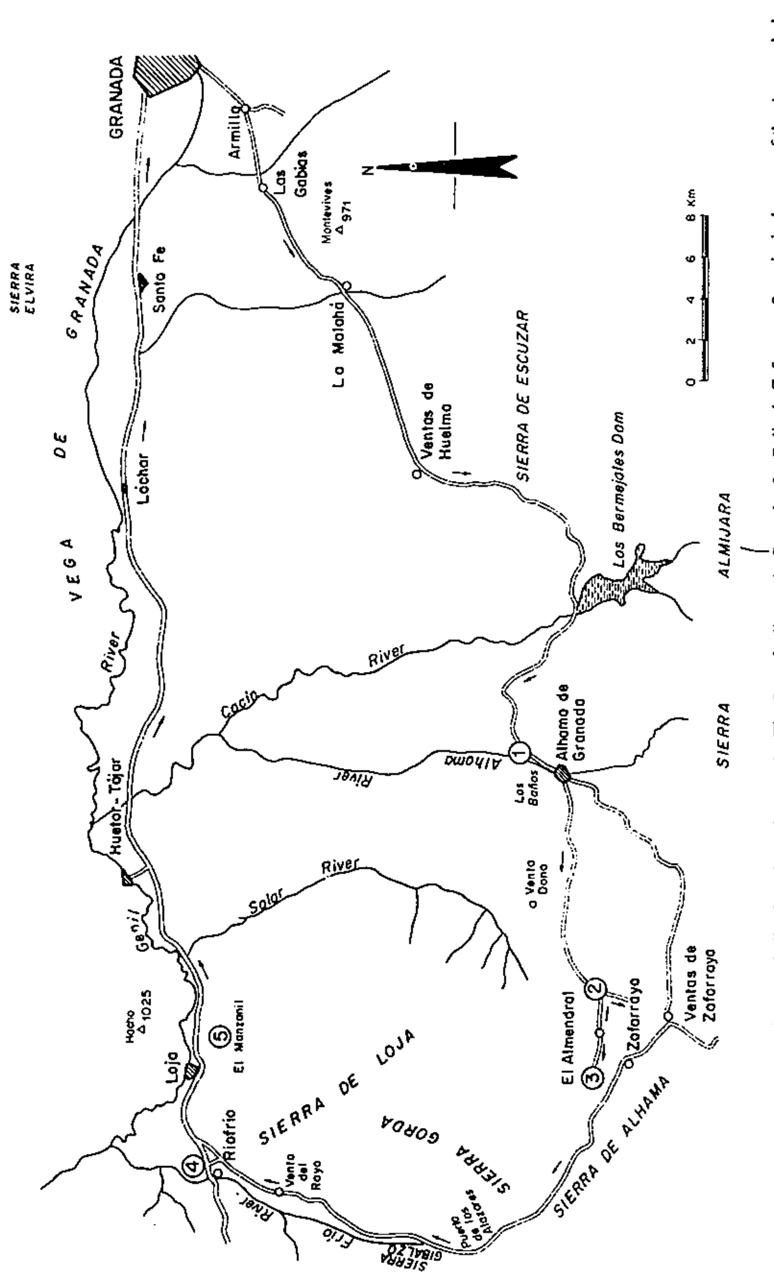
INTRODUCTION

The Sierra Gorda massif constitutes one of the principal karstic aquifers of southern Spain and of the Betic Cordilleras, both for its surface area (293 km^2 of carbonate outcrops) and for its water resources (more than 130 hm^3/year). This aquifer has many aspects of interest from the standpoint of karstic hydrogeology: numerous springs of diverse hydrodynamic and hydrochemical behaviour; different recharge modalities (rain infiltration, snow melt infiltration in the highest parts, and recharge from surface water in the polje of Zafarraya); thermal waters and their relationship with the seismicity of the region; the influence of the massif geological complexity in the hydrodynamic; the importance of the karstic morphology in the hydrogeological functioning of the aquifer; the importance of the recent hydrodynamic evolution, as well as the karstological and paleohydrological history, of the massif.

To these aspects we should add the problem, arising in the last few years, of the behaviour and the protection of the karstic hydrogeological system against pollution. In order of importance, the principal sources of pollution for this aquifer are: the use of great quantities of fertilizers (organic and inorganic) and pesticides on the irrigated crops in the three principal karstic-tectonic depressions (polje of Zafarraya, La Dona and Pilas Dedil); urban liquid and solid waste from the polje de Zafarraya (some towns having as many as 3,500 inhabitants); the livestock raising (some 60,000 sheep and goats on the massif).

In the last decade these potentially contaminating practices have expanded considerably (with the exception of livestock raising, which has remained at an economic standstill), above all in the polje of Zafarraya, which constitutes the main area of urban and agricultural development over the hydrological system.



...re 1.- General scheme of the itinerary, indicating planned stops. 1.- The Spa of Alhama de Granada; 2.- Polje de Zafarraya; 3.- principal ponor of the Arroyo de la ...lre; 4) Riofrio springs; 5.- springs in the Manzanil sector.

The major objective of this hydrogeological itinerary, the first to be published on the Sierra Gorda, is to offer a complete view of the hydrogeological massif, following a generally logical order, from the principal area of recharge to the principal discharge points (Fig. 1). Given the special character of the framework within which this study is carried out, we shall place special emphasis on those aspects of quality and pollution of groundwater, in light of the data available at present.

DESCRIPTION OF THE ITINERARY

Stretch from Granada to Alhama de Granada

The city of Granada is located in the intra-mountain basin of the same name, at the foot of the Sierra Nevada Mountains. This basin has a fill of Neogene post-orogenic materials, which can reach 4000 m in some of the five most subsident sectors detected by seismic profiles carried out by the Chevron Oil Company of Spain (Rodriguez Fernandez et al., 1989 and Morales et al., 1990). The recent Quaternary fill materials in the basin reach their maximum surface area (more than 200 km^2) near the city, constituting the Vega de Granada aquifer (Castillo, 1986). This aquifer is made up of a detrital alluvial formation of high permeability. Its genesis and hydrogeological behaviour is closely linked with the Genil River and its main tributaries in this sector: the Monachil and the Dilar Rivers. All these show a regime with important snow influence (Pulido-Bosch, 1980) and constitute an important rechargee for the detrital aquifer, either directly by losses in the flow, or by losses through the riverbed itself, or by losses along the numerous *acequias* (water channels, many dating from Arab times) which divert water from the rivers to the Vega.

Passing the town of Armilla and the military air base, we leave behind the recent Quaternary materials (characterized here by a flat relief). The road changes notably in slope at the height of Las Gabias, where we begin to cross Upper Miocene continental materials. Towards the southwest stands a striking hill called Montevives, composed of carbonate lacustrine materials which include an important mineralization of celestine and strontianite karstic cavities which appear in these carbonate materials show indices of thermal anomaly (Fernandez-Rubio et al., 1976).

Following the itinerary, we find Miocene materials of marls and laminated silts of fluvial-lacustrine origin, with frequent intercalations of gypsum. In the descent to the town of Malaha, coinciding with an area of greater subsidence, we see numerous sandy intercalations of turbiditic origin. The continental series of the Upper Miocene (Turolian and Ventian) culminate with deposits of white micritic limestone of lacustrine origin, although this formation is yet not observed in this sector. Halite, associated with gypsum, in the deepest parts is revealed in the exploitation of salt, which is visible next to the town. The saltworks are supplied by a small spring, of which the waters show a conductivity of 167 mS/cm and a certain thermal character (20 °C). On the edge of one of the hills situated to the northwest of the town are very broken-up dolomitic marble outcrops, corresponding to the Alpujarride Complex, related with a thermomineral spring which has been used since Arab times. The temperature of this water is 30 °C and with a conductivity of 2.7 mS/cm.

