

**HYDROGEOLOGICAL SURVEY  
OF THE BASIN OF FUENTE DE PIEDRA**

SHORT SURVEY, CONCLUSIONS  
AND GENERAL RECOMMENDATIONS

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in cooperation with: **EMPRESA NACIONAL ADARO DE  
INVESTIGACIONES MINERAS S.A.**

## 1. - INTRODUCTION

In cooperation with the Empresa Nacional Adaro de Investigaciones Mineras S.A., the Instituto Geológico y Minero de España (IGME) has carried out a hydrogeological survey of the basin of Fuente de Piedra in the light of the ecological problem affecting its lagoon, namely the threat posed in recent years to its colony of birds by drastic falls in the water level.

The survey was initiated as a joint IGME/ICONA venture in 1983 and later continued under a technical aid agreement concluded between IGME and the Junta de Andalucía in 1984.

The survey is of particular interest because of the close relationship between the lagoon of Fuente de Piedra and the aquifers of the endoreic basin of the same name, and because of the lagoon's status as one of Spain's most important wetlands, given that it is the habitat of a large colony of flamingos which regularly winter and breed there if there is sufficient water.

Consequent upon Law 1 of the Andalusian Parliament of 9 January 1984, which designated the Fuente de Piedra lagoon an integral reserve, it has become necessary to determine the quantity and quality of the groundwaters or surfacewaters supplying it. This survey attempts a preliminary assessment of these parameters, bearing in mind its terms of reference, which may be summarized as follows:

- to describe the aquifers of the area and ascertain their geometry, hydrogeological behaviour and hydraulic and piezometric characteristics;
- to provide a detailed climatological and hydrological study on the area;
- to take stock of the ways in which existing groundwaters are harnessed and used;
- to determine the quality of the groundwaters and the extent to which it varies;
- to establish the water balance of the basin and the lagoon; and
- to propose and analyze alternative means of increasing the lagoon's water resources.

## 2. - GENERAL CHARACTERISTICS OF THE BASIN

The Fuente de Piedra lagoon is situated in the north of the Province of Malaga. Its waters are saline, its area is 13 km<sup>2</sup> and it is the lowest part and natural outlet of an endoreic basin of 153.5 km<sup>2</sup>, located on the Atlantic-Mediterranean watershed.

The mean annual rainfall over the period 1948-1982 was some 453 mm. December and February are the months of highest rainfall, with values of between 60 and 70 mm. The driest month is July, with values invariably below 5 mm, followed by August with 5-6 mm.

The mean annual temperature over the period 1951-1982 was 16.6°C, with values over the year ranging from 12.7°C to 18.9°C. The coolest

month is January (9°C), followed by December (9.3°C) and February (10.1°C). The warmest month is August (26.1°C), followed by July (25.7°C) and September (22.6°C).

The potential mean annual evapotranspiration value (according to Thornthwaite) is 820 mm. July and August have the highest PET values, followed by June; the aggregate of the values for these three months almost accounts for 50% of the annual total.

The real mean evapotranspiration values (again according the Thornthwaite) lie between a minimum of 263 mm (for a useful reserve of 25 mm) and a maximum of 332 mm (for a useful reserve of 100 mm). The RET usually represents between 30 and 40% of the PET because of the drying-up process in the months of low water.

The useful rain values vary between a minimum of 125 mm (for a useful reserve of 100 mm) and a maximum of about 200 mm (for a useful reserve of 25 mm). On average, these figures account for between 28% and 43% respectively of the total rainfall.

The mean evaporation rate for the period 1962-1982 was 1,310 mm/year (minimum 1,166 mm, maximum 1,620 mm). There are large variations in the course of the year, with about 40 mm in December and January and somewhat more than 200 mm in July and August. However, these values, obtained by application of the Penham formula to establish the monthly water balances of the lagoon, have had to be increased systematically by 25% to make the balances consistent.

