ADVANCEMENT OF SEAWATER INTRUSION IN THE LLOBREGAT DELTA AQUIFER

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ABSTRACT

The Llobregat delta deep aquifer is located in the SW of Barcelona Metropolitan Area. It has been intensively exploited for groundwater since 1950. This has produced a potentiometric depression in its central part and the salinization of 30% of the confined aquifer below the delta area. Marine intrusion has been studied since 1965 and the results have been published in previous SWIM editions and elsewhere.

The main aquifer, a confined one, is thin (about 5 to 8 m near the coast) and very permeable, with transmissivities ranging between 1000 m²/day and 10,000 m²/day. The paper refers only to this deep aquifer, about 60 to 70 m below the central coastal area. A wide freshwater-saltwater mixing zone is found with chloride concentrations ranging from 1000 mg/l to 15,000 mg/l, instead of a sharp interface. By comparing the time evolution of chloride content in numerous wells and piezometers, the displacement of the 1000 mg/l Cl⁻ contour line is deduced. Seawater has penetrated inland from the coast following three preferential paths. The plumes always point to the principal abstraction wells of the delta. They are related to sedimentological features of the delta.

The plume in the central part of delta intrudes through a high permeability zone, where the aquifer is clearly confined by a silty wedge. The connection with the sea is located 5 km seawards, at a depth of 100 m. To the east and to the west the aquifer becomes unconfined, and brackish water can penetrate directly from the coastal zone.

The tritium content in water is less than 1 TU in salinized zones, in freshwater pockets trapped between the central and eastern plumes, and in a large freshwater zone between the central and western plumes.¹⁸O and ²H data show that Llobregat river water infiltration is the principal source of recharge of the deep aquifer, and water in the salinized areas is a
Fig. 1.- Simplified hydrogeological sections of the Llobregat river Lower Valley and Delta (modified from MOP, 1966; Custodio, 1981).
mixing of river water with marine water. Hydrochemical studies show the existence of cation exchange during the intrusion process. The Ca$^{2+}$ in the clay minerals is replaced by Na$^+$ and K$^+$ from the brackish water.

1.- INTRODUCTION

The Lower Llobregat (Baix Llobregat) aquifer system is formed by alluvial and delta aquifers situated a few km to the SW of Barcelona (Spain). Their age is Quaternary and they extend over about 100 km$^2$ (fig. 1). Aquifer exploitation started late in the XIX Century in the Lower Valley, mainly for the supply of the town of Barcelona. This was a major source of drinking water supply until 1955, when a large river water treatment plant was put into operation. Since then groundwater exploitation for the supply of Barcelona has decreased and currently the wells and the aquifer storage is used mainly as a strategic reserve for emergency situations, eg. during floods, surface water treatment plant breakdowns, serious river water pollution events or serious droughts. But other local town supplies have been increasing their groundwater abstraction. Intensive use of groundwater for industrial uses dates back to the end of the first quarter of this century and has been continuously increasing, peaking in 1975. The gravity center of abstractions was displaced from the Lower Valley and delta inner boundaries toward the delta centre (fig. 2). The maximum mean groundwater abstraction was 4.5 m$^3$/s, mainly in the 60's and 70's. Afterwards the increasing cost of abstraction due to groundwater level deepening and the advancement of saline water contamination forced the groundwater use to be reduced, and currently mean total uptake is about 2 m$^3$/s. It is continuous for industries and local town supplies, seasonal for agricultural and touristic uses and on an emergency basis for the supply of Barcelona, as mentioned above. Artificial recharge by carefully ploughing the river bed has been practiced since 1945 and by means of deep wells injecting treated river water since 1977.

The importance of the aquifer system justifies that diverse hydrogeological studies, both general and detailed, have been carried out by the Water Authority of the Eastern Pyrenees (now of Catalonia), the Polytechnic University of Catalonia, the International Course for Groundwater Hydrology, the Barcelona Water Works and other enterprises using groundwater from the area. The first study is that of Santa Maria and Marin (1910), but until 1964 there were no new contributions. From this date the studies are numerous and cover a wide range of topics: groundwater resources (MOP, 1966), modelling (Cuena and Custodio, 1971; Custodio et al., 1971, 1989; Iribar, 1985, 1992; Iribar et al., 1992; PHPO, 1985; REPO, 1971), hydrogeochemistry (Custodio, 1968; Custodio et al., 1971, 1991; Peláez, 1983) and general reports (Custodio et al., 1976; Custodio, 1981; Ferret, 1985; Llamas y Molist, 1967; Manzano, 1991).

