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5.1
Modelling as a tool of groundwater assessment

title: **The use of numerical model in the Delta Llobregat Aquifer focused in planning and management**

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INTRODUCTION

Llobregat's Delta Aquifers, near the city of Barcelona, are an important water source for urban, industrial and rural uses. Extraction above recharge in the 70's, and the proximity to sea, caused a significant saline intrusion. Increased awareness of the importance of conserving resources combined with worsening water quality lend to a progressive reduction of pumping and consequently an increase of piezometric heads and a decreased rate of seawater intrusion. Unfortunately at same time the recharge of the aquifer through infiltration has decreased due to urbanization and the construction of big infrastructures. Therefore the mass balance continues to be negative. For this reason a hydraulic barrier has been built to impede seawater intrusion, and two recharge basin systems have been built, with a third (the bigest) on the way, to compensate for the reduced infiltration. Presently the two basins systems aren't running yet, although they are ready. A first phase of the hydraulic barrier has been running for two years, at an injection rate less than a 30% of total planned injection, and a second phase is ready to start.

At present the total volume of extractions from these aquifers are approximately 60 hm^3 a year, of which more than 60 % corresponds to water supply companies.

A numerical model of flow and transport of low basin aquifers of Llobregat River was done in 2004 by Hidrogeology Group of Technical University of Catalonia (UPC). The model was built with their own code TRANSIN III (Galarza et al., 1995) at the request of the Catalan Water Agency (ACA) and covers the period of 1965–2005. The objective of this project was an accurate understanding of the hydraulic behaviour of the aquifers taking into consideration management and planning. The Llobregat Delta Community of Water Users (CUADLL) was given that model in order to examine it, update it and improve it as well as to take part in the aquifer's management and planning.

In this way CUADLL has the model ready to be used for different objectives, as needs come up. For example the model has been used to assess the impact of the artificial recharge measures on the aquifer and as a technical support for the Extractions Plan of Llobregat Delta and Low Valley Aquifers (Massana et al.). In this last work, a lineal relationship between recharge (natural and artificial) and extractions has been found, taking into account a sustainable condition to reduce salinity in the aquifer.

From the middle of 2007 through May 2008, the Llobregat basin suffered a serious drought. One of the measures taken against the drought was the recovery of some wells and the increase of pumping. CUADLL became concerned about the likely worsening of water quality from the aquifer. For that reason CUADLL used the numerical model to foresee the consequences of drought on the aquifer, and try to prevent possible problems.

DROUGHT SIMULATIONS

During the drought 2007–2008 of Llobregat basin, Water Agency of Catalonia ordered a set of exceptional emergency measures related to uses of hydraulic resources (Drought Order 84/2007 by Catalonian Administration). In this context and due to limited superficial resources, some of the measures were focussed on the necessity of increasing resources from aquifers. This exploitation had to be done according to the piezometric heads of aquifers. The indicator (N) is defined as the sum of the piezometric heads of five piezometers distributed along Low Valley until Prat de Llobregat (Fig. 1).

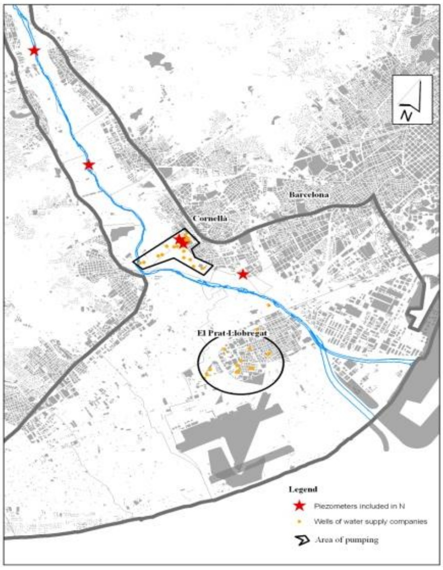

Figure 1. Situation of piezometers included in indicator N, and the water supply companies' pumping areas.

A piezometric state for every month is defined according the value of the indicator N by means of statistical methods, as shown in Table 1. On April 1 2008, N was equal to –20.4, and the aquifer was in State 1, very close to State 2

The Drought Order imposed a volume of extraction for Water Supply Company of Barcelona (SGAB) according to the piezometric state: 2 m^3/s if N corresponding to State 1, 1 m^3/s if N corresponding to State 2, and 0.5 m^3/s if N corresponding to State 3.

Table 1. Threshold values of piezometric state of aquifer by month.

	State 1	State 2	State 3
January	-17	-22	-32
February	-13	-22	-32
March	-12	-22	-34
April	-11	-21	-33
May	-12	-22	-30
June	-14	-24	-30
July	-11	-24	-30
August	-15	-23	-30
September	-12	-23	-29
October	-16	-22	-32
November	-11	-21	-30
December	-14	-19	-27

In this context Cuadll has carried out some simulations by means of the numerical model with the objective of bringing forward the piezometric evolutions.

