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INTRODUCTION

The Llobregat river lower valley and delta are in the Barcelona's Metropolitan Area, consisting of about 30 km^2 of alluvial valley, up to 1 km wide, and 80 km^2 of delta. The importance of the aquifer system cannot be understated as it is an strategic source of water for the city supply, the industries and the agriculture in Barcelona's surrounding areas. The big development of this area in the 1970's involved intensive pumping that caused both a piezometric depletion and a penetrating seawater intrusion body in the deep aquifer. Aware of the importance of these aquifers, local factories, suppliers and farmers founded the Water Users Community of Low Valley and Delta Llobregat (CUADLL) in the mid 1970's with the objective of protecting and self-managing the groundwater resources (Queralt, 2007).

The final stretch of Llobregat's river is divided in three hydrolgeological units which form three different water users' communities: Abrera's basin aquifer, Castellbisbal's basin aquifer and the Low Valley and Delta aquifers (the administrative limits of each community are shown in Fig. 1).

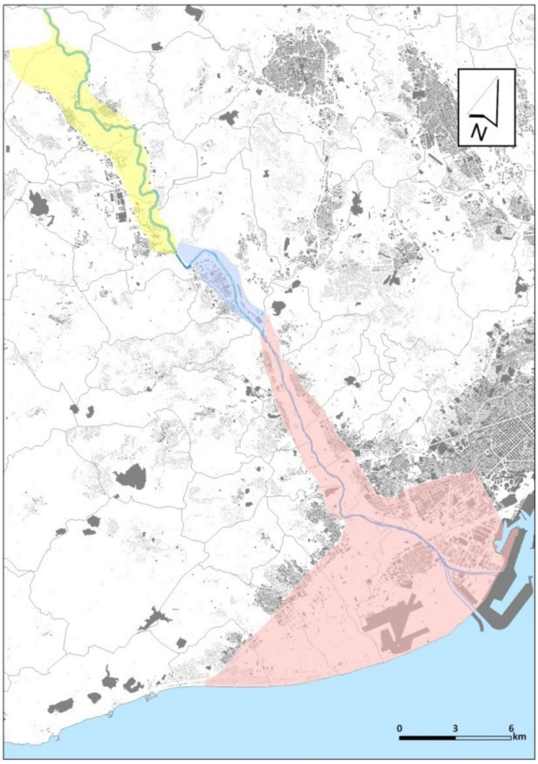

Figure 1. Situation of the different systems of artificial recharge. Different colours show the three different Water users communities (yellow is Abrera 's water users' Community, blue is Castellbisbal's water users' Community and the pink is Low Valley and Delta's water users' Community).

Geologically the delta is formed by a sedimentary package of sands, gravels and clays ranging from Pliocene to Quaternary in age. In the low valley, the aquifer is unconfined while in the delta there are two: the upper one which is unconfined and the deep one which is confined.

Both aquifers are separated by a silty wedge which appears at Cornellà and gets thicker towards the sea (Gàmez, 2008). The low valley and deep delta aquifer is the important one for drinking water and industrial supply in the metropolitan area.

In the last decades, this area has experienced a huge development. With the aim of becoming the main Southern European distribution centre, many infrastructures have been enlarged (the harbour, the airport, metro lines etc…) or constructed (highways, railroads etc...). Furthermore Barcelona and its metropolitan area have increased in size as well as its services areas. All this growth affected the aquifer recharge and led to increase in extraction. Therefore, artificial recharge needs to be done to improve the quality and quantity of water in the Llobregat's aquifers.

CUADLL has assessed the artificial recharge measures' impact by means of numerical models as well (Massana et al., 2007).

Moreover a recharge protocol is being written. This protocol contains quality and quantity variables, economical cost, and the joint viability of the different recharge systems.

ARTIFICIAL RECHARGE SYSTEMS

Due to the strategic value of these aquifers some corrective measures to improve the water's quality and quantity have been projected in the Llobregat's low valley and delta. One example is the hydraulic barrier which has been designed against the seawater intrusion. Others are recharging ponds, scarification and deep injection to compensate the reduced infiltration (Fig. 1).

All the artificial recharge methods will raise the groundwater resources leading to compensate the soil impermeabilization, avoiding the clogging of the river bed, stopping the seawater penetration and achieving the environmental objectives of the European Water Framework Directive.

Scarification

Scarification is a process which induces the aquifer recharge directly through the river bed. It is done upstream, in the upper part of the low valley. This method consists in removing the silty sediments of the river bed with a tractor so that the water can easily be infiltrated through sands and gravels.

This system of recharge has been used since the 1940's by Barcelona's Water Supply Company (SGAB). It is usually done in spring and autumn when the river flow is between 10 and 35 m3/s and the turbidity lower than 150 N.T.U.