Towards the south is the notable relief of the Sierra de Escuzar, composed mainly of carbonate materials of the Alpujarride. This relief, with a clear surface of karstic corrosion plane at 1200 m a.s.l., constitute the southern edge of the Granada basin, very well delineated by faults in a E-W strike, which show frequent present-day seismic activity. After the Ventas de Huelma and before entering Agron, we cross this edge, where metapelitic materials outcrop from the same units. To the north of Ventas de Huelma, towards the centre of the Granada basin, several deep wells (over 500 m) have been drilled to draw water and explore for hydrocarbons. Some of the perforations reach thermal waters at some 35 °C in temperature, and 3.7 mS/cm in conductivity. As with the spring at La Malaha, the hydrofacies of these wells are calcium sulphate.

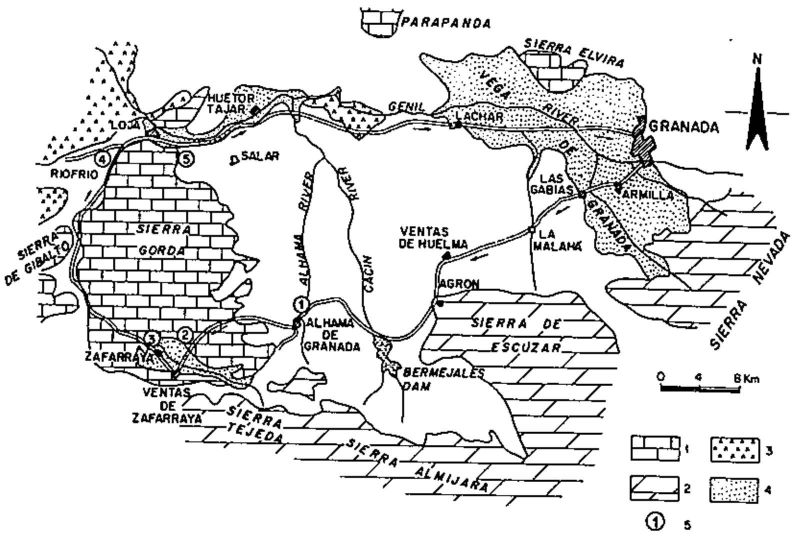


Figure 2.- Scheme of main aquifers which are observed along the route. 1.- Subbetic karstic aquifers; 2.- Alpujarride karstic aquifers; Triassic gypsum aquifers; 3: detrital alluvial aquifers; planned stops.

Descending to the Los Bermejales Reservoir (Fig. 2), we have a panoramic view of the high basin of the Cacin River. This fluvial course originates at the foot of the carbonate relief of the Sierra Almijara massif (Alpujarride Complex) in several karstic springs of substantial flow. The dam was constructed in the narrow canyon cut by the river in the conglomerate materials and cemented marine calcarenites from the Tortonian. These materials outcrop due to a fault in an E-W strike, which threw down the southern block, and constitute the first post-orogenic formation which filled the Granada basin. The high permeability is owed to the double porosity (intergranular and fissuring), although on occasions it also shows a certain degree of karstification. During the construction of the dam (finished in 1952), it was necessary to make 500 boreholes, vertical and inclined, into which concrete was injected, to make the sector designated for the dam impervious. After the injections, the losses were reduced to a maximum of 80 l/s.

Stop 1: The Spa of Alhama de Granada

One kilometer north of the town of Alhama de Granada, in the vicinity of a place called the Baños, there is an important hydrogeothermal anomaly, where at least three thermomineral springs are located: Baños Viejos, Baños Nuevos and Huerta Rodero. A fourth point, presumably thermal, consists of the well drilled by the IRYDA near the Huerta Rodero spring, which at present is sealed off for future exploitation. Nevertheless, another well drilled in the area (Barranco de los Pilones) proved negative despite a depth of 180 m, sufficient to have reached the water table. This indicates that we are faced with an exceedingly heterogeneous and anisotropic medium, in a zone of deep fracturing and high hydraulic conductivity, which allows the rapid rise of the waters, from which the groundwater flow is preferentially produced.

The best-known and most important spring is that of the Baños Viejos, famous (Limon, 1697) as far back as the Romans and Arabs. An ancient Arab construction survives in good conservation, called El Baño Fuerte (Perales, 1881), providing a present spa which has resisted the economic downturn of the last few decades. The spring of the Baños Nuevos owes it name to its appearance after an earthquake which devastated the region on 25 December 1884. It is also exploited at present by the same company which operates the Baños Viejos, winning an international prize awarded in Paris, as recognition of the phyico-chemical and therapeutic properties of the water.

Lopez Arroyo et al. (1981) compiled observations on the physical and hydrological changes the sector underwent after the 1884 earthquake. After the tremors, the spring of the Baños Viejos stopped flowing. The newspaper *Ideal* of Granada, on 27 December of 1884 collected notes on a visit to the spa on 28 December 1884, the morning of a new earthquake, which provoked an "enormous" fountain of thermal water in the Haza Zamora (the spring which is now known as Baños Nuevos). The Baños Viejos began at that point to flow with more than the ordinary quantity of water.

The geological conditions of the area of Alhama de Granada are complex, being in direct contact between the External Zones (or the Southern Iberian margin) and the Internal Zones (or Alboran Domain). This contact constitutes an area of major fracturing within the Betic Cordilleras (Sanz de Galdeano, 1983). One of its main features is the many geological units involved, with complex tectonic relationships still not well defined. The thermalism is linked to the Rondaide Units or Betic Dorsal, which according to a consensus, corresponds to the Internal Zones (Durand Delga and Foucault, 1967; Busnardo et al., 1969; Martin Algarra, 1987). The outcrops are not extensive and appear to be almost completely covered by Neogene materials of the fill of the Granada basin. The descriptions refer to the stratigraphic section of the Baños de Alhama; the age of the materials varies between the Lower and Middle Liassic, dated according to ammonites (Busnardo et al., 1966 and 1969; Braga et al., 1984), and consists of an alternation of decametric limestone banks and marls or limestone beds, with a thickness in excess of 120 m.

The three springs are aligned in a north-south direction at the same time as the altitude diminishes from 798 m a.s.l. in the Baños Viejos to 790 m in Huerta Rodero, in such a way that this appears to be the direction of the preferential flow of the groundwater. The discharges of the springs are uneven and diminish also in a north-south direction. The spring of the Baños Viejos is the most important, with an average discharge of over 30 l/s, while that of Baños Nuevos is about 2.5 l/s. Table 1 presents the results of chemical analyses. The dominant hydrochemical facies is magnesium-calcium bicarbonate-sulphate (Reyes, 1971; Cruz Sanjulian et al. 1972 and 1979; Cruz Sanjulian and Garcia Rossell, 1975; Granda, 1978; Granda et al., 1979 a and b; Cruz Sanjulian and Granda, 1979), although the spring of Huerta Rodero may occasionally present chloride-sulphate (Lopez Chicano, 1992).

The waters in these springs are hypothermal and mesothermal, with low salinity (total dissolved solids less than 1 g/l). Therefore, the mineralization is due principally to the duration of water-rock contact, not necessarily the influence of possible evaporite levels. Notable differences can be found in the values of the physico-chemical parameters among the springs. Thus, the conductivity, and therefore the salinity (TDS), rises from the Baños Viejos to the Huerta Rodero spring, in the same direction of the decline in the discharges. Something similar occurs with the chloride, the sulphate and the sodium contents. Conversely, the temperature decreases in this direction. All this appears to indicate a greater speed of the waters rising towards the most southerly points, together with a greater time of remaining in the aquifer towards the northernmost springs, which, for these latter, would

favour a cooling in the fastest rise. This is our interpretation of the marked temperature difference in the water of Huerta Rodero, with respect to the other springs, rather than an explanation involving a major mixing of cold surface water.

