THE STATE OF SEAWATER INTRUSION IN SPAIN

J.D. Gómez Gómez

J.A. López Geta

E. Garrido Schneider

Instituto Geológico y Minero de España, Madrid, Spain

ABSTRACT

The geomorphologic model of the coastline of Spain is quite similar along its entire length. It can be described as a succession of mountainous heights located close to the coast, often delimiting Tertiary and Quaternary coastal deposits no more than 20-30 km wide, and in some cases descending to the sea, forming cliffs. About 60% of all the coastal hydrogeologic units in Spain are affected to some degree by marine intrusion. The management and protection of surface and groundwater in Spain is regulated by the 1985 Water Law and by the revised text approved in 2001. The present article reviews the situation of some representative coastal aquifers in Spain that have been extensively studied and which are affected by seawater intrusion, to a greater or lesser degree.

INTRODUCTION

Spain enjoys a historical relation with the sea, as a result of its peninsular and continental situation, being open to the Atlantic Ocean and the Mediterranean Sea along a total of 7876 km of coastline (INE, 2001). Of this distance, some 3514 km of the mainland and the Balearic Isles correspond to the Mediterranean. This traditional relationship with the sea is also reflected in the population distribution, as almost 59% of all the inhabitants of Spain are settled in the coastal provinces, with most of these to be found along a narrow littoral strip. As an example, the population of the coastal municipalities of Catalonia amounted to some 2,728,000 inhabitants in 1996; in other words, some 45% of the total population of this region were concentrated into 7% of its total surface area (INE, 1998). A similar circumstance can be observed in the Valencia region, where a population of 2,099,343 (52% of the total inhabitants) occupy a coastal area of 3311 km^2 (14% of the total surface area).

These patterns of human settlement are favoured by the geomorphology of the Spanish coastline, which is fairly similar along its entire length. It can be described as a succession of mountainous heights that are close to the coastline and that often delimit coastal plains that are no more than 20-30 km wide and that sometimes reach the coast itself, forming cliffs; in other cases, the mountains give way to river valleys that on occasion form deltas. These coastal plains, which enjoy a mild climate, are intensively exploited, for tourism, urban development, agriculture and industry. Water demand, thus, is high and frequently cannot be met from available surface water. Coastal aquifers, therefore, are of key strategic importance as an immediate, and sometimes as the sole source of the water resources necessary for the social and economic development of these areas (MINER-MOPTMA, 1995).

The heavy demand for water, therefore, is reflected by an intensive degree of aquifer exploitation, which can lead to the appearance of seawater intrusion and thus endanger the sustainability of the exploitation regime. Nevertheless, salinisation of groundwater can also be due to other causes, such as the presence of saline geologic formations, saline fossil waters, or agricultural or industrial contamination (Lloyd & Tellam, 1988).

Coastal Sector	Coastal length	
	km	%
N Atlantic	2429	31
SWAtlantic	350	4
Mainland Mediterranean	2086	26
Balearic Isles	1428	18
Canary Isles	1583	20
Total	7876	100

Table 1. Length of different sectors of the coastline of Spain.

GEOLOGIC CONTEXT

The distribution of generic types of coastal aquifers in Spain is influenced by the different geologic domains present in the Iberian Peninsula, the Balearic Isles and the Canary Isles. The so-called siliceous Spain contains outcrops of the most ancient deposits – mainly granites, slates and schists – that comprise low-permeability formations and do not give rise to significant aquifers, except in isolated cases of thermalism or of mineral waters (IGME, 1980). Nevertheless, these small aquifers often solve the supply problems of villages and hamlets. This geologic domain corresponds roughly to the western third of the Iberian Peninsula, extending eastwards through Sistema Central and Sierra Morena. In coastal areas, it occupies the NWAtlantic sector.

The calcareous part of Spain is found in areas of large carbonate formations, mainly corresponding to the Mesozoic, but in some zones to the Tertiary. These formations are permeable by fracturing and by karstification, and are often drained by important springs, thus forming the most important rivers in Spain. These formations are associated with the largest structural bodies in the Iberian Peninsula, namely the Cantabrian

Cordillera, the Pyrenees, the Iberian System, the Catalonian Cordillera and the Betic Cordillera. These systems contain important aquifers that often reach extend to the coast, either on the surface, as is the case of the Garraf Massif, the Maestrazgo and Sierra de Gádor, or beneath other confining detritic formations that were deposited above them, such as some sectors of the Maestrazgo and Sierra de las Agujas. On the N Atlantic coastline almost all the important aquifers that have been identified correspond to the former category, that is, carbonate formations that extend on the surface as far as the coast. On the mainland Mediterranean coastline, however, detritic aquifer formations are more common; sometimes these are deposited over carbonate aquifers that reach the sea below the land surface.

The third great geologic domain in the Peninsula is constituted of sedimentary basins filled by Tertiary and Quaternary deposits. These formations mainly comprise detritic deposits of clays with different levels of consolidation and with a low degree of permeability. Frequently, however, they contain layers of sands and gravels with high porosity and permeability values (ITGE, 2000), and are of considerable dimensions in the basins of the rivers Ebro, Duero, Tajo and Guadalquivir. On the Mediterranean coastline they are represented by a succession of alluvial plains (such as Plana de Castellón and Plana de Valencia), river valleys (such as Río Vélez and Bajo Guadalhorce) and deltas (Ebro, Llobregat, etc.), which constitute detritic aquifers of great interest and which, in general, are intensively exploited.