An update of the model through February 2008 has been done. Figure 2 shows the calculated versus measured piezometric heads of two piezometers. It's important to note that the calculated values are simulated values, not calibrated values.

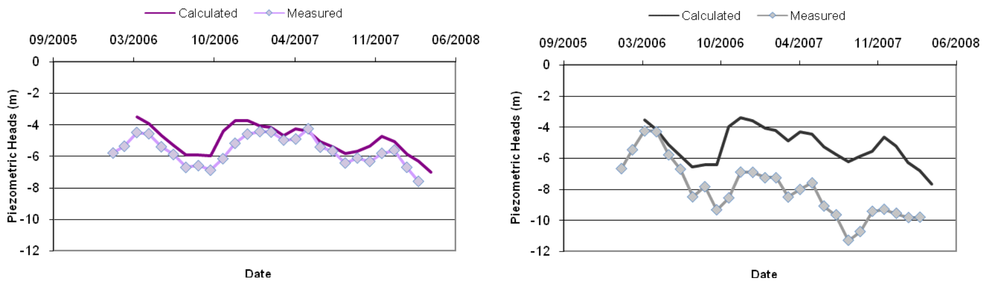

Figure 2. Calculated by simulation versus measured piezometric heads of piezometers Testimoni and Fives Lille. Note that there is a good relationship between simulated values and measures in piezometer Testimoni, and in piezometer Fives Lille only the form of evolution is well simulated.

A desirable relationship between simulated values and measures can be seen at some points. At other points only the form of evolution is simulated, and there are significant in values of piezometric heads. Despite the factor that the model has been shown to give relatively accurate results on a regional scale, on a local scale, its results aren't quite as accurate as we might hope. Furthermore, the model tends to produce results that are less dramatic than reality. Therefore in order to avoid an accumulation of errors some corrections have been carried out to better represent the evolution of simulated piezometric heads.

To continue the simulation from March 2008, the pumping has been changed according the Drought Order standards. The results are shown in Table 2 and Figure 3.

Table 2. Results of simulated indicator N, and the state of aquifer.

	N Simulated	State	Drought Order Pumping (m^3/s)
March	-18.28	1	2
April	-20.99	2	1
May	-23.14	2	1
June	-25.32	2	1
July	-28.28	2	1
August	-30.73	3	0.5
September	-29.74	3	0.5
October	-27.78	2	1
November	-30.15	3	0.5
December	-30.65	3	0.5

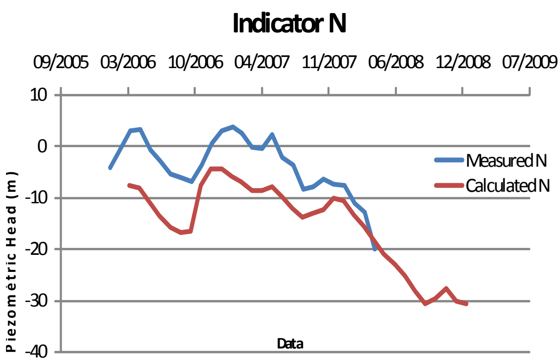

Figure 3. Simulated evolution of indicator N.

According to simulation results, indicator N enters into State 2 in April and, in spite of a reduction in pumping, N continues its fall until it enters into State 3. Then the reduction of pumping according Drougth Order allows ascension out of State 3, but of pumping increases again for just one month more because N enters into State 3 again. We have to be prudent with these conclusions. In fact, due to the model's tendency produces less dramatic results as was mentioned earlier, changes in N in piezometric state can be off by a month or so. This means: simulation results give us a superior temporal threshold of N value.

On the other hand it's important to note that while pumping is $1 m^3/s$ N decreases, and while pumps are $0.5\ m^3/s$ N increases. Thus N could be stabilized for pumping between 0.5 and $1\ m^3/s$. A similar conclusion was reached through other means in a separate project carried out for the Extraction Plan of Llobregat Delta and Low Valley Aquifers.

SUSTAINABLE EXTRACTIONS

The Drought Order is based in restricting pumping according to piezometric heads. In our aquifer, as has been discussed, the main problem is saline intrusion. Therefore the next step to take is the assessment of salinity evolution in application of Drought Order.

During work carried out by CUADLL as technical support for the Extraction Plan of Llobregat Delta and Low Valley Aquifers, a lineal relationship between recharge (natural and artificial) and extractions has been found, imposing a sustainable condition to reduce salinity in the aquifer (Massana et al.). At present, to satisfy this relationship with the current artificial recharge, supply companies pumping should be 50% less than pumps in a normal hydrological year, and much less than pumping of Drought Order for States 1 and 2.

In most of the simulations carried out by CUADLL, taking into account the currents conditions of artificial and natural recharge, and for any volume of supply companies extractions below $2 m^3/s$, a division of the aquifer in two areas is possible: an area in which chloride concentration declines relative to initial concentrations, and another in which chloride concentration increases (Fig. 4).