Deep injection (aquifer storage and recovery)

Late in the 1960's Barcelona's Water Supply Company (SGAB) built a treatment plant whose surpluses were used to be deeply injected into the aquifer through seven wells of 40 m depth that were designed for collecting. In a second stage, five more wells were drilled specifically for recharging purposes. Nowadays, these thirteen wells are still in use. They pump when it's needed and inject when treated water surpluses exist. The amount of recharged water by deep injection ranges from 0 to 14 hm^3/year, it varies to such extremes because it depends on the availability of the resources.

Recharge ponds

In order to increase the infiltration upstream, there are 3 projects of infiltration ponds in different stages of development along the Llobregat's low valley with the goal of recharging about 15 hm^3/year.

Castellbisbal recharge ponds

The Catalan Water Authority (ACA) and the water users' community of Castellbisbal (CUACSA) signed an agreement in 2002 to rebuild some old basins existing from the mid 1980's, and to transfer the exploitation and the maintenance of them from the former to the latter.

These ponds were inaugurated in April 2010, and consist of 14.000 m^2 of wetland surface and 6.000 m^2 of infiltration pond. Total amount of recharge predicted is 1.8 hm^3/year. The recharged water is collected from the river and in the interconnection of the two basins there's a control station which has been programmed to automatically take water samples at a pre-set frequency to check the water quality (amount of ammonia, conductivity and turbidity). When the water sample isn't up to set standard, the station is programmed to automatically close the interconnection floodgate by itself.

Another agreement was signed between CUACSA and the Spanish Geological and Mining Survey (called IGME) for a research and development project related to these ponds.

Sant vicenç dels horts recharge ponds

As a compensatory measure for impermeabilizing the area during the building of the Baix Llobregat's highway a recharge ponds of 1 Ha were constructed in Pallejà. Shortly after that, those same ponds were taken out of commission due to the fact that they lay directly where the high speed train railway (AVE) was to be built. So, Spanish railway infrastructures administrator (ADIF) was required to build the Sant Vicenç dels Horts basins on the right river bank in 2004.

The sedimentation pond is upstream with a surface of 4.000 m^2 and the infiltration pond is downstream and has 5.000 m^2. There are three possibilities for the sources of the recharged water. It can come directly from the river or when due to a draught or bad quality, there are 2 sources of regenerated water: from Reversible Electrodialysis Plant in St Boi or from El Prat's Waste Water Regeneration Plant. When coming from a plant, the water can be poured directly into the infiltration pond as the sedimentation process becomes unnecessary.

In March 2009, CUADLL made an infiltration test in these ponds. During the test the water recharged was diverted from the river through a pipe. The volume provided was 422,568 m^3 in 78 days, which results in a calculated infiltration rate of 1.08 m/day (1.98 hm^3/year). One conclusion of this test is that due to sedimentation while in the pipe, most of the turbidity of the water disappears by the time it gets to the sedimentation pond. Another finding in the test is that in order to obtain a constant rate of infiltration, a higher water column in the infiltration pond is needed over time. That is to say, the infiltration pond is affected by a clogging process. Figure 2 shows how the infiltration (divided by the water column height in order to see it properly) decreases over time, by more than half in three months.

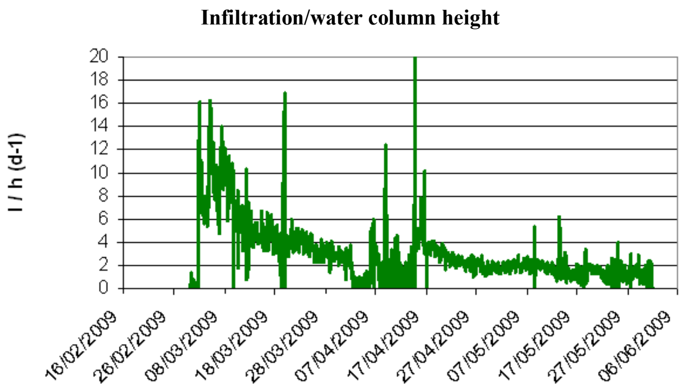

Figure 2. Infiltration rate observed during the test. It decreases by more than half in during the test due to a clogging process.

Santa coloma de cervelló recharge ponds

CUADLL signed an agreement signed with the Catalan Water Authority (ACA), the Environmental department of the Catalan government (DMAiH), Environmental Entity of the Metropolitan Area of Barcelona (EMSHTR) and Barcelona's Water Company (AGBAR) to build the recharge ponds in the Santa Coloma de Cervelló area. All the preliminary studies needed to create the project have been completed and the ponds will go into construction in 2011.

The geologic and geophysical characterization is one of these aforementioned preliminary studies. It was done by means of tomographies and test drillings interpretation. More than 30 test drillings were done, and 22 of these tests drillings were preserved as piezometers, configuring the monitoring network for the test and for the future recharge system. As a result of these studies, a geological interpretation of the media was obtained concluding that the clay and silt layer present in Santa Coloma area is thicker in the downstream direction (Figure 3).