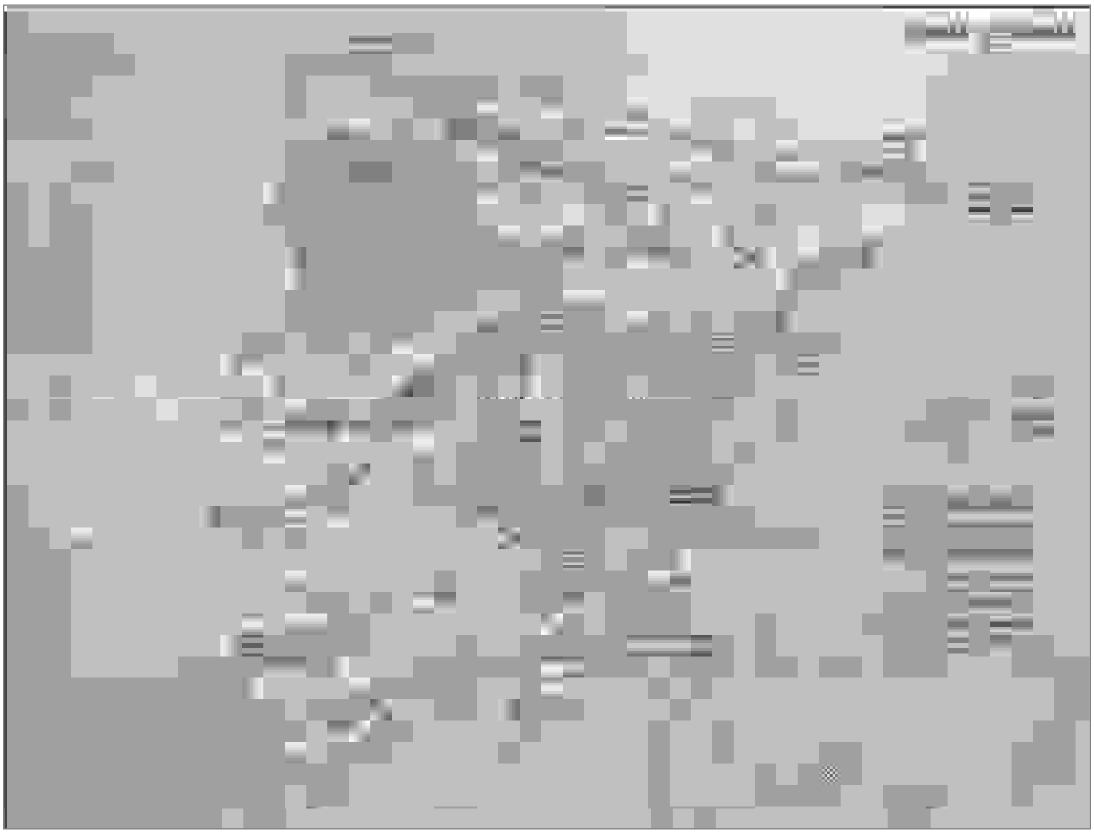

Figure 1. Detritic, carbonate and volcanic aquifer zones in Spain (MINER-MOPTMA, 1995).

CHARACTERISATION OF COASTAL AQUIFERS

The geomorphologic model of the peninsular coast is quite similar throughout its length, and can be described as a succession of mountain heights close to the coast that often delimit coastal Tertiary and Quaternary deposits no more than 20-30 km wide, although on occasion they reach the sea, forming cliffs.

From this model, and taking into account the nature of these formations, we can make an initial basic classification of coastal aquifers into two types, detritic and carbonate (the latter being associated with coastal cordilleras). Detritic aquifers are usually associated with zones of greater socio-economic development, with a high population density and intense agricultural and industrial activity. Another type of aquifer, the volcanic shelf, is only to be found in the Canary Isles, and is comprised of porous, permeable effusive rocks, with a fairly flat morphology. These aquifers, too, are associated with areas of considerable social and economic development.

According to their morphology, coastal detritic aquifers can be classified, in turn, into the following types (Custodio, 1981): deltas, small coastal alluvial plains, coastal plains and coastal piedmonts. These are mainly comprised of alternating layers of gravel, sand, silt and clay, with varying geometries and degrees of spatial continuity.

A typical hydrogeologic model of such detritic aquifers consists of the possibility of distinguishing two aquifer groups, an unconfined upper one and a confined lower one, the two being separated by a clay layer of low to medium permeability. The thickness of this clay layer normally decreases towards the edges of the basin, and it may even disappear, thus creating a point of contact between the two aquifer formations.

All the coastal aquifers in Spain can be described by their generic characteristics of one of these types, or as a combination of them.

Along the coastline of the Iberian Peninsula, and of the Balearic and Canary Isles, a total of 95 hydrogeologic units (HUs) have been defined. These make up 25% of all the units in Spain (considering each island within the Canaries as a separate unit). Each of these units may contain one or more aquifers. 72 of the units are on the Mediterranean coast (49 in the Peninsula and 23 in the Balearic Isles). In turn, these HUs are grouped into hydrographic basins, an administrative division that was defined in the 1985 Water Law (table 2).

The Balearic archipelago contains the greatest number of HUs (23), followed by the South basin with 19 and Catalonia basin, with 13. However, if we consider the surface area of these units, then the largest is the Júcar basin, with 5286 km^2, followed by the North basin with 5230 km^2 and the South basin, with 5224 km^2. The Canary Isles comprise a special case, in which the total surface area (7455 km^2) is considered.

Basin	Nº of coastal HUs	Area (km^2)	Irrigated area (ha)	Population	Water resources (hm^3/year)
North	10	5 230	-	1 419 480	903
Guadiana	1	600	6 400	60 000	98
Guadalquivir	5	2 754	16 010	569 640	87
South	19	5 224	137 100	1 382 810	576
Segura	6	3 534	63 990	744 520	64
Jucar	10	5 286	153 085	2 088 570	1 262
Ebro	1	1 030	18 700	88 000	135
Cataluña	13	2 169	12 564	2 700 000	575
Balearic Is.	23	3 693	23 932	654 000	397
Canary Is. (*)	7	7 455	72 107	1 663 770	720
Total	95	36 975	503 888	11 370 790	4 817

Table 2. General data on coastal HUs, grouped by basins
** Grouped by islands*

The hydrogeologic units where socio-economic development is greatest are also those supporting the most intensive exploitation of their water resources. Two indicative parameters of this level of development are the area of irrigated land and the population. In both respects, the Júcar basin is outstanding, with 153,085 ha and 2,088,570 inhabitants, respectively. In terms of population, it is only surpassed by Catalonia basin, with 2,700,000 inhabitants, and features a great deal of industrial activity and tour-ism. The South basin also features a considerable area of irrigated land (137,100 ha), a large population (1,382,810 inhabitants) and a well-developed tourist sector.

SEAWATER INTRUSION

IGME has established a network for the observation and control of marine intrusion, in which chloride concentration and conductivity are measured periodically, in order to monitor the temporal evolution of saline fronts. In 1999, a total of 869 measurements were obtained, corresponding to 415 wells. These were located in 26 HUs along the SW Atlantic, Mediterranean and Balearic coasts.

In 45% of these observation wells, the mean chloride content exceeded 250 mg/L, and in 22 of the 26 HUs this level was exceeded at some point. However, in coastal units other than those included in this sampling campaign the water content may be saline, as has been found in previous campaigns and specific studies. Figure 2 shows the distribution of the aquifers affected. Marine intru-

Figure 2. Distribution of seawater intrusion in coastal Hydrogeologic Units (modified from MINER-MOPTMA, 1995).

sion is present in a total of 56 units, to varying degrees.

Three degrees of intrusion have been classified: local, zonal and general (López Geta, 1996). Local intrusion corresponds to aquifers where this phenomenon takes place on a sporadic basis, within a well or concentration of wells that are intensively exploited, thus producing a rise in the fresh water / salt water interface. This category indicates an initial state of seawater intrusion or its appearance as a seasonal phenomenon. Zonal intrusion describes a higher degree of intrusion, in which the salinisation extends to an important area of the aquifer, and where the initial quality is not recovered during periods of recharge. Finally, general intrusion occurs when there is a landward advance of the fresh water / salt water interface along the whole coastal extension of the aquifer, arising from intensive exploitation taking place on all the land surface.

The main such problems in Spain are found on the Mediterranean coast of the Iberian Peninsula and in the Balearic Isles. These areas comprise a coastal length of some 2583 km, equivalent to 42% of the entire coastline of Spain, and are distributed over five administrative regions: Andalusia, Murcia, Valencia, Catalonia and the Balearic Isles. These areas contain a significant proportion of the country’s population and economic activity, including agriculture, industry and tourism.

The Catalonia and Balearic basins present the greatest number of units with general intrusion (6 and 4, respectively), followed in severity by the Júcar and Canary Isles basins, where the intrusion is predominantly zonal. On the other hand, the North basin presents no known salinisation, in any of its HUs.

In overall terms, about 60% of all the coastal units in Spain are affected to some degree by seawater intrusion, distributed as 17 % general intrusion, 31% zonal intrusion and 12% local intrusion.