Spring	Date	T °C	pH	Cond. 25°C	Cl^-	SO_4^{2-}	HCO_3^-	Na^+	Mg^{2+}	Ca^{2+}	K^+	TDS
Huerta Rodero	11/12/87	27.4	7.35	1173	124	303	192	61	44	110	7.7	842
	21/11/89	26.0	7.30	1190	121	312	217	60	44	120	7.7	882
Baños Nuevos	16/06/86	40.0	7.50	964	82	225	244	47	44	88	7.0	737
	17/10/86	40.8		948	75	242	213	44	44	82	8.8	709
Baños Viejos	29/01/88	44.8	7.15	910	85	230	207	33	39	104	6.3	704
	21/10/88	44.3	7.08	915	67	232	206	32	34	100	5.1	676

Table 1.- Hydrogeochemical characteristics of the thermomineral springs of Alhama de Granada (ionic values in mg/l).

The Sierra Gorda unit has been discarded as a possible recharge area for the thermal springs, since the recent well-drilling in the La Dona and Pilas Dedil sectors (situated barely 4 km to the west of the Baños), for groundwater exploitation, give piezometric levels of more than 200 m below the altitude of the springs (Lopez Chicano, 1989). It is more probable that the area is recharged by the Alpujarride aquifers, which have a piezometric level of less than 1000 m, a depth which would favour a high hydraulic head (the differences in hydraulic head act as a gravitational motor for the flow) and therefore a deeper flow. Given the geological complexity of the area and the anisotropy of the medium, the purely convective phenomena would pass to a secondary plane. Furthermore, according to Martin Algarra (1987) there is a paleogeographic-geologic relationship between the Alpujarride units and the Rondaide or Dorsal series of the Betic Cordillera. On the other hand, part of the water could circulate through the conglomerates and Tortonian calcarenites.

Cruz Sanjulian and Granda (1979) estimate a base temperature of around 86 to 90 C for these thermomineral waters, applying the Fournier and Truesdell method (1970). These authors also indicate that the presence of the travertines is an index of a low base temperature. These materials appear in a perched outcrop some 15 m above the current height of the Baños Viejos spring, providing evidence of an important dissolution of $CaCO_3$ in depth. The application of the geothermometer Mg-Li of Kharaka and Mariner (1989) to the data of these same authors (Granda, 1978) indicates even lower temperatures for the aquifer formation, between 62 °C for Baños Viejos and 72 °C for Baños Nuevos.

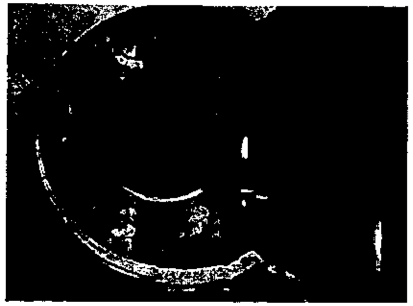
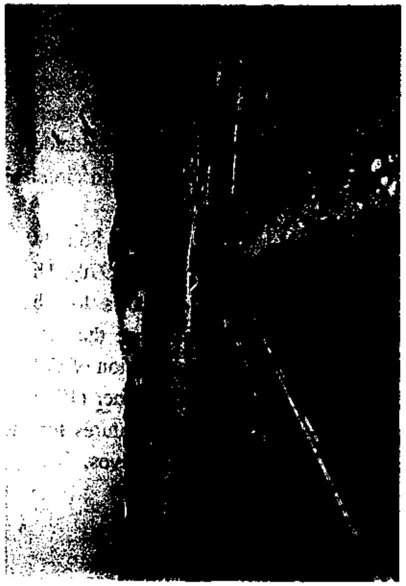


Photo 3.- The "Baño Fuerte". Inside view of the arabic place built in Baños Viejos spring. (Photo by Balnearios de Alhama)

Photo 4.- Hot water exiting from the Alhama Spa (January, 1987; photo by M. Lopez Chicano)



1.- Mining from hydrothermal deposits of Celestine at Montevives (Photo by A. -Bosch)

2.- Panoramic view of Alhama de Granada, with Los Baños and Sierra Tejeda. by M. Lopez Chicano)

The stretch from the Spa of Alhama de Granada to the polje de Zafarraya

On passing through Alhama de Granada we can see, in the cut of the road, the cemented marine conglomerates from the Tortonian. The Alhama River has carved a deep canyon in the calcarenite materials of the same age, a sector called *El Tajo* (The Deep Canyon), inside the town. We follow the principal road which, after crossing the divide between the Alhama River Basin and the Salar arroyo, leads to the Llano de la Dona.

The Llano de la Dona, consisting of an open polje upstream and downstream, is crossed by a tributary of Salar arroyo, dry except in periods of intense rains, which connects this area with another karstic-tectonic depression, also open, towards the north, and which is called the Llano de Pilas Dedil. Both peripheral depressions of the Sierra Gorda show a fill of marine and continental materials from the Upper Miocene, and one thin cover of alluvial from the recent Quaternary. From electric-geophysical prospecting (Lopez Chicano, 1989 and 1992) a thickness of over 100 m has been detected in this fill (Figure 3).

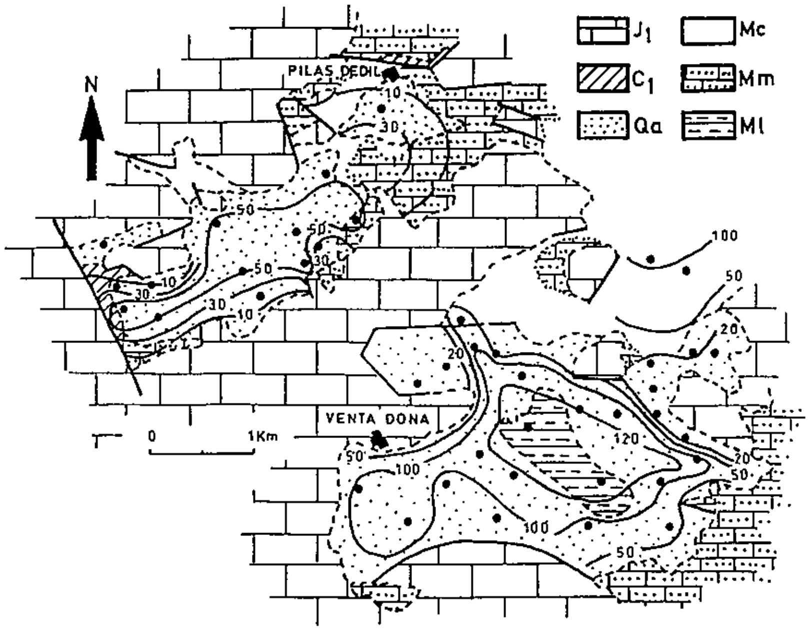


Figure 3.- Isobates of the resistive substrate in the poljes of La Dona and Pilas Dedil (values in m). J_1.- Jurassic limestone of Sierra Gorda; C_1.- Cretaceous marls and limestone marls; Mm.- Tortonian limestone; Mc.- continental marls and silts (Upper-Ventian Turolian); Ml.- lacustrine limestone and limestone marls (Ventian); Qa.- Quaternary alluvial.