The regime of the existing watercourses in the basin is irregular. The absence of stations for measuring flows precludes an accurate determination of the characteristic parameters of the surface hydrology. To ensure that these data are available in future, two stations have been designed and constructed in the Santillán and Humilladero streams and another has been installed outside the basin in Las Tinajas, a tributary stream of the Guadalhorce, following a study on their discharge characteristics.

### 3. - GEOLOGY AND HYDROGEOLOGY

The Fuente de Piedra basin is situated on the Subbetic ['Subbética' ?] stratum, whose substratum consists of Triassic argillaceous-evaporitic materials. A remote mountain chain (sierras of Humilladero, La Camorra and Los Caballos), composed of fundamentally carbonated materials of Jurassic age, is a vestige of the Mesozoic cover, which has very largely disappeared. Tectonically, both the Trias and the Mesozoic cover correspond to sliding strata which underwent a substantial displacement from more southern regions: hence the present chaotic arrangement of their materials.

Most of the basin consists of postorogenic formations of Miocene-Quaternary age which lie incongruously and horizontally on the Mesozoic substratum. The materials are for the most part detritus, basically molasses, which can be up to a hundred metres thick.

The most significant geomorphological feature of the area is its endoreism, a phenomenon that may be related to the karstic processes that occur in the Triassic substratum upon dissolution of the evaporitic materials - salt and gypsum - it contains.

The Jurassic carbonated formations, the Miocene molasses and the Quaternary fillings are permeable materials which constitute aquifers and are hydraulically connected to form a single entity that can be regarded as a discrete hydrogeological system. It is isolated from the other systems in the area and its limits coincide fairly closely with the limits of the Fuente de Piedra endoreic basin. At regional level, the Trias constitutes the impermeable substratum of the system, although locally, and because of the karstic processes mentioned above, it may behave like a permeable substratum.

#### 4. - PIEZOMETRY

The piezometric ['de isopiezas' ?] maps for 1973, June 1983 - period of intensive extraction following a prolonged drought - and May 1984 - period of maximum recharge following 8 or 9 months without extraction - reveal a number of general and common features from which it is possible to infer the morphology of the piezometric surface and the way in which the system functions. They show that the direction of the subterranean flow in the aquifers is from the limits of the system, i.e the watershed areas, towards the basin's centre, where the lagoon, as the lowest part of the system, is the point of outflow. The intense evaporation occurring in the lagoon for most of the year is conducive to a continuous subterranean flow towards it.

A comparison between the abovementioned maps also reveals seasonal piezometric variations in two areas - the northern parts of Fuente de Piedra and of Humilladero respectively - which are also the areas in which extraction activity is most heavily concentrated.

In the Fuente de Piedra area, the aquifer level falls below the lagoon level at the end of the period of low water and intensive extraction, and there is an obvious risk of its becoming salinized. However, after a period of rain and the interruption of extraction activities, it tends to return to its natural state, since, piezometrically, the area constitutes the lowest point of the system and is accordingly well supplied with water.

In the Humilladero area, the seasonal variations are not very great and there is no evidence yet of a seasonal salinization threat of the kind posed in the northern part of Fuente de Piedra. However, there is a slow but steady fall in the water level which could, at some future date, leave many local wells unusable and, ultimately, dry.

Thanks to the water-level measurements carried out in 1974 and 1975 and to those carried out regularly by IGME since 1979, it has been possible to determine the system's piezometric development over the last ten years. In that time, there was a clear, general tendency for the water level to fall in that part of the aquifer in which extraction activity is concentrated. However, the piezometric effects differ in two particular areas.

On the one hand, in the northern part of Fuente de Piedra, the aquifer responds rapidly to periods of rainfall, and the tendency to recover is checked only in the immediate vicinity of the site of large-scale and continual extraction.