Basin	Coastal HUs (Nº)	No intrusion	Local intn.	Zonal intn.	General intn.
North	10	10	0	0	0
Guadiana	1	0	0	1	0
Guadalquivir	5	2	0	2	1
South	19	9	4	4	2
Segura	6	2	2	1	1
Jucar	10	0	1	7	2
Ebro	1	0	0	1	0
Catalonia	13	2	4	1	6
Balearic Is.	23	14	0	5	4
Canary Is.	7	0	0	7	0
Total	95	39	11	29	16

Table 3. Degree of intrusion in coastal HUs.

MANAGEMENT

The management and protection of surface and groundwater in Spain is regulated by the 1985 Water Act and by the revised text of 2001. According to this norm, groundwater forms part of the public water domain as regards the availability and use of water resources. The management of this public water domain is the responsibility of the State Administration where the hydrogeographic units exceed the ter-ritorial limits of a single Comunidad Autónoma (Spanish territorial division). When river basins lie entirely within the territory of a single Comunidad Autónoma, the latter administration may exercise the functions governing the public water domain. In the case of interregion basins, many of these functions (such as authorisations, concessions, basin management plans, project planning and realisation) are delegated to Basin Water Authorities or Hydro-graphic Confederations.

The parliamentary norms regarding the application of the Water Law are compiled in Royal Decrees 849/1986 and 927/1988, in which the Regulation of the Public Water Domain and the Public Administration of Water and of Hydrologic Planning, respectively, are specified.

The regime of water use is also regulated by the Water Law. All private use of water, except when this does not exceed 7000 m^3/year within the period in question, requires an administrative concession, which is granted at the discretion of the Water Authority, according to the stipulations and forecasts of the Hydrologic Plan, on a temporary basis, for a period not exceeding 75 years.

Concessions for groundwater use must specify the following: the annual volume to be used; the maximum instantaneous water flow; the purpose and destination of the water extracted; the maximum depth of the well; the characteristics of the extraction pump; the requirement, if applicable, to install instruments to measure the water level and flow; the duration of the concession, and any other relevant conditions.

To establish the maximum volume that may be extracted from a given aquifer or HU, it is necessary to take into account the conditions established in the corresponding Hydrologic Plan, as well as the evolution of piezometric levels and water quality.

The Basin Authority must maintain a Water Register to record concessions for the use of surface water and of groundwater, in addition to any changes that may be authorised concerning the ownership of the concession or changes in any of its essential characteristics.

As far as possible, and for each HU, the Basin Hydrologic Plans must establish norms for the authorisation of research and for concessions for use.

The Water Framework Directive (2000/60/CE) is an instrument that provides the legislative framework for the future management of aquifers, and one of its main principles is the sustainable use of water. The following are the main tasks assigned to European Union member states in this respect (Grima et al. 2002):

- Define the quality and quantity of groundwater.
- Identify trends in the evolution of groundwater.
- Identify the impact of human activities on groundwater.
- Identify the results of protective and corrective measures.
- Identify the relation of groundwater to associated ecosystems.

CASE STUDIES

Castellón Plain

Several sectors of this detritic aquifer are affected by seawater intrusion. It has been the object of numerous studies since the 1980s (IGME 1981, 1982, 1987, Morell *et al.* 1987a, 1987b, 1988, 1996, Fide-libus *et al.* 1992, Giménez 1994, Esteller 1994, etc.), concerning its hydrogeologic characteristics, the hydrochemistry of the intrusion and other contamination processes, and the creation of mathematical models.

The aquifer is located on the Spanish Mediterranean coast, near the city of Castellón. It lies on a coastal plain constituted of Tertiary and Quaternary detritic deposits. The latter comprise gravels, sands and conglomerates embedded within a mainly silt-clay matrix. This group, of continental origin (alluvial mantles and fans, terraces, etc.), marine origin (littoral strand) and mixed origin (albufera and marsh silts, brown silts and littoral dunes), rests, depending on the zone in question, on Mesozoic deposits, which comprise a second aquifer, or on Miocene Tertiary sediments. The latter are formed of sandstones and clays or marls, with lateral changes of facies to polygenic conglomerates, and with marly limestones at the top. The permeable deposits are considered to be an integral part of the Castellón Plain aquifer, together with the Quaternary formation (ITGE, 1990).

The hydrogeologic limits of the Mio-Quaternary aquifer are defined by the outcrops of Mesozoic deposits and by the Mediterranean Sea. To the north it is bounded by the Cretaceous limestones of the Javalambre-Maestrazgo System, with which it is hydraulically connected. The western boundary is mainly unconfined due to its contact with Muschelkalk and Jurassic limestones and dolostones, as well as with Buntsandstein sandstones; some sectors are confined by the outcropping of impermeable Keuper and Bunt materials. The southern boundary is also unconfined; this is a conventional limit with the detritic deposits of the Sagunto Plain aquifer.

The thickness of the Mio-Quaternary sediments tends to increase from west to east, exceeding 250 metres, although this diminishes near the coast. Groundwater flow normally takes place from inland zones towards the sea, although in some sectors this is reversed, due to the intensive exploitation of water resources. The aquifer is mainly fed by lateral transfer from neighbouring aquifer systems, and to a lesser degree by infiltration from irrigation surpluses, from the river Mijares and from rainfall.

The map of piezometric isolines (fig. 3) corresponds to May 1999, and reveals a zone of piezometric depression in the triangle formed by Chilches-Moncófar-Nules, where the groundwater is as much as 1 m below sea level to the north of Nules. This is an area where intensive use has been made of groundwater supplies, especially for agriculture. An appreciable degree of seasonal recovery was observed in October 1999, although around Chilches and Moncófar, water levels remained slightly depressed.

This continuing situation has led to the development of marine intrusion (Morell, 1989), as described below.

As a consequence of this intensive exploitation of groundwater for agricultural use in the zone of Chilches-Moncófar-Nules, and for urban and agricultural use between Castellón and Benicasim, high chloride contents have been observed in these two areas, proceeding from the intrusion of marine waters into the aquifer, forming saline domes in both areas. The isochloride maps for May and October 1999 calculated from the ITGE monitoring networks (fig. 4) show chloride concentrations exceeding 1600 mg/L in the southern area and 600 mg/L in the North.

