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title: **Seawater intrusion control by means of an injection barrier in the Llobregat delta, near Barcelona, Catalonia, Spain**

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INTRODUCTION

The aquifers of the lower valley and delta of the Llobregat

The geological make-up of the Llobregat delta has been well known since the middle of the 20th century (Marqués, 1984; Simó et al., 2005; Gámez, 2007). There is a silt and clay wedge that separates two sand and gravel aquifers: an upper one with thicknesses of 15 meters below current surface, and another aquifer with thicknesses of 10 to 20 meters approximately, which is the main and most important aquifer (Fig. 1). It is confined and very transmissive (1,000 to 5,000 m^2/day). The main aquifer of the Llobregat Delta is primarily used for urban and industrial supply, linked to the Lower valley aquifer that is a strategic resource for supplying Barcelona and its metropolitan area.

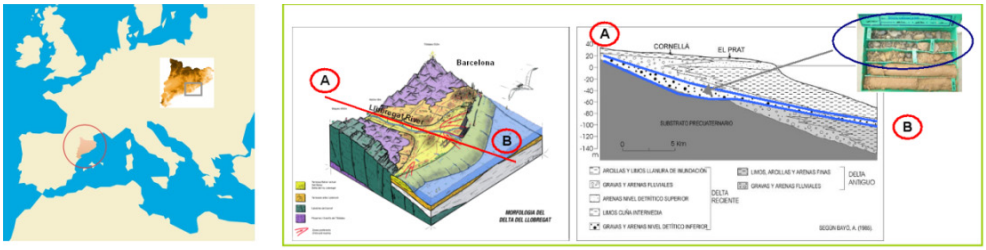

Figure 1. Location and geological configuration of the Llobregat main aquifer.

The seawater intrusion

Seawater intrusion processes have affected the main delta aquifer since the 1960s. The intensive exploitation over time of groundwater resources, along with the excavation of part of the confining layer, has led to the progressive deterioration of groundwater quality (Custodio, 1987; Custodio et al. 1976; Custodio et al. 1989; Iríbar, 1992; Iríbar et al., 1997). The seawater intrusion fronts are advancing along the dock of the port of Zona Franca and along La Ricarda, currently occupying a third of the area of the delta (Fig. 2). Water abstraction counts currently for approximately 54 hm^3/year, but it exceeded 100 hm^3/year the 1970's. The sustainable value to avoid groundwater deterioration is around 40 hm^3/year.

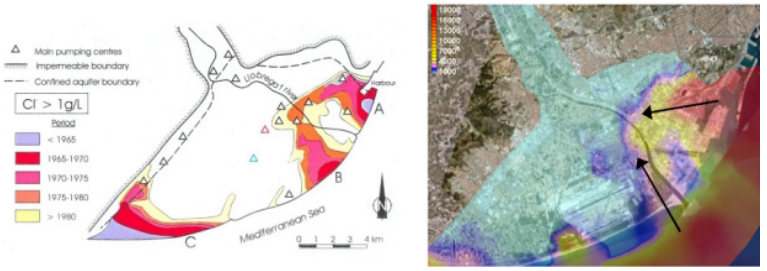

Figure 2. Progress of seawater intrusion (left) and 2007 chloride concentration (right) in the main Llobregat delta aquifer (Catalan Water Agency data). Seawater intrusion currently occupying a third of the area of the delta, and is moving inland from the sea in the direction indicated by the arrows.

Artificial recharge in the Llobregat aquifers

To mitigate the water deficit, the Catalan Water Agency, along with government agencies operating in the same area, Agbar S.A. and the Users' Community, are carrying out various artificial recharge actions and an Extractions Distribution Plan. In the lower valley of the Llobregat, recharge ponds are being constructed in three areas, which will provide a total additional recharge of 6 to 10 hm^3/year, and Agbar is traditionally performing scarification activities in the Llobregat river bed to enhance recharge, as well as direct recharge through injection wells.