On the other hand, the northern part of Humilladero responds with

far greater difficulty to the same periods of rainfall, which merely produce a slight pause in a generalized process of water loss. Furthermore, the aggregate loss since 1974 is of a far greater order of magnitude in the Humilladero area.

#### 5. - EXTRACTION OF THE GROUNDWATERS

According to the count made in 1983, the total number of catchment points in the Fuente de Piedra basin is 408, distributed by municipal district as follows:

Fuente de Piedra .....	265 points
Humilladero .....	84 points
Mollina .....	42 points
Sierra de Yeguas .....	17 points.

Most of the catchment points currently in use are concentrated in a 28 km<sup>2</sup> area in the north-east part of the lagoon.

The total volume of water extracted in 1983 was 3 Hm<sup>3</sup>, representing a fall on the estimated volume of 7 Hm<sup>3</sup> for 1974.

Over the past nine years, irrigated land in the basin has increased by 5%, in spite of the fact that the crops once grown have largely been replaced by varieties requiring less water or even no water, notwithstanding their lower yields.

Average irrigation volumes, calculated on the basis of the data gathered in our surveys, were 7,100 m<sup>3</sup>/ha in 1974, rising to 2,865 m<sup>3</sup>/ha in 1983.

#### 6. - HYDRAULIC CHARACTERISTICS OF THE AQUIFERS

Pumping tests have revealed exceptionally high transmissivity values in the carbonated aquifers of the sierras of La Camorra and Humilladero, confirming their karstic nature. In the Miocene, these values range from 2 to 80 m<sup>2</sup>/h, while the average values of the area close to the lagoon have been put at 5 to 35 m<sup>2</sup>/h.

The value of the only storage coefficient whose accuracy can be guaranteed is  $1.3 \times 10^{-2}$ . Effective porosity values, calculated on the basis of the desaturation produced between 1973 and 1984, lie between 3.8 and 5.1%.

#### 7. - QUALITY OF THE GROUNDWATERS

In general, the groundwaters of the basin are quite densely mineralized. The areas in which all the significant ions are most highly concentrated are the lagoon and its north-eastern extension, broadly coinciding with the more extensive Triassic outcrops of the basin. The area of lowest concentration, on the other hand, is in the eastern part of Fuente de Piedra, notably in the depression between the sierras of La Camorra and Humilladero, which is occupied by an extensive outcrop of Miocene materials. Other areas of low ionic concentrations are for the most part coextensive with the margins of the basin and close to its watershed.

There seems to be some connection between high ionic concentrations

and the depth of the catchment points. An increase in salinity has been noted in some of these after they have been deepened, so that drilling to an excessive depth would appear to be ill-advised.

This situation could be due to differences between two areas within the same aquifer: one deep and located in the immediate vicinity of the Triassic substratum, in contact with which the water circulates and becomes progressively salinized, the other superficial and more influenced by infiltrating rainwater. The separation would be maintained (with the help of the difference in density) by a phenomenon similar to that which occurs in the coastal aquifers.

However, we should not rule out another hypothesis, which is that there is a deep circulation of water, located entirely in the Trias, through a network of karstic conduits carved through its evaporitic materials. The deep part of the lagoon, whose water has far higher ionic concentrations than the other parts, could reach some of these conduits.

Since, from all appearances, the quality of the groundwaters of the area is now steadily deteriorating, it is advisable that the recently-started systematic and periodic checks should be maintained.

#### 8. - WATER BALANCES OF THE BASIN AND LAGOON

The total water resources of the Fuente de Piedra basin for an average period (1962-1982) have been evaluated at between 18 and 22 Hm<sup>3</sup>/y. Approximately two-thirds of this amount infiltrate into the aquifers, which means that the subterranean resources of the basin can be put at about 13 Hm<sup>3</sup>/y. The remaining third is surface runoff (about 6 Hm<sup>3</sup>/y.). Direct rainfall on the lagoon will account for an additional 6 Hm<sup>3</sup>/y.