The Piper diagram (Fig. 6) shows the points of the water quality control network (fig. 5) for 1995 and 1999. Point 3024-7-1, which is representative of the northern sector, between Castellón and Benicasim, presented a sodium-calcium chloride facies in 1995, which had evolved to sodium chloride by 1999 as a consequence of the

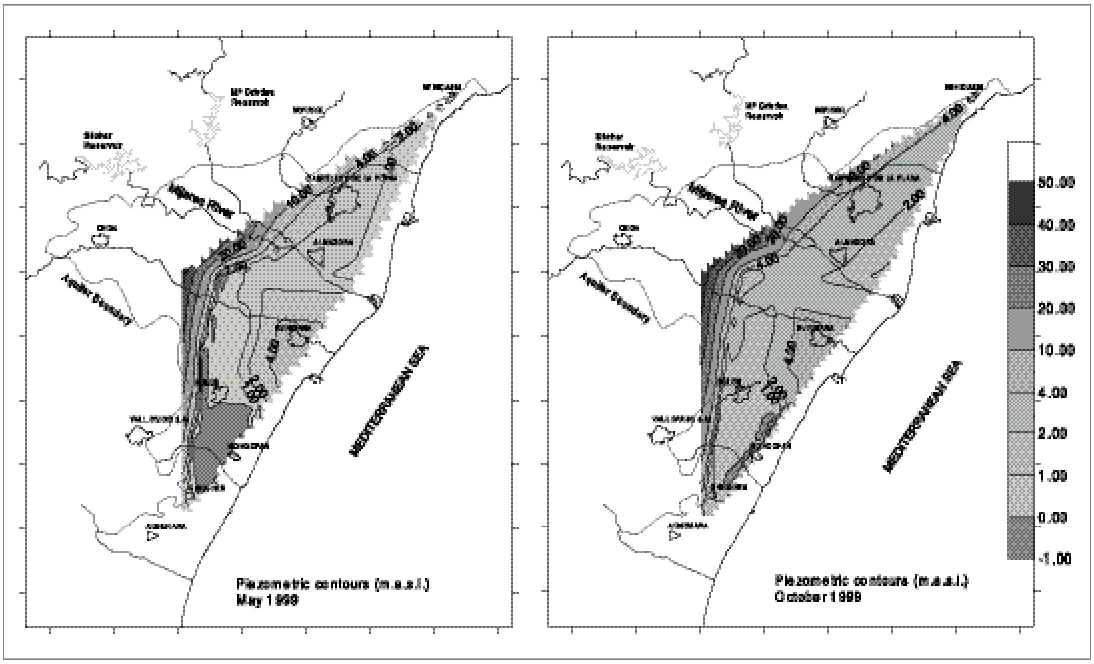

Figure 3. Maps of piezometric isolines for May and October 1999.

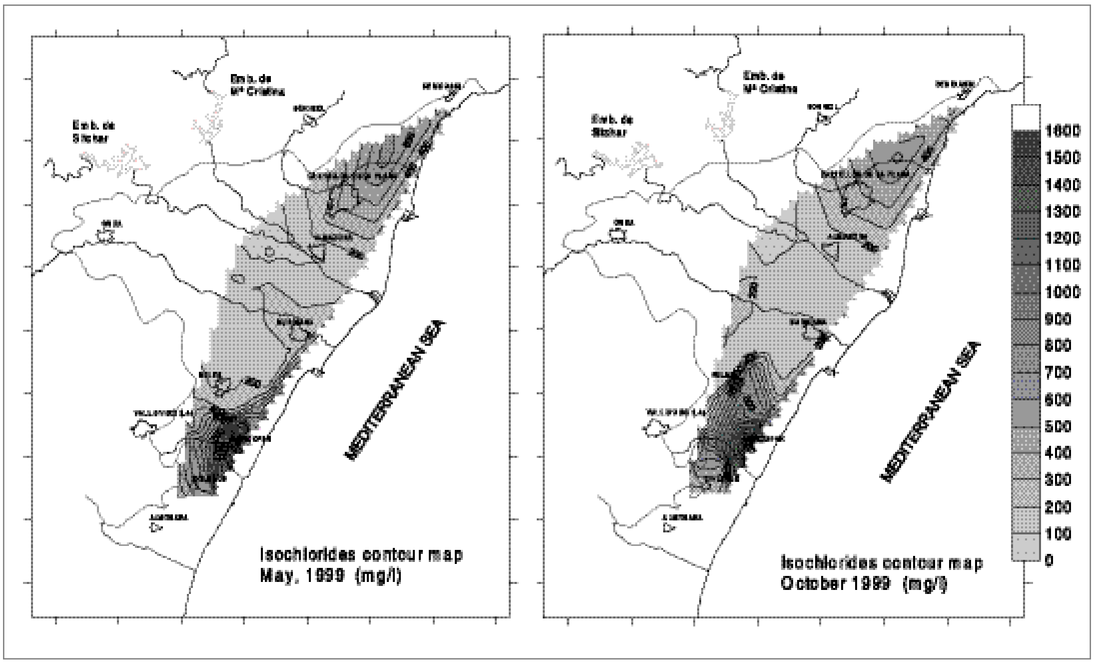

Figure 4. Maps of isochlorides after periods of recharge (May) and of extraction (October).

effects of marine intrusion; the aquifer water had become mixed with increasing proportions of sea water. At point 3026-1-41, which is characteristic of the Chilches-Moncófar-Nules sector, a calcium-magnesium-sodium chloride facies was observed in 1995. This was considered to represent a phase of advancing intrusion, but one in which a sodium chloride facies, evidence of an extreme state of marine intrusion, had not yet occurred. With regard to the other points sampled in 1995 and 1999, these presented calcium or calcium-magnesium sulphate facies, which is probably indicative of the influence of geologic formations at the edge of and beneath the aquifer, in conjunction with the excessive use of agricultural fertilisers (Morell et al., 1996). Nevertheless, these areas were not found to be affected by marine intrusion

Table 4 shows the most significant values for ion exchange measured at the ITGE quality control points in 1995 and 1999. Analysis of the rNa/rCl ratio in 1995 reveals that only point 3026-1-41, which is representative of the Chilch-

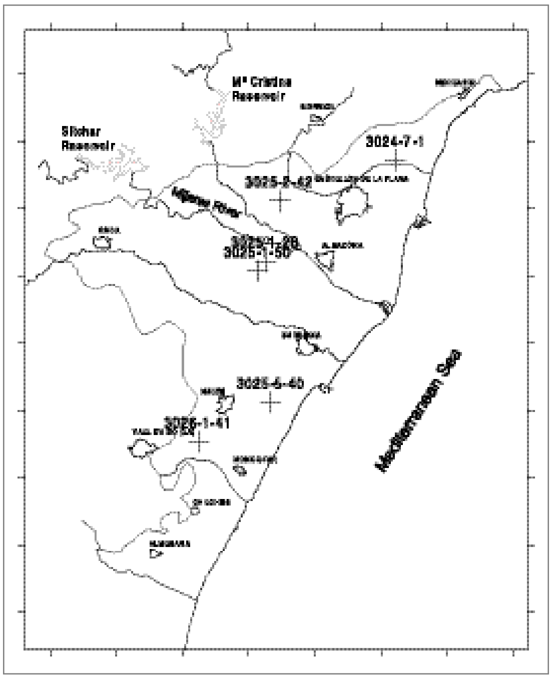

Figure 5. Hydrochemical quality monitoring network established by IGME.

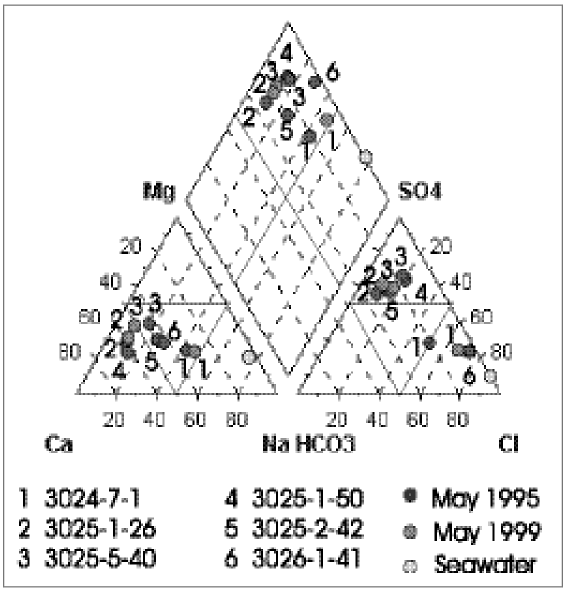

Figure 6. Piper diagram showing points sampled in 1995 and 1999.

es-Moncófar-Nules sector, presented a value below that of sea water, together with high chloride content. This indicates that the zone is affected by an advancing phase of marine intrusion. Point 3024-7-1 in the northern sector between Castellón and Benicasim also presented values similar to those of sea water, with a high chloride content. The effects of marine intrusion were apparent in this area, too, though to a lesser degree. The other points in the central zone of the aquifer presented values corresponding to those of fresh water, although the 1999 measurements revealed increasing salinisation and the rNa/rCl indices approached those of sea water.