In these areas, the agricultural landscape has been rapidly changing in the last few years, due to the transformation from dry crops to irrigated crops (primarily table vegetables and legumes), by captation and exploitation of the Sierra Gorda aquifer. The wells which have been drilled reach depths of 400 and 500 m, finding the piezometric level at some 350 m (with altitudes similar to those of the northern springs). To minimize cost of the pumping at these depths, ponds are filled at night (for special nighttime electrical rates) for irrigation. The hydrofacies is calcium bicarbonate, with a nitrate concentration of about 8 mg/l.

Between the poljes of La Dona and Zafarraya, our route crosses a spectacular karstic corrosion plain, cut into the limestone of the Sierra Gorda. Various conical hills in the form of exposed hums are visible near the road. Next, the road leads through a small polje of the highest altitude thus far.

Stop 2: Panorama of the polje of Zafarraya

The polje of Zafarraya constitutes the principal internal karstic depression of the Sierra Gorda, extending in a ESE-WNW direction for 10 km, with a maximum width of 3.5 km in the central-western sector, and with an altitude of between 1000 m and 886 m, decreasing towards the northwest. This is the only functional polje of the Sierra Gorda--that is, with endoreic drainage. The closed basin associated with the polje has a surface area of 151 km², 65 % of which corresponds to carbonate karstic materials of the Sierra Gorda aquifer (Figure 4). A good part of the basin (22 km²) is an extensive alluvial plain. The southwestern sector is occupied by metapelitic and carbonate materials of the Alpujarride Domain, an outstanding example being the Sierra Tejeda, at the foot of which originates the fluvial course of the basin called the Arroyo de la Madre.

The Arroyo de la Madre is a seasonal course which longitudinally crosses the polje of Zafarraya, from ESE to WNW. Under normal pluviometric conditions, the arroyo loses most of its flow (by infiltration into the limestone of the Sierra Gorda) at the entry of the polje, between the points AM-l and AM-3 of Figure 4. Only after storms or long periods of rain, the water reaches the western sector of the polje (point AM-6), where the main area of ponors is situated. On certain occasions, specially for discharges of over 3 m³/s, the infiltration capacity of the ponors is surpassed, producing periodic flooding in the western sector of the polje. Recently a tunnel has been constructed to divert the arroyo towards the Viñuela Dam (southern Mediterranean basin),which has raised a serious argument between the government and the irrigating communities of Zafarraya. After a period of heated conflict, an agreement was reached to divert the water only in periods of flood risk.

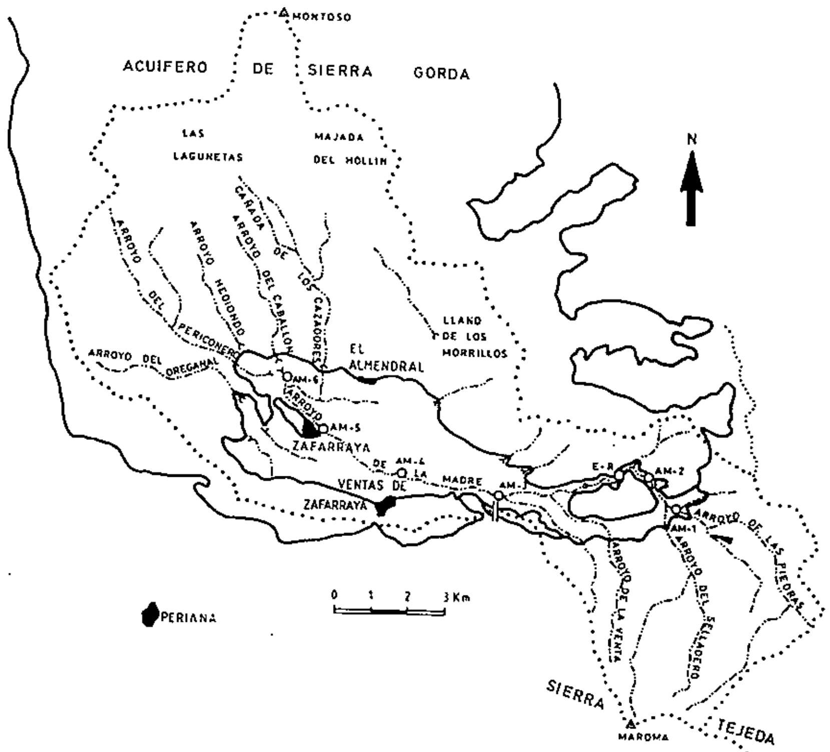


Figure 4.- Hydrographic network of the closed basin of Zafarraya. The position of the carbonate-aquifer materials of the Sierra Gorda are indicated, as well as the detrital alluvial material filling the polje and the positions of the points of the differential gaugings (AM), the diversion of the Arroyo de la Madre towards the reservoir of the Viñuela (near point AM-3) and the gauging station of Los Revuelos (E-R).

From a geological point of view, the Zafarraya depression has characteristics similar to those of La Dona and Pilas Dedil, being comprised of Miocene marine and continental fill as well as Quaternary alluvial deposits. Meanwhile, the maximum thickness of the latter can exceed 200 m (Ollero and Garcia, 1984a; Lopez Chicano, 1989) near the Ventas of Zafarraya (Fig. 5), and the geological complexity is greater, when the two different geological units come into play (Sierra Gorda and Zafarraya units) with Cretaceous-Paleogene sandy marl materials (Fig. 6).

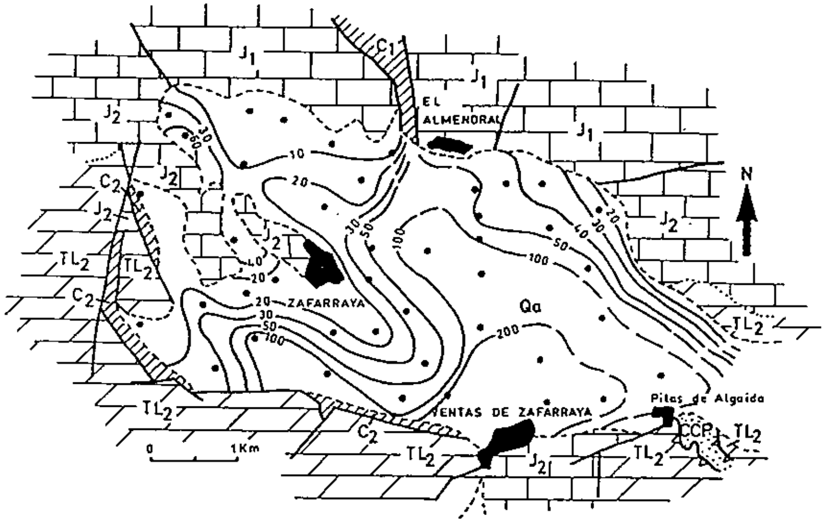


Figure 5.- Plan of isobates (values in m) of the resistive substrate of the polje of Zafarraya. Zafarraya unit: TL_2.- dolomite; J_2.- Liassic limestone; C_2.- Cretaceous-Paleogene marls and limestone marls. Sierra Gorda unit: J_1.- Liassic limestone; C_1.- Cretaceous-Paleogene marls and limestone marls. CCP.- flysch of the Periana-Comenar Complex; Qa.- Quaternary alluvial.

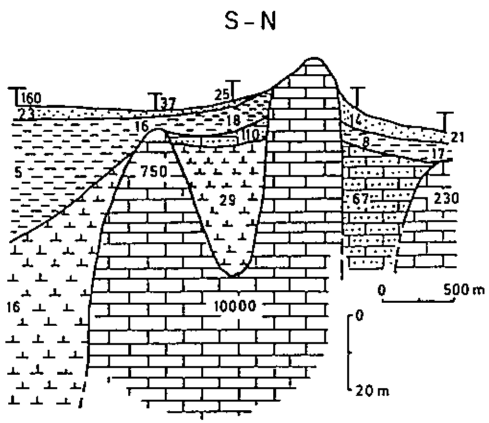


Figure 6.- Geological interpretation of a geo-electric profile in the western sector of the Zafarraya polje. 1.- Mesozoic carbonate materials; 2.- Cretaceous-Paleogene marls and limestone marls; 3.- Tortonian calcarenites; 4.- Upper Miocene bluish marls; 5.- Quaternary lutites; 6.- Quaternary sand, silt and conglomerates; 7.- electric well cross-section. The numbers indicate resistivity in Wm of the geo-electric layers.