Figure 4. The two areas in which aquifer can be divided due to its improving or worsening of chloride concentration relative to initial concentration.

The first area corresponds to where the most important industries, especially the supply companies, are located. The second area is located near the sea, and its initial concentrations in its control points are quite high yet. Note that there is a small zone in the middle of the second area that corresponds to the surrounding of current hydraulic barrier.

In this context, the idea is to change the sustainable condition to manage the aquifer in the short term while the artificial recharge isn't fully implemented.

So the question is: at what level should supply companies' pumping be set at in order to ensure that the final chloride concentration at the end of simulation is less than 400 mg/L (recommended chloride concentration in our aquifer)? Five simulations over forty years have been carried out to answer this question: supply companies pumping equal to 20 hm^3/year, 30 hm^3/year (the normal scenario), 40, 50 and 60 hm^3/year. Note that last simulation corresponds to maximum extractions as stipulated Drought Order. The results of these simulations are summarized in Figure 5 where three areas are defined:

- Blue zone: chloride concentrations are less than 400 mg/L for any volume extraction. In other words, this zone fulfills the recommended chloride concentration with pumping of State1.
- Red zone: chloride concentrations are over 400 mg/L for any volume extraction. This zone, at present conditions, never fulfills the recommended chloride concentration. Fortunately the second step of hydraulic barrier is coming soon, and the previsions are that the eastern area of delta will improve (as we have assessed by means of simulations as well, in other projects).
- Green zone: chloride concentrations are less than 400 mg/L when volume extraction is less than the indicate pumping beside the points in the figure. Note that there are maximum volumes that don't correspond to any simulation. That is because the final concentration is not exactly 400mg/L. Another division of blue zone is done: a subzone that fulfills the recommended chloride concentration with pumping of State 2 (pale green), and the other that fulfills the recommended chloride concentration only with pumping of State 3 (Dark green).

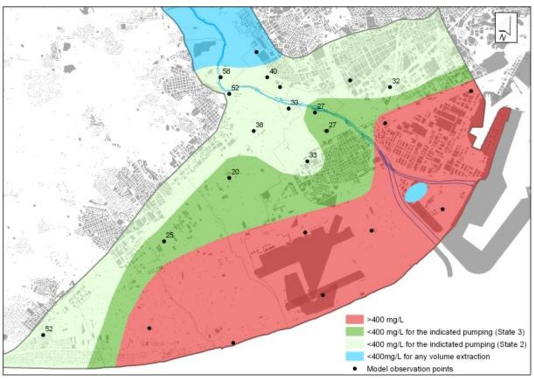

Figure 5. Aquifer can be divided according to the final chloride concentration: blue area in which chloride concentrations are less than 400 mg/L for any volume extraction; red zone in which chloride concentrations are over 400mg/L for any volume extraction; and green zone in which chloride concentrations are less than 400 mg/L when volume extraction is less than the indicate pumping beside the points.

Figure 5 gives us an idea of the consequences of variation of supply companies' pumping. In fact the indicate extraction beside the points shows the maximum extraction volume, that over this value, the quality water in each point tends to have values over the recommended value. The following conclusions could be deduced from Figure 5: only one area of Water Supply Companies fulfills the recommended chloride concentration for any pumping; and a huge area of Delta will be more than 400 mg/L with currents extraction (normal scenario, 30hm^3/year for supply companies pumping). Thus it's important to be conscientious of extractions in periods of drought as well.

CONCLUSIONS

According to simulation results, indicator N could be stabilized for pumping between 0.5 and 1 m^3/s. As earlier discussed, a similar conclusion was reached through other means in a separate project carried out for the Extraction Plan of Llobregat Delta and Low Valley Aquifers, where pumping, with a imposed sustainable condition to reduce salinity in the aquifer, is little higher than 0.5 m^3/s. Therefore the model would be use to correct or strengthen the method of N indicator and pumping according to the piezometric states, taking into account the evolution of salinity levels.

Due to the behaviour of the model in dramatic situations, simulation results give us a superior temporal threshold of N value.

With current artificial and natural recharge, only one area of water supplies companies pumping fulfills the recommended chloride concentration for any pumping. And with currents extraction (normal scenario) as well, it can observed that in some areas there is an improvement in chloride concentrations, but a huge area of Delta will have chloride concentrations above the recommended level (400 mg/L), or even a decline in water quality. Furthermore, the map of Figure 5 is an important management tool because it shows where water quality fulfills the recommended level and where not at a specific extraction volume.

Therefore at current extraction and artificial recharge, there is a huge area of delta whose quality water is not improving. Thus the European Water Framework Directive in this aquifer won't be fullfilled. Furthermore, as seen, in drought situations extractions may even increased. Fortunately, the second phase of hydraulic barrier is starting, and two of the three systems basins are ready to work. Thus it's very important to implement the planned artificial recharge as soon as possible.

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