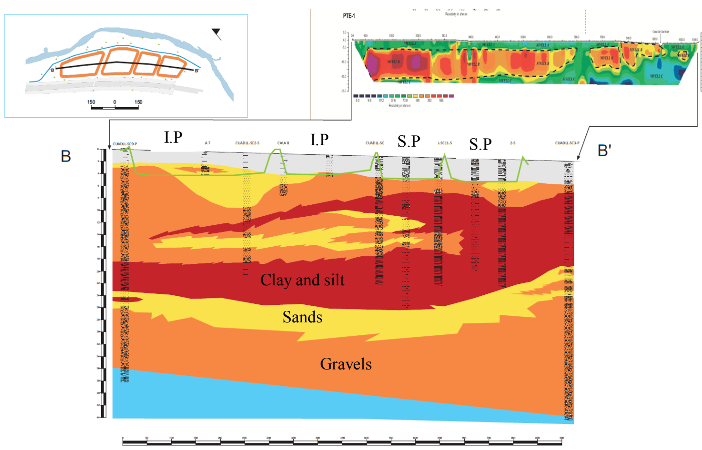

Figure 3. Tomography and geological cross section with the basins profile overlapped. The 2 sedimentation ponds (S.P) are located downstream. This is because of the type of dirt, which is more impermeable downstream than upstream. Clay and silt layer is thicker in that direction, for that reason the basins are projected upside down.

For that reason the basins are projected upside down: infiltration ponds will be located upstream of the area, and the sedimentation ponds downstream where the vertical hydraulic conductivity is smaller.

Two different kinds of infiltration tests were done. The first one was by means of infiltration rings at 2 or 3-meter depth aimed to learn the behaviour of superficial layers (seven tests in different locations).

The second kind of infiltration test was by means of pilot ponds at the depth of projected ponds. Two small ponds of 150 m^2 were dug in different places. These tests' results were used by the hydrogeologic model to calibrate hydraulic parameters of the vadose zone, especially vertical hydraulic conductivity. The infiltration rate deduced from these tests ranged from 1 m/d (in the fist pilot pond) to 10 m/d (in the second). The big difference is due to the location of each pilot pond, thus exactly where the future infiltration ponds will be located is very important.

We built a hydrogeologic model of the area and modelled 2 sections: transversal and longitudinal related to the river. The most important conclusion drawn from this model is the minimum infiltration rate, which would be around 8 hm^3/year (Luna et al., 2009). This rate is between the two values obtained from the pilot ponds. The model also foresees that only a 5% of the infiltrated water would flow towards the river.

As the model, the pilot ponds and the geologic characterization all indicate, the local flow induced by the infiltration is in the upstream direction, due to the clay layer's shape: water flow doesn't infiltrate vertically through clays, but it flows over the clay layer until its end, where it infiltrates through sands and gravels.

HYDRAULIC BARRIER

The seawater intrusion appeared in Llobregat's delta in the 1970's. While constructing Barcelona's harbour, the impermeable layer that separates the aquifer and the sea was excavated, so the seawater moved inland. The hydraulic barrier was created to raise the groundwater head near the coast to avoid seawater penetration.

The first stage of the hydraulic barrier consists of 4 wells in the delta's area that inject water into the aquifer. It started in March 2007 with an injection flow of 2.500m^3/day. Injection water comes from El Prat's Waste Water Treatment Plant after several advanced treatments: ultrafiltration, UV disinfection and reverse osmose (50%). This pilot stage has 8 points of monitoring network that have shown an improvement of the groundwater quality (Ortuño et al., 2009).

Nowadays, a second stage of this hydraulic barrier is in trial. It consists of 14 wells with a total injection flow of 15.000 m^3/day.

CONCLUSIONS

Water management is quite complex due to the urban and industrial development of the Llobregat's area and the resulting large number of infrastructures built (roads, railroads, airport, large harbour and its service areas...). This development has a negative affect on the aquifer recharge, since they increase surface runoff, modify groundwater flow, and discharge contaminants. Artificial recharge done by SGAB since the 1970's (scarification and deep injection) is not enough and needs to be increased.

For all these reasons and in order to increase available water resources, three artificial recharge ponds are planned in the low valley and delta area. These 3 ponds each are in a different stage: Castellbisbal's recharge ponds were inaugurated in April 2010; Sant Vicenç dels Horts ponds are ready to recharge and in Santa Coloma de Cervelló recharge system all the preliminary studies have been completed and the ponds will be constructed soon. Moreover the brand new hydraulic barrier against seawater intrusion is presently in trial and will contribute 5.5 hm^3/year to the aquifer. In fact, Llobregat's area is probably one of the places in the world with more variety of recharging methodologies.

In order to regulate all the technical specifications of the artificial recharge, ACA and CUADLL are writing a recharge protocol for the different recharge systems. The quality parameters of the recharged water will also be considered in this protocol.

By 2012, all these measures working together will mean a total volume recharged of 24 hm^3/year, which is almost half of the annual extraction in the low valley and delta. This volume artificially recharged will guarantee the quality and the quantity of the Llobregat's aquifers and will achieve the environmental objectives of the European Water Framework Directive.

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