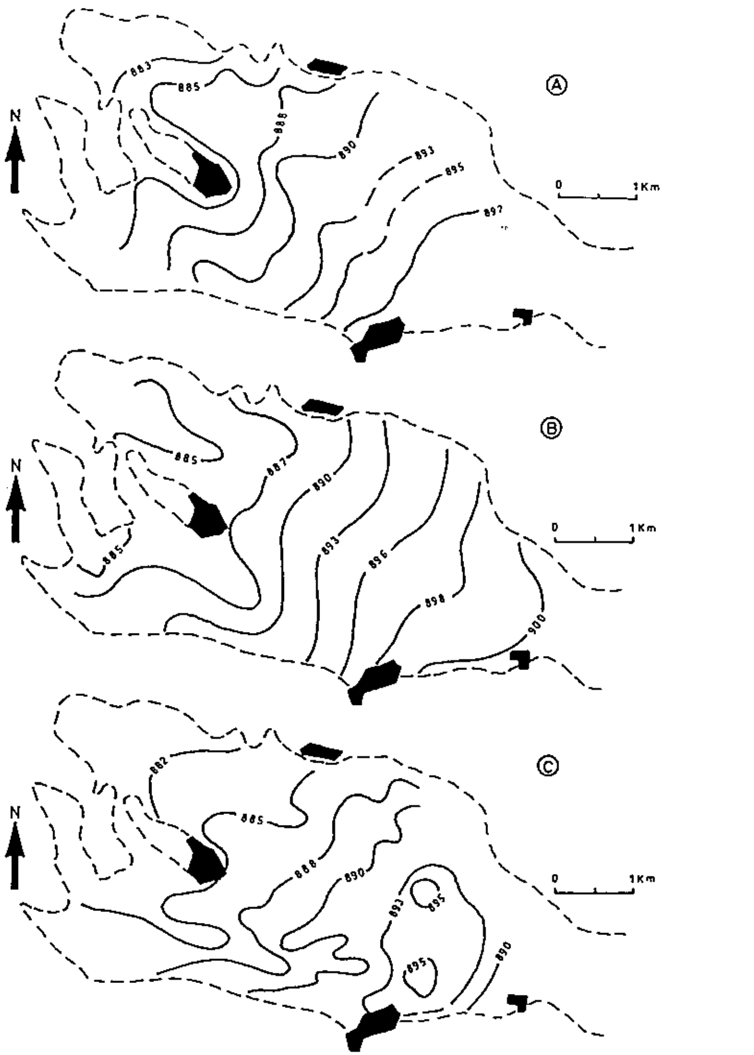


Figure 7.- Three situations of the piezometric surface in the alluvial aquifer of the polje of Zafarraya, according to: A.- Hidalgo (1974a; August 1968); B.- IGME (1983; October 1974); C.- Ollero and Garcia (1984b; July 1982).

Hydrogeologically, we can consider two major aquifers in this area: the Quaternary detrital alluvial of the polje fill, and the carbonate-karstic of the Sierra Gorda. The former, of greater hydraulic potential, feeds the latter (Hidalgo, 1974a), specially in the westernmost sector, towards which a preferential flow is produced (Fig. 7). The karstic aquifer has piezometric variations of great magnitude, even more than 130 m (Hidalgo, 1974b; Lopez Chicano, 1992), and presents a groundwater flow towards the east and north (Fig. 8); nevertheless at the height of Zafarraya there is a hydrogeological divide whieh distributes the flow preferentially towards the north and south (the discharge sector of the Guaro River). The most exploited sector of the karstic aquifer is the eastern part of the polje of Zafarraya, over 60 wells functioning, distributed within hardly 3 km^2. This area shows a certain independence from the rest of the aquifer (Lopez Chicano and Pulido-Bosch, 1989; Guzman del Pino et al., 1991), where we observe important falls in the piezometric levels and multiple influences between the wells.

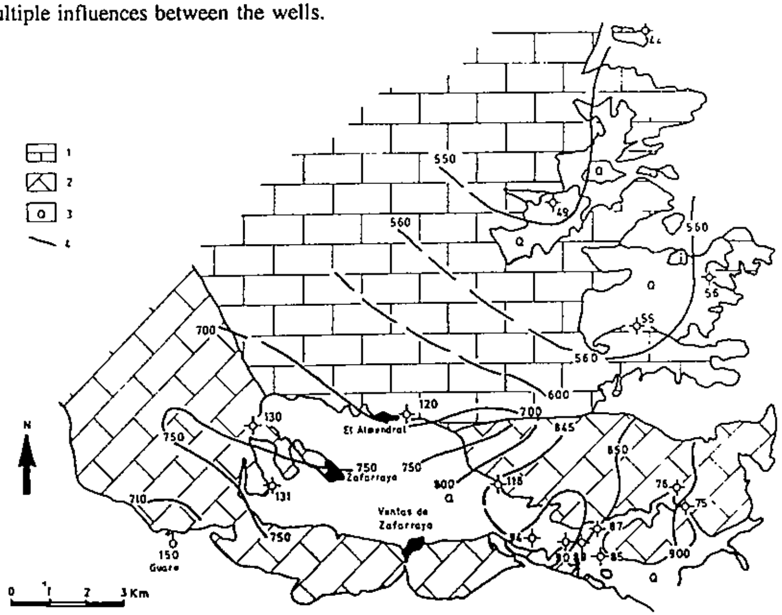


Figure 8.- Estimated piezometric surface of the southearn sector of the Sierra Gorda (November 1989), according to Lopez Chicano (1992). 1.- Liassic limestone of the Sierra Gorda unit; 2.- limestone and dolomite of the Zafarraya unit; 3.- Quaternary alluvial of the polje of Zafarraya; 4.- Equipotencial line (in m a.s.l.).

The economic development of the Zafarraya polje has been spectacular in the last few years, due to the transformation of dry crops to irrigated crops (mainly table vegetables such as lettuce and tomato), by the use of groundwater. The altitude of the area (around 900 m

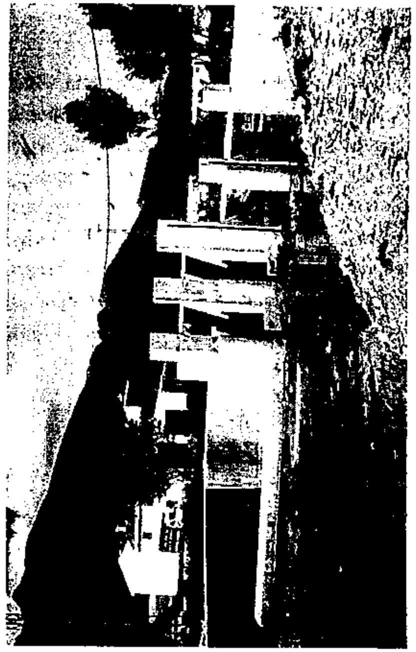
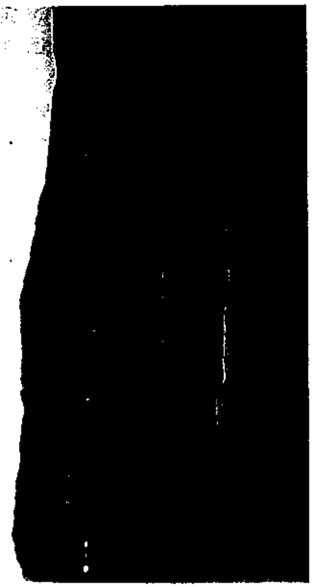


