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NUMERICAL MODELLING AS A PREDICTIVE TOOL TO GROUNDWATER MANAGEMENT EVEN WITH LIMITED DATA (GIRONA, SPAIN)

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Abstract: Quantifying groundwater resources may be a difficult task depending on the availability of phenomenological data and the robustness of the proposed conceptual model. This was the case of the Plioquaternary aquifer of the Girona and Salt Plain (Catalonia, NE Spain). However, the Catalan Agency of Water, which is the organism responsible for the management and planning of the coastal, surface and groundwater in the so-called Inner Catalan Basin, decided to gather all data and to develop a groundwater flow model with the aim of improving the quantitative understanding of this aquifer.
When building-up the model, it was hard to characterise the detritic multilayer aquifer associated to the Selva Depression. The initial simulations showed that implementing the only relevant pumping wells identified within the area (106 m3/yr for industrial use) caused a regional groundwater head drawdown of the order of 10-15 m, reaching thus 3-4 km distance. This response posed the question about the sustainability of exploiting 3 new human supply wells that were drilled to mitigate droughts affecting surface resources and the constraints that should be imposed on their pumping regime in order to prevent negative impacts.
Given these results, it was decided to conduct a one-week pumping test in which the 3 wells would achieve up to 240 L/s with the objective of verifying the regional effects foreseen by the numerical model. The test was carried out during the spring season and definitely corroborated what the model had shown: a metric head drawdown at the whole aquifer domain.
These sequence (integrating data – formulating a preliminary numerical model – conducting a field test to verify numerical results) has proven very effective to obtain realistic results. Now, a more accurate pumping regime has been determined for the reserve human supply wells that limits their abstraction rates as a function of the availability of surface resources, i.e. to define an objective contingency plan for such reserve wells

Key words: Girona Plain Plioquaternary aquifer, prior groundwater flow modeling, pumping test for validation, draught reserve wells, contingency plans.

1. INTRODUCTION

The Catalan Agency of Water (the Agency) is the organism responsible for the management and planning of the coastal, surface and groundwater in the so-called Inner Catalan Basin, in NE Spain. In 2008, the Agency decided to bring into service three deep wells drilled in the Girona Plain plioquaternary aquifer (Figure 1) due to the intense drought affecting Catalonia during 2007 and 2008. This formation is relatively unknown but eventually it could provide drink water in times of emergency, according to preliminary information. However, long-term pumping effects at rates as high as 240 L/s were not known and had to be determined prior to establishing an adequate pumping regime.

The Plioquaternary aquifer is an extensive formation filling the Selva's Depression with tertiary detritic and quaternary alluvial materials that are locally connected. It may be defined as a multilayered heterogeneous system containing high levels of clays but also sand and gravel deposits up to 20-25 m thick, so it is quite transmissive in some areas.

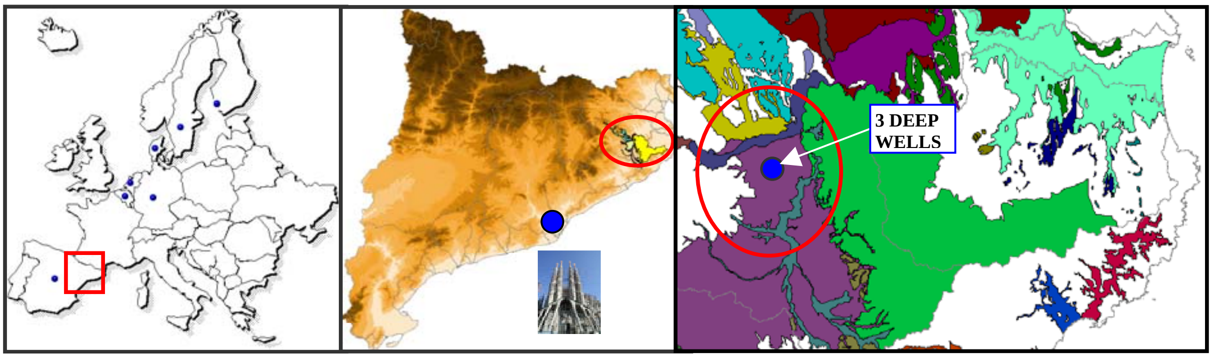


Figure 1: Location of Girona Plain Plioquaternary aquifer, 100 km NE Barcelona, in NE Spain.