THE LLOBREGAT HYDRAULIC BARRIER

The hydraulic barrier project

The most emblematic project to improve the quality of the aquifer is the construction of the positive hydraulic barrier using reclaimed water (Ortuño et al., 2008). The objective is to halt the advance of seawater intrusion. The barrier has being implemented in two phases (Fig. 3). Phase one has been in operation since March 2007 with an injection flow of 2,400 m^3/day in four injection wells. The second phase has a total injection flow of 15,000 m^3/day to 11 injection wells operating since April 2010. There are 17 specific monitoring piezometers with remote-control data systems for water temperature, head and water electrical conductivity. The aquifer monitoring network also includes 13 wells and 7 existing piezometers, covering more than 30 km^2, in order to follow the impact of the barrier.

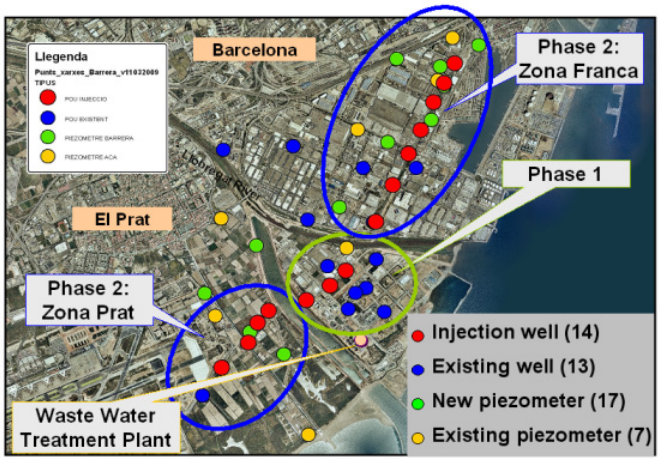

Figure 3. Hydraulic barrier network configuration: injection wells (red) and monitoring points (blue, green and orange). The project has been performed in two phases.

Injection water

The injection is reclaimed water from the El Prat Waste Water Treatment Plant, near Barcelona, and undergoes several treatments. Water is subjected to secondary and tertiary treatment, the latter consisting in ballasted coagulation-flocculation, lamellar decantation, filtration and disinfection. Tertiary treatment is used for the environmental uses: Llobregat river flow increase and wetlands (Cazurra 2008), and to feed the treatment plant of the hydraulic barrier. At the Hydraulic Barrier Plant, ultrafiltration, reverse osmosis (50% of the water) and UV disinfection are

performed, prior to the distribution to the injection wells (Fig. 4). The water quality control is carried out in compliance with the requirements of the Sanitation Authority.

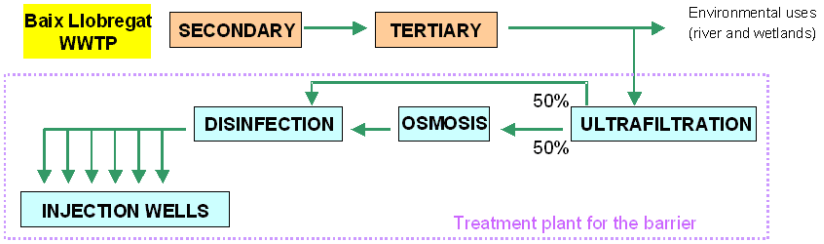

Figure 4. Water treatments prior to its injection in the aquifer. The injection is reclaimed water from the tertiary effluent of the El Baix Llobregat WWTP (Barcelona) and, after being subjected to ultrafiltration, reverse osmosis and disinfection, is sent to the wells.

Investment and exploitation costs

The total investment for the construction of the Llobregat hydraulic barrier amounts to €23M contributed by the Catalan Water Agency, the Spanish Ministry of the Environment and Rural and Marine Affairs, and the European Commission. The total cost of exploitation is €0.28/$m^3$of injected water.