It must be emphasized that these values are for an average year, obtained from what is deemed to be a representative 20-year period (1962-1982), and that very substantial variations occur in real years.

It must also be borne in mind, when considering these values, that the volume of water extracted by pumping in 1983 was 3 Hm<sup>3</sup>.

With total reserves of between 100 and 160 Hm<sup>3</sup>, the storage capacity of the aquifer is considerable, responding to the rainwater infiltration and the pumping with significant piezometric variations. Against this, its diffusiveness is poor, so that the subterranean outflow towards the lagoon varies within very narrow limits and is characterized by considerable inertia. It has been roughly estimated that, under average conditions and with an extraction volume of 3 Hm<sup>3</sup> per annum, the subterranean flow will be some 10 Hm<sup>3</sup> per annum.

Finally, the lagoon, the system's natural point of outflow, is replenished by direct rainfall, surface runoff from the basin and the subterranean flow from the aquifer, while evaporation is its only discharge. In general, replenishment exceeds potential evaporation between November and March, whereas potential evaporation (1.1 to 3.8 Hm<sup>3</sup>/month) exceeds replenishment (the subterranean flow often being the only source) between April and October. The possibility of retaining water in the lagoon in the

low-water period depends, therefore, on the existence of surpluses in the wet season.

The average volume of water in the lagoon over the period 1962-1982 has been put at 9 Hm<sup>3</sup>. A distinction is drawn between the period 1962-1971, with an average volume of 18 Hm<sup>3</sup> and the retention of water in the lagoon in the low-water periods, and the period 1972-1982, with an average volume of 2 Hm<sup>3</sup> and frequent drying-up of the lagoon in the low-water periods. It is estimated that in the 20-year period from 1962 to 1982 (sufficiently representative in terms of rainfall), the lagoon dried up in 21% of the months.

It could be that the drying-up of the lagoon in the 1972-1982 low-water periods is primarily attributable to climatic factors, in which case we are dealing with a cyclical phenomenon.

To give a rough idea of the impact pumping has on the volume of the lagoon's waters, a 2.4 Hm<sup>3</sup> decrease or increase in the amount pumped out in each year of the 1962-1982 period would have left the lagoon dry for 11% or 29% respectively, rather than 21%, of the months comprising that period.

Finally, as far as the water balances of the basin and the lagoon are concerned, it must be pointed out that, while a good qualitative knowledge of the behaviour of the Fuente de Piedra basin has been acquired, the quantitative estimates have to be taken as approximations because of the unavailability of direct measurement data, insufficient observation periods or the simple lack of detailed information (on evaporation, extraction by pumping, piezometric monitoring, hydraulic parameters of the aquifer) - deficiencies that have obliged us to make assumptions or extrapolations. Even so, in support of the relative accuracy of our estimates, it has to be said that the monthly figures for the water balance of the lagoon for 1962-1982 are quite compatible with the historical data that it has been possible to obtain regarding the presence or absence of the colony of birds. (This does not apply to the most recent years, in which, despite months with a negative balance, the colony has remained in the lagoon thanks to the effective corrective measures taken by ICONA).

#### 9. - ALTERNATIVE MEASURES TO PREVENT OR COMPENSATE FOR THE DRYING-UP OF THE LAGOON

A detailed analysis of the various alternative measures that could be taken to prevent or compensate for the drying-up of the lagoon should not conclude with a recommendation that it be continuously supplied with water either from its own basin or from one outside the Fuente de Piedra area. Any increase in the inundated area would increase evaporation and ultimately exacerbate the present loss of resources.

It is equally important to guard against a continuous supply of water with a high salt content, since this could impair the quality of the aquifer linked to the lagoon by causing an inversion of the subterranean flow towards the aquifer in the low-water periods.