2.- THE LOWER LLOBREGAT AQUIFERS: HYDRAULIC BEHAVIOUR

Three main aquifers exist in the Lower Llobregat aquifer system: i) the lower valley aquifer, ii) the delta deep aquifer and iii) the delta shallow aquifer.

The Lower Valley aquifer is formed by river terrace coarse gravels and sand, which are highly permeable (100 to 800 m/day). This formation continue below the present morphological
delta towards the coast, where they are at 50 to 70 m depth. To the sides they change to sediments from local creek alluvial fans and beach deposits. All together form the deep delta aquifer. Geophysical data show that this gravel and sand layer, with decreasing thickness, extends seaward and outcrops (directly or through a thin cover of younger sediments) at the sea bottom, about 4 to 5 km offshore and around the 100 m isobate, at least in the central area of the present delta (Serra and Verdaguer, 1983; Manzano, 1986).

The deep delta aquifer is confined by estuary and pro-delta wedge-shaped sediments, that have been quickly accumulating since about 8000 years ago (Manzano et al., 1986). These sediments consist of clay, silt and fine sand, rich in organic matter and with peat layers towards the bottom. They act as an aquitard that presents a very low vertical permeability in the centre, but laterally, towards the inner boundary with the mountain they change into predominatly sandy sediments, which are much more permeable.

Covering this aquitard there are beach and colian sands, old channel gravels and silt from littoral lagoons (albuferes), closed by very recent and even historical sand bars (alfaces). River floods have spread on them a layer of silt, the tradional highly productive cropland, a large part of them now transformed into urban, industrial, service and communication (harbour, airport, train and road) areas. This set is the shallow delta aquifer, mainly a water-table one. It has some hydraulic continuity with the deep delta and the lower valley aquifers in the inner parts, where the aquitard changes into a sand formation.

Figure 3 shows schematically the groundwater flow pattern in the aquifer system, both under undisturbed and under influenced situations. This hypothesis agrees with hydrochemical and environmental isotope data (Custodio et al., 1992).
Fig. 3.- Schematic flow pattern of the aquifer system coherent with hydrodynamic and hydrochemical data.
Under undisturbed conditions the main features are:

a) Current land altitude in the downstream end of the Lower Valley, where it spreads to form the delta and the intermediate aquitard begins, is about +11 m above sea level.

b) Along the Lower Valley, at its downstream end, the river was draining recharge produced by rainfall on the river terraces, infiltration from creeks tributing at the sides and perhaps Llobregat river water infiltration at the upper reaches since the slope is high and the alluvia very permeable.

c) The potentiometric level in the deep delta confined aquifer was enough to allow for freshwater to outflow through the submarine bottom, directly where it outcrops or where the sediment cover is thin. This is true for the central part of the delta, but not for the right hand side, where the deep aquifer potentiometric head is lowered due to the absence of the confining layer.

d) The aquitard produces a confining effect enough to reduce leakage flow to a small quantity in the central part.

e) In a few thousand years all saline water filling the deep aquifer in the central delta has been flushed out and replaced by freshwater.

The disturbance produced by groundwater abstractions, placed mainly at the downstream end of the Lower Valley and at the delta centre, produces a deep potentiometric inverted depression cone that since the 60's has been below sea level along the coastline. At the Lower Valley the water table is permanently below the river channel level, and consequently river water infiltration passes through the unsaturated zone. A few wells are close to the coastline but do not essentially affect the shape of the potentiometric surface. The following essential points are to be considered:

a) The whole Lower Valley is a recharge area. Part of this recharge is taken out by local wells and the remainder goes to the deep delta aquifer, where it is abstracted by the wells there, especially in the central area.

b) The freshwater that was placed between the delta center and the submarine outflow now flows towards the wells in this area, followed by marine water penetrating into the aquifer through favorable zones. The displacement front is changed into a wide mixing zone.

c) Wells near the deepest part of the inverted potentiometric depression cone receive water from both sides, that is to say, recharge from the Lower Valley and groundwater coming from the seaside. These waters mix, in proportion depending on the potentiometric gradient at both sides. After new wells near the coast were put into operation the situation explained before has occurred there too. They have received first the impact of seawater intrusion, and at the same time they protect against salinization other wells sited landward, if they continue to be exploited.