The rHCO3/rCl and rSO4/rCl ratios presented the same tendency, with the values corresponding to points 3026-1-41 and 3024-7-1 being closest to those of sea water, which confirms the development of marine intrusion in these sectors. The central sector revealed high values of these indices, proof of the dominance of sulphate facies in the aquifer and the very slight mixing with sea water.

Fuengirola alluvial aquifer

The Fuengirola aquifer comprises an example of a coastal alluvial aquifer on the S Mediterranean coast of the Iberian Peninsula with problems of seasonal local intrusion (Linares, 1997). This aquifer is located in the S of the province of Málaga and has a surface area of 17 km^2, above which intensive agricultural and tourist-urban activity has developed.

It constitutes a detritic complex with lateral changes of facies, formed by Pliocene levels and a fundamentally alluvial Quaternary level in which permeability is greater. These aquifer levels communicate both with each other and with the river Fuengirola, which loses water to the upper and middle parts of the aquifer, but receives water from the lower part. The levels of the piezometric surface of the Pliocene aquifer are higher than those of the Quaternary, which reveals the strong gradient and vertical supply towards the alluvium.

Sampled Wells	rNa/rCl (1)		rMg/rCa		rHCO$_3$/rCl		rSO$_4$/rCl		rCl	
	May-95	May-99	May-95	May-99	May-95	May-99	May-95	May-99	May-95	May-99
3026-1-41	0.452	--	0.678	--	0.046	--	0.322	--	33.001	--
3025-5-40	1.143	0.706	0.891	0.746	0.827	1.336	3.751	3.167	2.398	3.018
3025-2-42	2.025	--	0.679	--	1.583	--	3.545	--	1.439	--
3025-1-50	1.020	--	0.364	--	0.709	--	3.040	--	1.918	--
3025-1-26	1.179	0.919	0.452	0.528	3.179	2.151	5.385	4.475	0.959	1.326
3024-7-1	0.873	0.745	0.721	0.754	0.413	0.124	0.556	0.376	9.365	20.252
Seawater	0.837	--	4.354	--	0.005	--	0.111	--	613.29	--

Table 4. Ion ratios in wells sampled in 1995 and 1999.
(1) r=meq/L

The Pliocene deposits are constituted of an alternance of conglomerates, sands and marly clays, outcropping in the northern sector of the depression, to occupy a surface area of some 8 km^2. The Quaternary aquifer mainly comprises the alluvium of the river Fuengirola, and locally colluvial deposits, terraces and beaches. The Plio-Quaternary complex is surrounded by the Alpujárride and Maláguide Palaeozoic deposits, on which they rest and which constitute an impermeable boundary of mainly schistose lithology (ITGE-JA, 1998).

Exploitation of this complex is based on the alluvial Quaternary aquifer, whose resources have been evaluated at 16-23 hm^3/year. Input to the aquifer is estimated at 1.5-3 hm^3/year from the direct recharge of rainfall, 1 hm^3/year from irrigation surpluses and 14-19 hm^3/year from the infiltration of surface run-off. The water output comprises 6.5 hm^3/year extracted by pumping and 10-17 hm^3/year by subterranean discharge to the sea.

The monitoring network established by IGME (fig. 7) periodically records piezometric levels and obtains chemical analyses of the majority ions. This is normally carried out in twice-yearly campaigns.

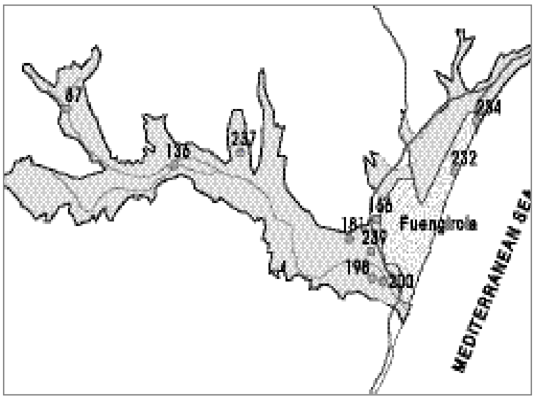

Figure 7. Piezometric and hydrochemical quality monitoring network.

The piezometric campaign of May 1999 (fig. 8) found values to be high, above sea level, due to recharge from the river to the aquifer after a period of heavy rainfall. Nevertheless, the map of piezometric isolines corresponding to October 1999 revealed a generalised piezometric depression at the mouth of the river Fuengirola, extending 2.5 km upstream and with a minimum value of 9 m below sea level.

The evolution of the historic series of piezometric records shows levels had descended significantly, to a minimum value during the drought that finished in 1995, and with a considerable recovery after this, due to a period of abundant rainfall. During the last four years, levels have remained fairly stable, except for seasonal falls at some wells close to the river mouth (e.g. well Nº. 198).

The map of chloride isolines corresponding to November 1999 (fig. 9) reveals a maximum value at well Nº 198, where 497 mg/L was recorded after a period of intensive extraction,

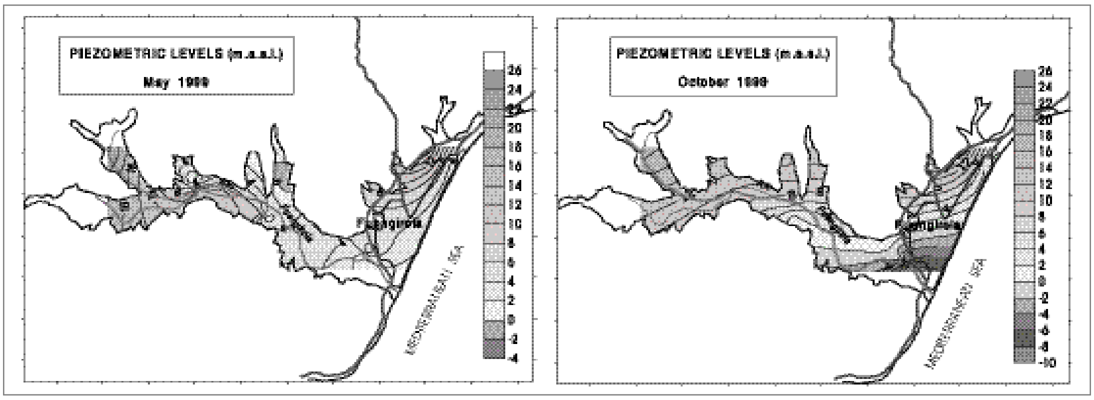

Figure 8. Maps of piezometric isolines after a period of recharge (May) and of exploitation (October).