Photo 7.- Diversion of Arroyo de La Madre to the Viñuela dam (Photo by A. Pulido-Bosch)

Photo 8.- Works for the water transfer of Arroyo de La Madre. (Photo by M. Lopez Chicano)



5.- La Dona polje. (Photo by M. Lopez Chicano)

6.- The Zafarraya polje panoramic view from Sierra Tejeda. (Photo by M. Lopez-
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a.s.l.) and the abundant rainfall (nearly 1000 mm/year) provide a certain microclima which favours harvests in periods of little market competition. Paralleling this economic development has been the deterioration in groundwater quality. For some time now the water of the detrital aquifer has not been safe for human consumption, both from the chemical and the bacterial standpoint (Arrebola, 1971; Arrebola and Garcia Olmedo, 1971; Hidalgo and Fernandez-Rubio, 1974). The nitrate contents of the water of this aquifer exceeded 50 mg/l in a wide sector (Ollero and Garcia, 1984c), reaching concentrations as high as 140 mg/l. In the karstic aquifer, bacteriological problems were detected, as well as high contents of organic matter in the Guaro springs (IGME, 1983; Diputacion Provincial de Malaga, 1988), the discharge point of the Sierra Gorda closest to the polje of Zafarraya.

Third stop : Principal ponor of the Arroyo de la Madre

On this stop we shall visit the main drainage area of the Arroyo de la Madre, where it is frequent to find accumulations of solid residues carried by floods, pesticide containers and dead animals. This is an alluvial ponor, with limestone outcrops of the Sierra Gorda barely below a Quaternary detrital cover. Only in periods of strong rains is there water flow at this point; in general, in the dry periods the water which reaches the ponor is waste water, hardly treated in the Zafarraya purifying plant. The capacity of maximum infiltration of this drain, and others nearby, is an estimated 3 m^3/s (Lopez Chicano, 1992), although this value varies with the state of fill in the ponors and with the depth of the piezometric level in the carbonate material.

This is the point most vulnerable to ponor pollution of the entire hydrogeological system, since through this the pollution reaches the saturated zone of the karstic aquifer. The connection of this ponor with the main points of discharge of the system has been demonstrated by fluoresceine injection (Anguita and Fernandez Montero, 1969; Hidalgo, 1974a; IGME, 1983).

Zafarraya-Riofrio stretch

On passing the town of Zafarraya, it is possible to appreciate the karren form which shows the limestone of the aquifer. The oldest houses of the town are situated on the high parts of a conical relief, or hum, as a measure of protection against the overflow of the Arroyo de la Madre. The road ascends towards the Puerto de los Alazores, passing the solid-waste dumps of Zafarraya, the position of which, over the karstic materials, can be inferred

from the smoke given off by the spontaneous combustion. We can see different karren forms in the dolomite and limestone of the Zafarraya unit, as well as various poljes, such as the polje of the Llanos del Puerto, where beautiful examples of the Mediterranean forest are still preserved.

In Puerto de los Alazores there are outcrops of clayey materials of the flysch of the Periana Colmenar Complex, occupying the lower parts and corridors which divide the Sierra Gorda aquifer from the karstic massifs which comprise the Alta Cadena (situated to the west). Figure 9 shows a geological cross-section illustrative of the structure of the area. The proximity of the Sierra de Gibalto to the Sierra Gorda suggests a hydraulic relationship between the two aquifers; nevertheless, the sierras are not connected, given that in the valley there is an important discharge of the Gibalto to the Arroyo de las Mozas, at 735 m a.s.l., far above that of the springs on the northern border of the Sierra Gorda.

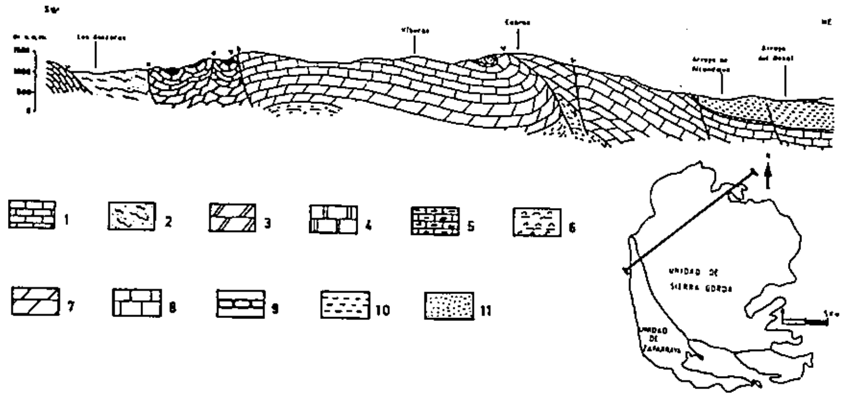

Figure 9.- Geological section. 1.- Alta Cadena Complex; 2.- Periana Colmenar Complex. Zafarraya Unit; 3.- bottom dolomites; 4.- Liassic limestone; 5.- limestone with chert. Sierra Gorda Unit; 6.- Triassic substratum; 7.- bottom dolomite; 8.- Liassic limestone; 9.- nodular limestone; 10.- Cretaceous marls and limestone marls; 11.- Upper Miocene.

The route continues to the northwest edge of the Sierra Gorda, crossing alternatively limestone materials of the aquifer and detrital materials of the Lower Pleistocene which seals the aquifer. To the west of the Venta del Rayo, we find a group of springs of La Tajea, and somewhat farther ahead the tanks of the Riofrio fishery are visible, where we arrive after a descent which takes us to the western prolongation of the Granada basin.

Photo 11.- Waste water exiting from Zafarraya village purifying plant to the Arroyo de la Madre. (Photo by M. Lopez Chicano)

Photo 12.- An aerial view of the highest part of Sierra Gorda. (Photo by CIECSA)

9.- Main ponor of Arroyo de La Madre, flooded during wet season. (Photo by M. Chicano)

10.- Small swallow holes in the Zafarraya polje. We can see some residual pesticide s.

Fourth 4. The springs of Riofrio

On this stop we shall visit the group of springs which constitute the principal discharge of the karstic Sierra Gorda aquifer, at 515 m a.s.l.. These springs are the origin of the Frio River, the main Genil River tributary of the entire Sierra Gorda. The flow of the Frio River is currently monitored by a continuous record at a gauging station near the Puente Califal. The average volume at this point, with a catchment area of 101 km^2, exceeds 50 hm^3/year (Lopez Chicano, 1992). Around 92 % of this volume comes from the drainage of the Sierra Gorda (76 % corresponds to the springs of Riofrio and about 16 % to La Tajea), which imposes a moderate regulatory character on the fluvial course (Fig. 10). The Arroyo de las Mozas or Arroyo Salado join with the Frio River immediately upstream of the gauging station. The flow comes from direct rainwater runoff, from the discharge of the Sierra Gibalto, and, above all, from the La Tajea spring.

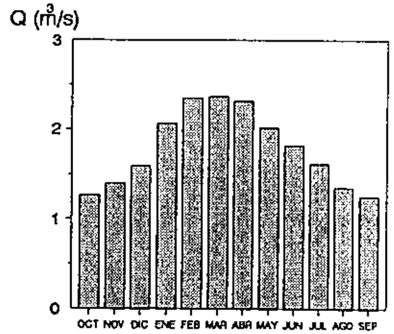

Figure 10.- Average monthly discharges of the Frio River in the gauging station next to the Puente Califal (1968/69 to 1987/88).