d) The vertical water head gradient in the aquitard favours a downward flow from the shallow aquifer. This flow is only significant at the sandy areas at the delta sides.
Fig. 4. Chloride ion distribution in the Lower Valley and delta deep aquifers in 1965, when the system was already disturbed but with seawater just arriving at the coastal zone. Waters with more than 250 mg L\(^{-1}\) Cl\(^{-}\) far form the sea correspond to young river recharge water polluted by brine disposal into the river, upstream. Water with less than 150 mg L\(^{-1}\) Cl\(^{-}\) are old river waters infiltrated before they were polluted with brines, and contributions from the sides. Coastal saline water represents the first stages of seawater intrusion at the E side (Na\(^{+}\) decreased with respect to Cl\(^{-}\)) and remnants of unfished formation marine water at the W side (Na\(^{+}\) in excess with respect to Cl\(^{-}\)). The lower figure represents the advancement of marine intrusion through more permeable paths, leaving between them old water, less mobile, until it is consumed.
3.- HYDROCHEMICAL DATA ON THE ADVANCEMENT OF MARINE INTRUSION

Hydrochemical studies to define and quantify the flow pattern in the aquifer system, as well as the marine water intrusion situation have been carried out since 1985 (MOP, 1966; Custodio et al., 1991), when groundwater exploitation was already intense and when marine water intrusion in the deep delta aquifer was just reaching the coastline.

Figure 4 shows the chloride ion distribution in 1965 in the Lower Valley and deep delta aquifers and the advancement of marine intrusion through three different plumes. Two of the plumes merge at the delta center, leaving a freshwater pocket surrounded by saline water. Its surface area has been progressively decreased due to groundwater abstractions inside it. The advancement of the 1 g/l isochloride line has been relatively fast in the center of the delta, up to 400 m/year, and the plumes have extended towards the more exploited well fields (figure 2). The saline plume at the center of the delta coincides with the pre-glaciation palaeovalley of the Llobregat river, which is the most permeable part of the deep delta aquifer along the coastal zone. At the eastern boundary of the delta, the deep aquifer is covered by a sandy formation, and sea water penetration is only hindered by the thin muddy deposits on the sea bottom.

At the SW delta boundary highly saline water already existed in 1965, over about 2 km². They were identified as the remnants of an unfinished flushing of marine water by freshwater (Custodio, 1981) since there was a clear decrease of Na⁺ relative to Cl⁻. The low land altitude where the deep aquifer becomes unconfined did not allow enough freshwater head to flush out the marine water, even before aquifer exploitation started. Currently abstractions along the inner boundary have reversed the process and saline water has penetrated towards the main wells of the area.

In the salinized parts of the deep delta aquifer, high permeability, high dispersivity, small aquifer thickness (about 5 m) relative to the flow paths length and a displacement inside a confined area along a large distance without flushing, has produced a very wide saltwater-freshwater mixing zone with small or inexistent vertical salinity stratification.

In order to better understand the mechanisms of marine water intrusion, additional hydrochemical and environmental isotope data were required, from the aquifers as well as from the intermediate aquitard.

The study of the aquitard pore water chemical and environmental isotope characteristics (Custodio et al., 1971; Manzano et al., 1990; Peláez, 1983) shows that connate marine water is present from the top of it down to a depth below which water mixes with fresh water penetrated from the underlaying deep delta aquifer (Manzano et al., 1992). This progressive dilution is explained as the result of the upward water head gradient sustained during a period of 6000 to 8000 years since the aquitard was formed. Pore water has a tritium content undistinguishable from zero tritium units (less than 1 TU).

The study of dissolved ions in the deep delta aquifer water, both the absolute values and
Fig. 5.- Chemical maps of the deep delta aquifer corresponding to the period 1980-1990. a) hardness; b) sulphate; c) ratio rMg/rCa; d) ratio rNa/rK.
Fig. 6.- Advancement of salinization in a delta deep aquifer well (Cal Bitxot), placed in the center of the central sea water intrusion plume. Points represent actual samples and the line the theoretical (closed system) mixing of fresh and marine water, deduced by means of the chloride content.
the ratios between them, confirm that in the salinized areas there is a mixing process of freshwater with marine water in a medium already equilibrated with marine water (fig. 5). Data used in figure 5 corresponds to samples taken over a long time period (1980-1989) since only occasional water samples have been taken. The salinized areas are always associated with high water hardness and high $\text{SO}_4^{2-}$ contents, as well as high $r\text{Mg}/r\text{Ca}$ and $r\text{Na}/r\text{K}$ ($r=\text{meq/l}$) ratios, which are not found in the non-salinized areas. In the wells in which there are differences between the theoretical (closed system) expected mixing of fresh and marine water and the actual mixing (fig. 6), the observed differences are due to cation exchange phenomena. Part of the dissolved Na$^+$ and K$^+$ pass to the sorbed complex in exchange for Ca$^{2+}$. Also, the $\text{SO}_4^{2-}$ content is less than the value expected from the mixing, calculated by taking the $\text{Cl}^-$ as conservative. This sulphate reduction is due to anaerobic conditions in the deep aquifer.