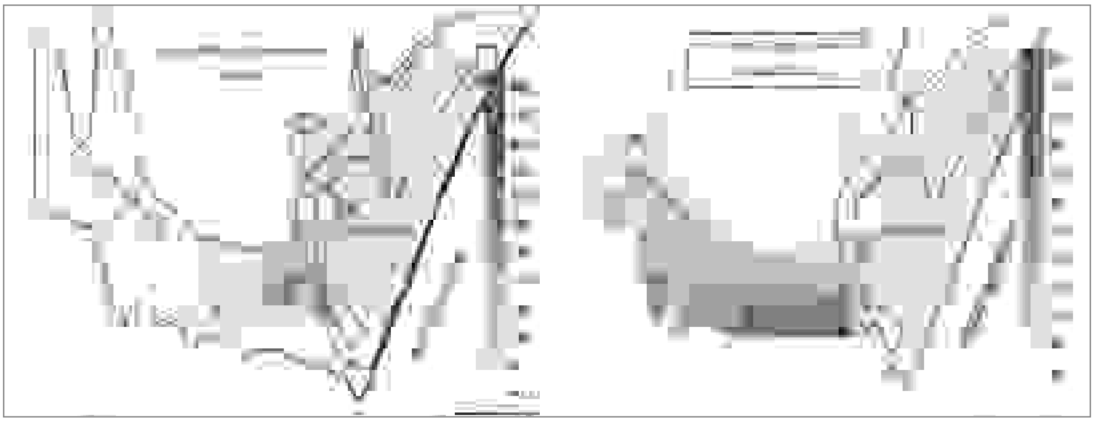

Figure 9. Chloride isolines after a period of recharge (June) and of exploitation (November).

which led to a phenomenon of rising cones of saline water. These concentrations decreased, however, after the recharge period (June 1999).

The maximum historic values were recorded in 1995, after a period of drought which led to 3106 mg/L of chloride content being recorded at well Nº 194 (close to Nº 198). Since this date, concentrations of chloride have fallen.

The predominant water types in the alluvial aqui-fer are calcium-magnesium and magnesium-sodium bicarbonate, which correspond to fresh water, although in well Nº 198, affected by rising levels of salt water, the facies is magnesium-sodium chloride.

The evolution of ion ratios (table 5) shows that the aquifer water contained a significant proportion of sea water in 1995, due to the marine intrusion produced by intensive exploitation during the drought, as well as by an absence of recharge. The values recorded in 1999 show an evolution towards fresh water at most of the monitoring points, except those furthest from the coast (Nº 87 and Nº 136), where the increase in rCl- could be due to another cause.

Sampled Wells	rNa^+/rCl^- (1)		rMg^{2+}/rCa^{2+}		$rHCO_3^-/rCl^-$		rSO_4^{2-}/rCl^-		rCl^-	
	Oct-95	Nov-99	Oct-95	Nov-99	Oct-95	Nov-99	Oct-95	Nov-99	Oct-95	Nov-99
6-87	2.830	0.977	0.902	1.519	0.990	1.014	6.520	2.510	3.611	4.316
7-136	0.771	0.581	2.036	3.646	6.529	3.382	0.912	0.484	0.959	1.721
7-166	-	-	1.857	1.488	1.238	2.043	0.371	1.057	5.219	2.680
7-181	1.061	1.335	2.879	1.955	2.533	2.920	2.216	2.008	3.075	2.313
7-198	-	-	3.141	2.484	0.016	0.359	0.048	0.124	113.681	14.161
7-200	0.609	0.676	3.163	2.898	0.039	1.263	0.251	0.219	78.618	2.764
7-232	0.848	1.428	3.721	1.679	0.026	3.359	0.086	0.760	437.236	1.918
7-234	0.953	1.199	0.994	1.485	0.280	1.785	0.316	1.813	10.494	2.793
7-237	1.076	0.997	2.369	2.316	4.548	4.923	0.563	0.999	1.777	0.959
7-239	0.363	0.962	2.913	3.025	0.749	2.024	0.302	1.209	11.735	4.203
Seawater	0.85		5.08		0.004		0.101		600.93	

Table 5. Ion ratios at wells sampled in 1995 and 1999.
(1) r=meq/L

Analysis of the historical series shows that ma-rine intrusion in this aquifer has a temporary nature (at present, seasonal) due to salt water upcoming (López-Geta *et al.* 1988), as the concentrations of chloride diminish in periods of recharge and of low pumping rates, thus enabling recovery to the quality levels of fresh water.

The Llobregat delta

The hydrogeologic unit known as Baix Llobregat includes the lower valley and delta of the river Llobregat, an area in which it is possible to distinguish three aquifers, each with a different pattern of behaviour, but where the delta, sensu strictu, is the most relevant from the viewpoint of the effects of marine intrusion. At present, much is known about this aquifer, as reflected in the numerous studies of the hydrogeology of the delta carried out since 1960 (Manzano, 1991).

The delta is a tabular structure that has developed over the coastal shelf beneath the Coastal Cordillera. It measures about 60 km^2 of emerged surface, slightly tilted towards the SE. A series of detritic deposits have been identified. These are of Pleistocene – Holocene age and arose as a consequence of variations in the sea level; they are frequently pene-trated by contemporary boreholes and wells. These deposits comprise (Fig. 10):

- Top-level sands of the delta front, intercalated by levels of clays, silts and gravels. Their thickness varies from 12-20 m and in the central zone they are covered by a silt-clay layer no more than 5 m thick. These deposits define an unconfined sur-face aquifer that covers the whole surface area of the delta.
- Lower, prodeltaic silts, somewhat clayey, with a maximum thickness of 45 m at the coast, and which locally contain gravels and sands. This deposit constitutes an intermediate wedge that acts like an aquitard and that individualises the two main aquifers in the central part of the delta. Its thickness decreases progressively until it disappears at each side of the formation and towards the N, enabling the connection of the surface and the deep-level aquifers.
- Alluvial gravels, with a sandy matrix. These comprise a deep-level aquifer that is confined and presents a high degree of lateral continuity. It extends beneath the sea bed and its thickness varies from 3.6 to 11.5 m at the edges (Sant Boi-Castelldefels), where it connects with the surface aquifer to form a single unit. It outcrops some 4 km offshore, at a maximum depth of nearly 100 m (Custodio, 1994).
- The substrate of the delta is made up of two Plio-Pleistocene formations: an upper one, comprising conglomerates, sandstones and clays, with a maximum thickness of 52 m, and a lower, claytype formation. Both formations are highly cemented.

The flanks of the delta are in contact with low permeability Miocene deposits in the Montjuic sector, with Triassic deposits in the area of Gavá, and with Palaeozoic deposits in the San Boi sector, which define the natural boundaries of the unit.

Groundwater flow is preferentially in a SE direction, following the predominant direction of the surface course of the river Llobregat until it penetrates the delta area, where it divides into the two aquifers described above. From this point on, its functioning is differentiated: the hydraulic properties and the piezometry characterise each of the two aquifers independently.

The average transmittivity of the upper aquifer (CAPO-SGOP, 1966) is 500-900 m^2/day in the central zone, but can reach 3000 m^2/day at the edges of the aquifer where it is undivided. The drainable porosity is approximately 0.15-0.20.