The resources of the springs of Riofrio, the position of which is shown in the scheme of Figure 11, are used mainly in various fisheries in the area, primarily raising trout, and not having any regulatory system for the discharge. The use for irrigated crops and for the supplying of villages is minor. The coefficient of depletion of the springs is very low, around 0.004 $days^{-1}$, indicating a great regulatory capacity of the karstic aquifer. The same is shown in a correlation analysis for the discharge measured in the gauging station of the Puente Califal (Lopez Chicano, 1992). Figure 12 shows the autocorrelogram for these discharges for the period 1981/82 to 1986/87. If we make an abstraction of the brusque decrease of the function of the auto-correlation to k values of 3 to 4 days, due to the influence of the surface runoff in Arroyo de las Mozas, the autocorrelogram indicates a memory of the system drained by the Riofrio and La Tajea springs, around 57 to 80 days. These high values, together with other data suggest that the Sierra Gorda aquifer presents a hydrodynamic behaviour more similar to that of a fissured aquifer, or homogeneously karstified, than that of a karstic aquifer in the strict sense.

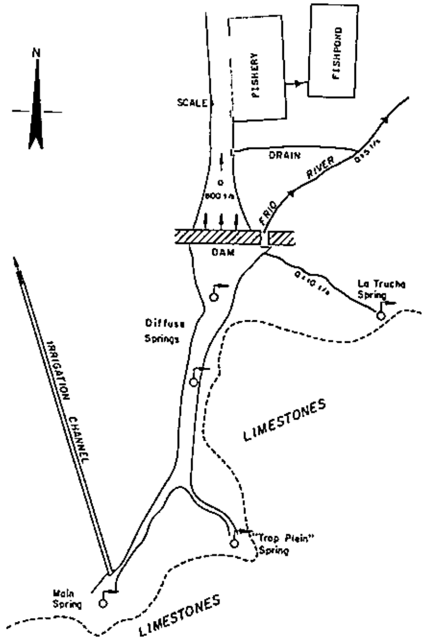

Figure 11.- Scheme of the locations of the springs visible in the Riofrio sector, according to IGME (1983).

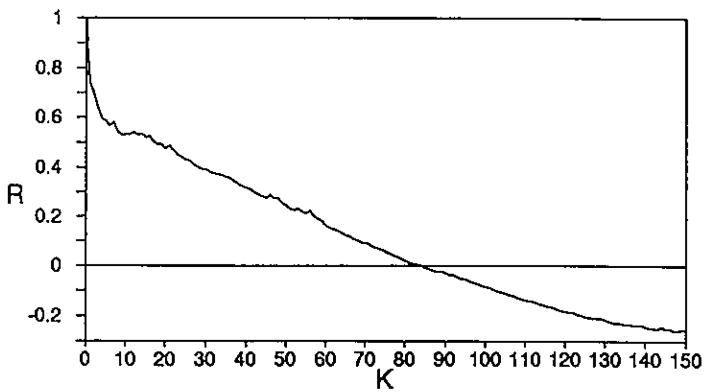

Figure 12.- Autocorrelogram of the discharges of the Frio River in the gauging station of the Puente Califal, for 1981/82 to 1986/87.

The waters are of calcium or magnesium-calcium bicarbonate facies, with temperatures around 14.5 °C and conductivity of 400 μS/cm. Lopez Chicano (1992) has carried out a periodic monitoring of the major chemical parameters of the waters of the Trucha spring. Figure 13 shows the evolution of the conductivity (at 25 °C) for the hydrological year 1986/87, in comparison with the discharge of the river in the gauging station and the pluviometry recorded in Riofrio. In general, the conductivity rises progressively in the dry season, although close observation reveals abrupt rises and falls in relation with the periods of the most intense precipitation and with discharge peaks in the hydrogram. It is patent, therefore, that there is a piston flow, a reflection of the rapid functioning of the karstic network from the beginning of the feed. All this, together with the unimodal distribution of the conductivity values, and the low variation coefficient (around 2.5 %) of this parameter, indicate a high degree of regulation of the aquifer, capable of greatly homogenizing the chemical composition of the infiltration water.

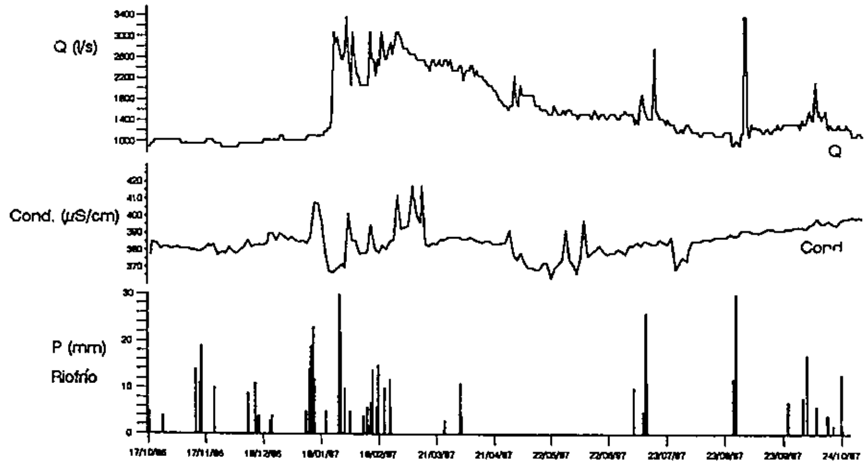

Figure 13.- Evolution of the conductivity of the water of Trucha spring (Riofrio sector), during the hydrological cycle 1986/87. The discharge of the Frio River in the gauging station next to the Puente Califal, and the daily rainfall registered at Riofrio, are indicated.

Finally, although the average values of the nitrate content in these springs are not high (about 6-10 mg/l), in the last few years a progressive rise has been detected (Lopez Chicano et al., 1992), probably due to the influence of the potentially contaminating agricultural practices in the Zafarraya polje. This subject is covered in more depth in one of the chapters of this book. Here we briefly note the incidence of the polluting activities on the waters of these springs.

Riofrio-Manzanil stretch

The itinerary continues across the northern sector of the Sierra Gorda massif, at the height of Loja. Towards the north of the dual carriageway, and within this city, we find several springs of considerable discharge related with the same hydrogeological system, at altitudes of 470 to 510 m a.s.l.: Pines, Genazal, Fuente Santa, La Encarnacion, Borbollote, Terciado or Yola and La Rosadilla springs. All of these are very near the Genil River, which in this sector has high salinity and is noticeably contaminated by the many activities upstream (Sanchez Caballero et al., 1986).

Aside from the visible springs, described above, there is very probably a hidden discharge of the Sierra Gorda towards the Genil River. The differential gaugings carried out (Lopez Chicano, 1989, 1992) appear to confirm this relationship. There are various stretches where the river cuts into travertine formations originating from the principal springs. These are places of difficult access, connected with the Sierra Gorda aquifer, constitute likely areas for the uncalculated discharge. The diffuse discharges from the system in the town of Loja also escapes monitoring, this being evident in the periods of intense pluviometric recharge when the groundwater flows from under the foundations of certain houses in the town.

We should emphasize that the policy which is being followed in the town of Loja, to guarantee its water supply, does not include any regulatory effort, aside from the construction of concrete cisterns, but rather consists of captation, by gravity, of a progressively higher number of springs. This policy carries the consequence that in normal periods, the supply exceeds 1000 l/inhabitant/day, whereas in times of drought part of the population remains without water until a new spring is exploited.