In a small area close to the W delta boundary, near the mountains, high water hardness and sulphate content are found in groundwater with less than 1 g/l Cl$^-$. This is due to infiltration of irrigation return flows and the leaching of building demolition debris used to fill old deep gravel pits.

At the coastal zone of the SW delta boundary the $r\text{Na}/r\text{K}$ and $r\text{Mg}/r\text{Ca}$ ratios follow patterns different to some extent to what is found in the central delta area, due to the reversal of the groundwater flow direction mentioned above (unfinished saline water flushing and later saline water intrusion).

4.- ENVIRONMENTAL ISOTOPIC DATA

In order to better define the groundwater flow hypothesis, some environmental isotope studies have being carried out as part of partial studies, with a few samples at different times (Marqués da Silva and Custodio, 1988; Iribar, 1992). But by putting together these data it is possible to confirm and discuss the groundwater origin.

The tritium content pattern (there is data from several different years) show that there are some samples with a high content in the areas where young waters are to be expected according to their chemical characteristics, such as those showing saline pollution in river recharge water due to potash mining activities upstream. Toward the coast the tritium content falls sharply to values below the measurement error (1 TU). The boundary between the two areas coincides reasonably well with potentiometric minima and the main pumping wells at the delta centre in a position closer to the coast (fig. 7). This confirms the flow pattern hypothesis. Saline water at the marine intrusion areas show unmeasurable tritium content, coherent with the hypothesis of marine water penetrating at about 100 m below sea level around the year 1960. However, it seems that the most saline waters (about 50% seawater) at the well established seawater intruded areas, show measurable tritium contents (1 to 3 TU). These preliminary data, still to be checked, would show sea water already affected by thermonuclear bomb tritium. This means that through the preferential seawater penetration paths seawater may have moved 4 km in 30 years, especially through the offshore part of the delta. This implies a deep delta aquifer mean permeability of 40 m/day, coherent with what
Fig. 7.- Tritium content distribution in TU in the deep delta aquifer water. In the coastal zone values are below the detection limit (1 TU) except in a few points close to the coast, where data from 1992 imply a possible young (post-thermonuclear) marine water. There is no data from the western area.
Fig. 8.- Relationship between $^{18}$O and Cl$^-$ and between $^2$H and Cl$^-$. 
can be expected offshore. This value takes into account the effect of bottom sediments on the submarine outcrop.

Stable water isotope studies \( ^{18} \text{O}, ^{2} \text{H} \) show that fresh groundwater in the Lower Valley aquifer and in the deep delta aquifer have light values, close to those of the Llobregat river, and confirms that river water, from colder and high elevation areas, is the main recharge source (Custodio et al., 1991). Some heavier samples correspond to local recharge by precipitation at the delta boundary, mainly mountain runoff infiltrating in the creek alluvial fans. \( ^{18} \text{O} \) and \( ^{2} \text{H} \) values from salinized groundwater plot on a straight line connecting freshwater with marine water (fig. 8), which means simple mixing with no evaporation processes.

\(^{14} \text{C} \) data does not show the existence of old groundwater, even when tritium content is nil, but for one sample. This shows that residence time in the deep delta aquifer under natural conditions was relatively short, of a few centuries at most, and consequently the hypothesis of submarine outflow of freshwater in confirmed.

5.- CONCLUSIONS

Intensive exploitation of aquifers in the Baix Llobregat area has produced seawater intrusion into the deep delta aquifer. The process has being identified and measured by means of hydrochemical and environmental isotope data. They lead to a flow pattern hypothesis coherent with what is shown by hydrodynamical data. Sea water encroaches through preferential areas, producing saline plumes, and there is a gradual transition from freshwater to marine water, without noticeable stratification and a wide mixing zone.

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7.- REFERENCES


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