For the lower aquifer, transmittivity values range from less than 100 m^2/day to the SW of the airport to over 20,000 m^2/day in the Cornellá sector; the storage coefficient is 10^{-3} to 10^{-5}, while the average porosity is 0.3.

The intermediate aquitard presents permeability values ranging from 0.01 m/day at the aquifer contact points to 0.0001 m/day in the rest of the formation (Iribar, 1992).

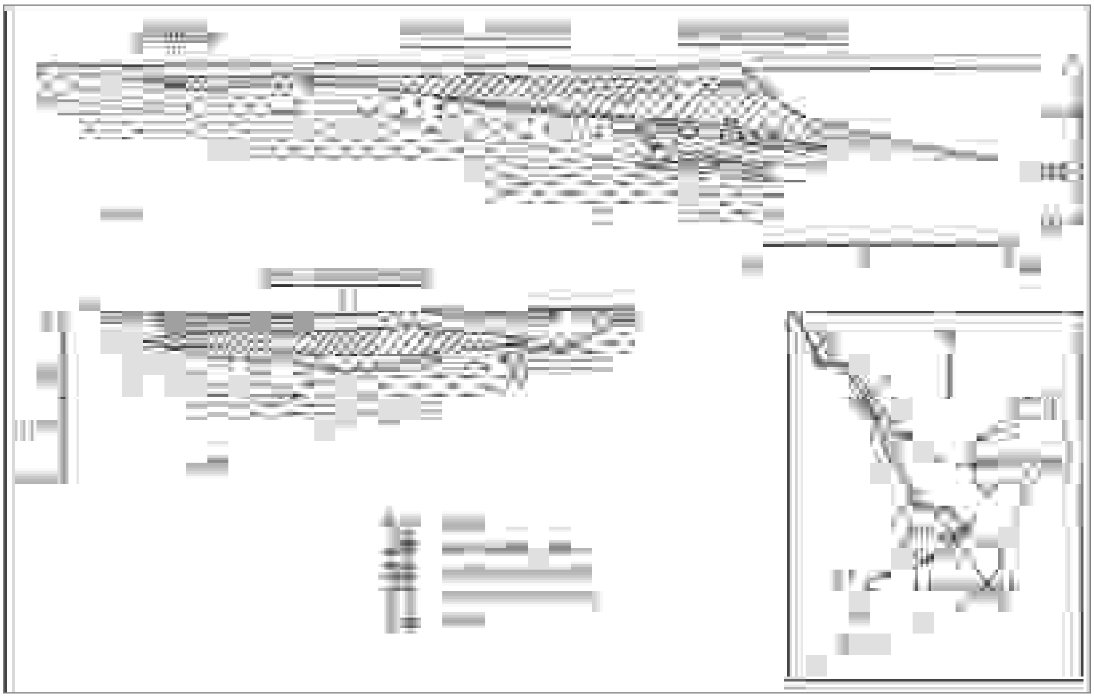

Figure 10. Hydrogeologic cross-section and function diagram (simplified from Custodio et al. 1971).

Recharge of the surface aquifer mainly takes place by direct infiltration from the river Llobregat, from irrigation surpluses and from rainfall, although a small element of recharge should also be included with respect to the losses from urban supply networks and drainage channels in urban areas. The aquifer discharges directly into the sea, by lateral transfer to the deep aquifer, by percolation to the intermediate silt layer and by the drainage of the lower course of the river Llobregat from the Castelldefels motorway. Other, minor, sources of drainage result from canals, ditches and drains. Pumped extraction from this aquifer is sporadic and of small volume.

In the deep aquifer, factors contributing to re-charge include the following: surface water input from the area of the lower valley of the river Llobregat, when this forms part of the undivided aquifer; the direct infiltration of precipitation; the infiltration of irrigation surpluses; losses from canals and water-transport networks, in addition to other lateral inputs or from the surface aquifer itself in lateral zones of the delta. Additionally, we should take into account the infiltration derived from the percolation of the intermediate layer of silts, the water volume introduced by artificial recharge and, finally, water entry from the sea. The only outlets from the lower aquifer at present correspond to the significant levels of pumped extraction for urban and industrial supply.

A simplified water balance of the aquifer has evaluated the recharge of the whole Llobregat delta at a maximum of about 110 hm^3/year (ITGE, 1989), while output, measured exclusively as pumped extraction, had gradually decreased to 46 hm^3/year by 1993 (Vilaró, 1996).

The degree and origin of salinisation varies depending on the lithologic level and the aquifer being considered. The surface aquifer tends to be less salinised than the deep aquifer, such that some wetlands close to the metropolitan area of Barcelona are still of a fresh water type. The coastal strip is normally more affected by marine intrusion.

The intermediate aquitard retains a high degree of natural salinisation, due to the permanence of delta-formation saline waters. Until relatively recent times, this was still undergoing a slow process of washing, due to the circulation of grounwater in the lower aquifer, which because of their higher piezometric level were more conducive to a rising flow (Manzano and Custodio, 1995); nevertheless, this process today has been affected by the inversion of natural hydraulic gradients.

In the deep aquifer, there is a higher degree of salinity than in the surface aquifer, due to an advance of the mixing zone between fresh and sea waters, caused by the extraction of groundwater. Due to the high degree of mixing, this tends to be a gradual transition process between the two water types. The natural routes for the advance of saline penetration are the paleocourses of the river and coarse-lithology Pleistocene deposits (piedmonts and lateral alluvial fans), as well as through other more permeable zones of the western edge of the delta (Custodio, 1994), areas which broadly speaking coincide with the Castelldefels-Viladecans sector and with a large area to the south of El Prat de Llobregat-Airport-Duty Free Zone.

Chloride concentration has risen since 1998 in the salinised central zone, and this is more evident when a long-term comparison is made; increases exceeding one gram per litre have been recorded at certain wells. The reason for this may lie in the sharp jump in groundwater extraction rates in 1998-1999 by the industrial sector and to supply the urban area of El Prat. This fact coincided with a noticeable fall in piezometric levels in the deep aquifer in this zone. Although the result of the latter processes was an immediate increase in salinity in the wells that were furthest from the coast, the effect could extend in the long term if extractions continue at the present rate. The area affected would thus be enlarged in coming years, and wells closer to the coast would be affected.

A series of public works projects are being executed, and others are still at the planning stage, included within the so-called Delta Plan to achieve a socio-economic reactivation of a sector to the S of Barcelona. These actions include civil engineering work in the port and airport of Barcelona, in the river Llobregat and in wetlands. Due to the scale of these projects, they could alter the hydrogeologic dynamics of the aquifers and create a turning point in the evolution of groundwater quality, especially with regard to the surface aquifer. The repercussions on a system that is, in any case, a fragile one should be taken into account in the planning of these projects and in the corresponding studies of environmental effects. All practical steps should be taken to prevent saline intrusion or to limit its advance.

The case of the deep aquifer is somewhat different. This aquifer is highly vulnerable to variations in the rates of recharge and extraction. As the latter is closely related to the evolution of water demand, it is necessary to draw up an appropriate schedule for the future regulation of groundwater extraction in the most highly salinised zone and to prevent the advance of salinity. Moreover, a halt to extractions would imply the disappearance of the barrier effect they exert; increasing recharge into the deep aquifer to counteract the penetration of saline water could also be considered a priority objective. The latter could be achieved by increasing the volume of irrigation surpluses or by reutilising surface water for purposes that were hitherto reserved for ‘clean’ water. This would have a double effect: on the one hand, it would reduce the volume of prime water required (whether surface water or pumped from the aquifer) and, on the other, it would increase the re-charge of surplus resources.