The measures that are most to be recommended are those that would enable small supplies to be brought in, at no great cost, to mitigate the severity of the emergencies that occasionally arise as a result of prolonged droughts. In line with this approach, it

would be advisable to improve the wells that exist already inside the lagoon and to construct others (or acquire some of those already drilled) in the surrounding area, while trying to prevent their siting in the heavy extraction areas.

It is not advisable to harness the waters of the carbonated aquifers of the sierras of Mollina and Humilladero, since these provide the basin's best quality water, which must be used solely to satisfy the present and future demands of the local towns.

As for the possibility of tapping the surfacewaters of basins close to the Fuente de Piedra, the best idea would be to build some conduit to transfer water from the las Tinajas stream, which is less than a kilometre away from the lagoon. This would have to be preceded by a detailed study of the hydrological regime and its supply capacity in the light of the data furnished by the flow-measurement station. If it were possible to improve the existing tunnel, this would undoubtedly be an effective and inexpensive solution. Alternative schemes involving the transfer of water from more distant sites in the Guadalhorce basin should be given more careful study in view of their high cost.

It is clear that the plans thought to be most appropriate for bringing groundwater to the lagoon are in no way mutually exclusive. On the contrary, it would be sensible to consider them simultaneously, as this would prevent any spatial concentration of the extraction activity and consequential damage to the aquifer.

The above measures are compatible and, where possible, they should be combined with regular extractions of mud ['vaso' ?] from the lagoon in order to maintain the irregularities of its bed, which is steadily becoming homogenized.

Finally, it must be pointed out that, whatever the approach adopted, it has to be accompanied by a body of legal provisions which, given the hydrogeological link between the basin and the lagoon, covers the basin as a whole. Moreover, these provisions must take into account, not only the conservation of the lagoon itself, but also the conservation of the aquifers to which it is linked.

#### 10. - FUTURE ACTION AND COMPLEMENTARY MEASURES

In concluding this short survey, we would draw attention to the desirability of pursuing the hydrogeological studies on the Fuente de Piedra basin in greater detail, with a view to determining an upper limit for the volume of water extracted by pumping, while trying to secure compatibility between current uses of the water and its maintenance in the lagoon and reducing as far as possible the amount lost through evaporation. A study is planned on the feasibility of using pumps to regulate the flow of groundwater to the lagoon. Two possible approaches are envisaged:

- 1) Determining pumping sites and a pumping system which ensure that the effect on the subterranean flow to the lagoon has the smallest possible impact on the volume of water in the lagoon.
- 2) Determining a pumping system for reducing the subterranean flow to the lagoon so that in rainy months the level of the lagoon is maintained solely by rain and surfacewaters, while in drier



months or seasons it is maintained with the help of pumped groundwaters.

In order to develop this project and advance our understanding of the lagoon's hydrogeological regime, the following measures are recommended:

- Daily monitoring of the evaporation of the lagoon's waters.
- Daily monitoring of the surface runoff to the lagoon.
- Daily monitoring of the level of the lagoon.
- Monthly monitoring of the volume of water extracted by pumping in the aquifer.
- Extending the piezometric monitoring system and carrying out monthly measurements, particularly in the areas surrounding the lagoon, the extraction areas and the areas where the aquifer is replenished.
- Keeping a continuous record of piezometric variations at a number of significant points.
- Taking steps to improve knowledge of the hydrogeology of the aquifer and, in particular, its hydraulic parameters: transmissivity and distribution, as well as effective porosity.
- Seasonal monitoring of the quality of pumped water, particularly in the wells near the lagoon and in the wells whose floors are close to the Triassic formation.
- Constructing a mathematical model of the basin which simulates its different hydrological elements and its internal connections. Adjusting the model, simulating alternatives and carrying out a feasibility study.

It is important for the hydrogeological monitoring to be carried out over several years, since there is a close correlation between the quality of the model adjustment and the length of the observation period.

Finally, we would stress the need for an adequate legal framework for the monitoring and management of the resources of the entire basin, so that any abuse that came to light could be dealt with appropriately.