Fifth. Springs in the Manzanil sector

In the sector called Manzanil, there are three discharge points with average flows of more than 100 l/s (Fig. 14): Manzanil or Pasaderas, La Cadena and Porrinas. In periods of heavy rain, other *trop plein* springs appear, such as the Cadena Alta, which can discharge more than 90 l/s. All together, the average discharge of this group of springs exceeds 500 l/s. The altitude of these springs is between 510 and 530 m a.s.l.

The water is used primarily for irrigation in the surroundings of Loja, for which there is a complete system of acequias (irrigation channels) and diversion canals from the springs, and in the fishery downstream of the Porrinas spring. Until a few years ago, the water was used to power a stone-cutting operation, for which a small dam was built between the springs of La Cadena and Manzanil. Currently a restaurant business has acquired rights to the

Photo 13.- Groundwater discharge area in Riofrio. Note the fishponds of the fishery. (Photo by M. Lopez Chicano)

Photo 15.- Plines spring, clearly related to a fracture. (Photo by M. Lopez Chicano)

Photo 14.- Discharge from the "trop-plein" spring in Riofrio. (Photo by M. Lopez Chicano)

Photo 16.- Reservoir in the Manzanil area. (Photo by M. Lopez Chicano)

property and has transformed it into a recreational area.

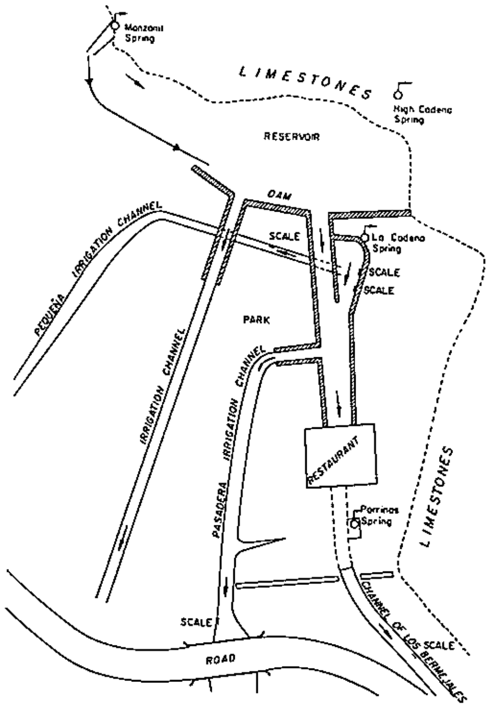

Figure 14.- Scheme locating the main springs visible in the Manzanil sector, according to IGME (1983).

Between 1974 and 1982, the IGME provided the springs with limnometric scales and a spillway to monitor the discharges; nevertheless, the data obtained has not proved very reliable, due to the complexity of the network of acequias and diversion canals (IGME, 1983), as well as to the influence of the constant level imposed by the reservoir, in direct contact with the limestone of the aquifer. There are discharge data for the entire group of springs, taken by the Comisaria de Aguas del Guadalquivir between 1968 and 1972 (Delgado et al., 1974). Although old, the hydrograms obtained (Fig. 15) provide additional information. The depletion coefficients are nearly 0.002 days^{-1}, lower than in the case of Riofrio, which suggests a greater natural regulation of the aquifer. We also see a certain disagrement between the hydrograms of Riofrio and Manzanil (Hidalgo, 1974a), which could indicate a slower response to the pluviometric imput of this area.

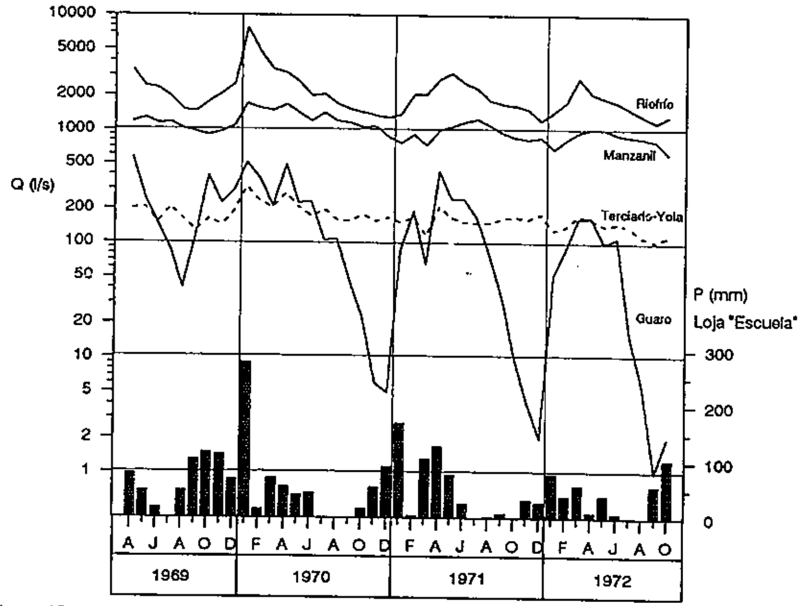

Figure 15.- Hydrograms obtained from the direct monthly gaugings carried out by the CAG in some of the springs of the Sierra Gorda.

The dominant hydrofacies is also calcium or magnesium bicarbonate, depending on the lithological composition of the aquifer. The conductivity (25 °C) varies between 450 and 480 μS/cm; the temperature between 15.5 and 16.5 °C. The sulphate contents are around 50 mg/l, and the chlorides are about 30 mg/l. All these values of physico-chemical parameters are somewhat higher than those registered in the Riofrio springs. The nitrate content of the water is low, varying from 7 to 15 mg/l (University of Granada, 1990).

At this stage of the itinerary, we might examine the great diversity of the discharge points in the karstic aquifer of the Sierra Gorda. The great number of springs -all of which are permanent, except Guaro, and have substantial average flows- suggests the idea of an absence of great karstic channels, well developed and hierarchical, which could connect the recharge areas with the drainage areas; but rather there seems to a be certain homogeneity in the development of the karstification which exploits the principal sets of fractures of the massif, these being connected to the springs. Certain sets of fractures appear to have a more important hydrodynamic role than do others. Nevertheless, all the systems are more or less karstified, the entire carbonate mass contributing to the storage and transmission of water.

The intense karstification observable on the surface of the massif does not have a counterpart in the hydrodynamic functioning of the deep karstification, at least in the saturated zone. The highly regulatory behaviour is reflected in a great storage capacity. The unimodal distribution of the mineralization of the water which emerges in the springs of Riofrio reinforces the idea of a hydrodynamic behaviour more similar to that of fissured or homogeneously karstified aquifers (diffuse flow), since a hydrochemical homogeneity is equivalent to a certain hydraulic homogeneity.

Loja-Granada stretch

Returning to Granada, we cross extensive outcrops of essentially detrital materials with intercalations of carbonate levels, of fluvial-lacustrine origin from the Lower Pleistocene. Towards the north, we find the rich vega of Huetor Tajar, stretching parallel to the Genil River; here irrigation is highly profitable, asparagus being the dominant crop.

Passing Cacin River, we find Triassic outcrops in Keuper facies, very rich in gypsum levels. These evaporite materials constitute pseudokarstic aquifers which discharge highly saline waters into the Genil River. Somewhat farther along, and towards the north, the limestone mass of Parapanda stands out as an important karstic aquifer, with a corrosion plain similar to that of the Sierra Gorda.

At the height of Lachar we again reach the aquifer of the Vega de Granada. The irrigated crops constitute the principal productive activity here, sustaining the economy of numerous communities which surround the city of Granada. Towards the north we can distinguish the carbonate relief of the Sierra Elvira (Middle Subbetic), where there is an important geothermal anomaly, with water at temperatures of around 32 °C.

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