Other actions proposed for zones where marine intrusion is greatest include the installation of hydraulic barriers, appropriately sited along the coastline, to function by means of recharging treated wastewater and simultaneously pumping saline water to force the direction of groundwater flow back towards the sea.

REFERENCES

CAPO-SGOP1966. Estudio de los recursos hídricos totales de las cuencas de los ríos Besos y Bajo Llobregat. 4 vol. Barcelona.

Custodio, E. 1981. Evaluación y causas de la contaminación por invasión de agua marina en los acuíferos de la costa peninsular y en las áreas insulares. In: Proc. Jornadas sobre análisis y evolución de la contaminación de las aguas subterráneas en España, pp. 447-503, CIHS/AIH-E, Bar-celona.

Custodio, E. 1994. Experiencias de salinización de acuíferos: consideraciones generales deducidas de la situación de España. Análisis y Evolución de la Contaminación de las Aguas Subterráneas, T. II, pp 79-110. Alcalá de Henares (Madrid).

Custodio, E., Cuena, J. & Bayó, A 1971. Planteamiento, ejecución y utilización de un modelo matemático de dos capas para los acuíferos del delta del río Llobregat (Barcelona). 1er. Congreso. Hispano-Luso-Americano de Geología Económica, S. 3ª. T I, 171-198, Madrid-Lisboa.

Esteller, M.V. 1994. Consideraciones sobre el aprovechamiento de los recursos hídricos en la Plana de Castellón. Utilización de aguas residuales para riego. Tesis doctoral. 446 p. Universidad de Granada.

Fidelibus, M.D., Giménez, E., Morell, I. & Tulipano, L. 1992. Salinization processes in the Castellón Plain aquifer. In: E. Custodio and A. Galofre (Eds.), Study and modelling of salt water intrusion into aquifers. Proc. 12th Salt Water Intrusion Meeting, pp. 267-284. Barcelona.

Giménez, E. 1994. Caracterización hidrogeoquímica de los procesos de salinización del acuífero detrítico costero de la Plana de Castellón. Tesis doctoral. 390 p. Universidad de Granada.

Grima, J., Custodio, E. & López Geta, J.A. 2002. Papel de los organismos públicos de investigación en la implantación de la Directiva Marco del Agua. Jornadas sobre presente y futuro del agua subterránea en España y la Directiva Marco Europea. Zaragoza.

INE 1998. Nomenclátor 96. Padrón municipal de habitantes. INE difusión, CD-rom.

INE 2001. Anuario Estadístico de España. Madrid.

Iribar, V. 1992. Evolución hidroquímica e isotópica de los acuíferos del Baix Llobregat. Tesis Doctoral. Universidad Politécnica de Cataluña. Inédita.

IGME 1980. Mapa geológico de la Península Ibérica, Baleares y Canarias. E. 1:1.000.000. Madrid.

IGME 1981. Problemática de las aguas subterráneas en la provincia de Castellón. Ministerio de Industria y Energía. Madrid.

IGME 1982. Estudio de los acuíferos costeros de la provincia de Castellón. Proposiciones para la optimización de la gestión integral de sus recursos hidráulicos. Ministerio de Industria y Energía. Madrid.

IGME 1987. Proyecto para el desarrollo del Plan de Gestión y Conservación de acuíferos en las cuencas: Medio-Bajo Júcar y Pirineo Oriental. Piezometría, calidad e intrusión. Madrid

ITGE 1989. Las aguas subterráneas en España. Estudio de síntesis. 600 p. Madrid.

ITGE 1990. Planas de Castellón y Sagunto. Serie: Manuales de utilización de acuíferos. Madrid.

ITGE 2000. Unidades hidrogeológicas de España. Mapa y datos básicos. Madrid.

ITGE-Junta de Andalucía 1998. Atlas hidrogeológico de Andalucía. 216 p. Madrid.

Linares, L. 1997. Situación actual y perspectivas de los acuíferos de la provincia de Málaga. Tierra y Tecnología, 16 y 17: 29-37.

Lloyd, J.W. & Tellam, J.H. 1988. Caracterización hidroqímica de las aguas subterráneas en áreas costeras. In: Proc. 1st Int. Simposium Tecnología de la Intrusión en Acuíferos Costeros, Vol. I, pp. 1-18, Almuñécar.

López-Geta, J.A. 1996. Papel, utilización y gestión de los acuíferos litorales. In: Las aguas subterráneas en las cuencas del Ebro, Júcar e Internas de Cataluña y su papel en la planificación hidrológica. AIH-GE. pp. 169-176. Lleida.

López-Geta, J.A., Parra, J.L. & Rivera, A. 1988. Acuífero costero de Fuengirola (Málaga). In: Proc. 1st Int. Simp. Tecnología de la Intrusión en Acuíferos Costeros, Vol. II, pp. 317-335, Almuñécar.

Manzano, M. 1991. Síntesis y estado actual de los trabajos sobre la hidrogeología del delta y valle bajo del río Llobregat (Barcelona). Hidrogeología, estado actual y perspectiva, pp.203-228. Curso Internacional de Hidrología Subterránea. Barcelona.

Manzano, M. & Custodio, E. 1995. Origen de las aguas salobres en sistemas acuíferos deltaicos: aplicación de la teoría de la cromatografía iónica al acuitardo del delta del Llobregat. VI Simposio de hidrogeología. T XX, pp179-204, Sevilla.

MINER-MOPTMA 1995. Libro blanco de las aguas subterráneas. Serie Monografías, 135 p. Madrid.

Morell, I. 1989. Salinización por intrusión marina. Aspectos teóricos y metodológicos. Aplicación a los acuíferos costeros de la provincia de Castellón. 211 p. Diputación de Castellón. Castellón.

Morell, I., Giménez, E. & Esteller, M.V. 1987a. Ejemplo de utilización de registros verticales de conductividad, temperatura, pH y oxígeno disuelto. Aplicación a los acuíferos de Oropesa-Torreblanca y Moncófar (Castellón). IV Simp. Nac. Hidrogeología, XI: 171-183. Palma de Mallorca.

Morell, I., Giménez, E. & Esteller, M.V. 1987b. Iones minoritarios en los acuíferos costeros de la Comunidad Valenciana (estudio preliminar). II Congreso de Geoquímica, Soria.

Morell, I., Giménez, E. & Esteller, M.V. 1988. Comportamiento iónico y procesos fisico-químicos en acuíferos detríticos costeros de las planas de Oropesa, Castellón y Gandía. (Com. Valenciana). Hidrogeología, 3: 21-33.

Morell, I., Giménez, E. & Esteller, M.V. 1996. Application of principal component analysis to the study of salinization on the Castellon Plain (Spain). The Science of the Total Environment, 177: 161-171.

Vilaró, F. 1996. Las aguas subterráneas en el Plan Hidrológico de las Cuencas Internas de Catalunya. Las aguas subterráneas en las cuencas del Ebro, Júcar e Internas de Cataluña y su papel en la Planificación Hidrológica, pp. 31-36. AIH-GE. Lleida.