PHASE 1 EVALUATION AND RESULTS

Injected water

Injection of the phase one began on 26 March 2007, and since then around 1,800,000 m^3 of reclaimed water have been injected in 4 injection wells. Some parameters (electrical conductivity, pH and temperature) of the injection water are logged automatically, and bacteriological and physicochemical parameters (BOD, COD, P, N, Cl, NO_3 and TOC) are monitored weekly. Monthly monitoring of major elements, metals, and volatile organohalogenated compounds is performed. The average chloride content of injected water is 347 mg/l, which is similar to that found in aquifers in areas that have not been affected by seawater intrusion. The electrical conductivity of the water is around 1500 mS/cm, and turbidity is less than 0.09 NTU. To date, the presence of coliforms, escherichia coli and nematodes has not been detected in any of the samples. Injection water accomplishes the Drinking Water Quality Regulation requirements.

Well clogging

No change has been noted in the specific flow (flow/head increase) of the four injection wells over the last three years of operation, which would imply that no clogging incidents have been detected. This is attributed in part to the high quality of the water, as reverse osmosis and ultrafiltration prevent physical clogging, and disinfection prevents bacteriological clogging, and in part to the strict cleaning program. The wells are cleaned through the use of electropumps or compressed air once a week.

Aquifer improvement

The analyses and field monitoring of the aquifer show a progressive decrease in the amount of chlorides (Fig. 5), sodium, calcium, magnesium, iron and ammonium, and a slight increase in

nitrates, which are present in the injected water. The barrier clearly has an oxidizing effect on the otherwise highly reducing medium; as a result, different hydrochemical and reactive-transport studies are being carried out to determine if mobilization of metals or another processes taking place. Until now, sodium for calcium ion exchange has been identified, and the injected water is slightly oversaturated with respect calcite. These hydrochemical studies, as well as those carried out to identify clogging processes, are important factors to understand the behavior of the barrier and for a correct management for the complete barrier.

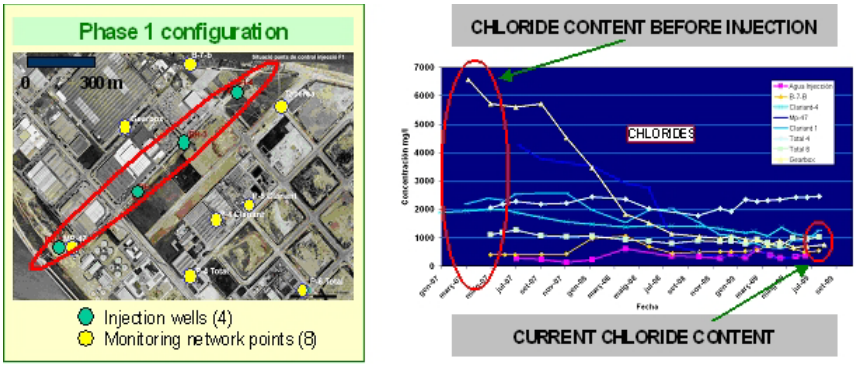

Figure 5. Pilot phase configuration of the hydraulic barrier project and chloride evolution in the monitoring control points between January 2007 and September 2009. Water injection started March 2007.

DISCUSSION AND CONCLUSIONS

A positive hydraulic barrier injecting highly treated reclaimed water into the aquifer has been constructed in order to stop the advance of the seawater intrusion in the main Llobregat delta aquifer. The pilot phase of the project has been working during the last 3 years, showing highly positive results. No clogging has been appeared in the 4 injection wells, and it is attributed to the high water quality, with ultrafiltration, reverse osmosis and disinfection, and to the strict cleaning program. Substantial improvement of the groundwater quality has been also observed in wells surrounding the injection points. This shows that the concept and technology of the hydraulic barrier are able to contain the advance of the saline water fronts. Currently, hydro-chemical studies and modelling are carried out to identify ion exchange, mixing processes or mobilization of metals in the aquifer. These hydrochemical studies, as well as those carried out to identify clogging processes, are important to understand the behavior of the barrier and implement the appropriate management. The results from the two-phase development of this project has been extremely positive in terms of learning from mistakes, calling the different teams, government agencies and business involved to action, thus achieving and improved a better guarantee of success for the future of the entire project.

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