Quantifying groundwater resources may be a difficult task depending on the availability of phenomenological data and the robustness of the proposed conceptual model. However, the Agency decided to gather all data and to develop a groundwater flow model, based on several hypothesis due to the lack of hydrogeologic information. The main goal was improving the quantitative understanding of this aquifer but also determining sustainable extraction regimes.

2. DEVELOPING THE FLOW MODEL

The conceptual model is based on a simplified previous model and on limited information about wells, extraction, lithologies, and some quantitative parameters.

A previous 2D steady state numeric model had been developed to simulate the more superficial layer of the Plioquaternary aquifer in order to evaluate the High Velocity Train impact on this formation.

Besides, only one pumping test was available and some lithological columns where it is possible to distinguish one shallow and another deep formation, sometimes separated by a low permeable unit. In global terms, the deep aquifer shows a confined behavior and would be recharged by the upper formation, according to available data.

The final groundwater flow model[1] was implemented in Visual Transin 1.1 code (r65), which is a pre- and post-process system based on code TRANSIN[3]:

- Quasi-3D 3 layers model with an extended domain for the deep aquifer (Figure 2), represented by layers 2 and 3. The recharge is estimated from meteorological stations.

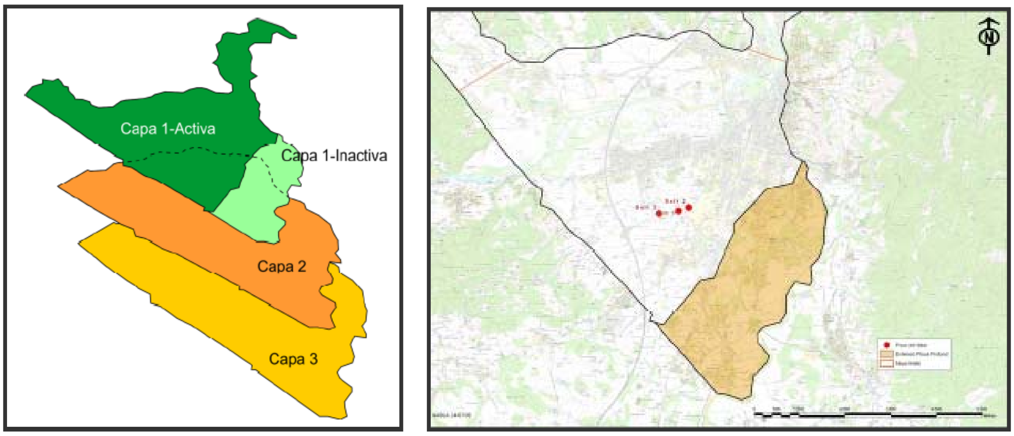


Figure 2. Quasi-3D new model[1] scheme (left), which implies extending horizontally the previous model (layer 1, right) and adding layers 2 and 3 to simulate the multilayer behaviour of the deep aquifer. Also, a transient regime was implemented.

- Hydraulic conductivity obtained from the only pumping test carried out in the deep aquifer (layers 2 and 3, Figure 2). A thickness map of both (shallow and deep) aquifers was also done (Figure 3), which allowed to compute transmissivity values in each cell, with a maximum value of about 300 m^2/day.
- Adding extraction from the deep aquifer ($1{,}30\cdot10^6$ m^3/year) and the shallow layer ($0{,}13\cdot10^6$ m^3/year)
- Refining the mesh near the 3 supply wells and extending it to the new areas (Figure 3).

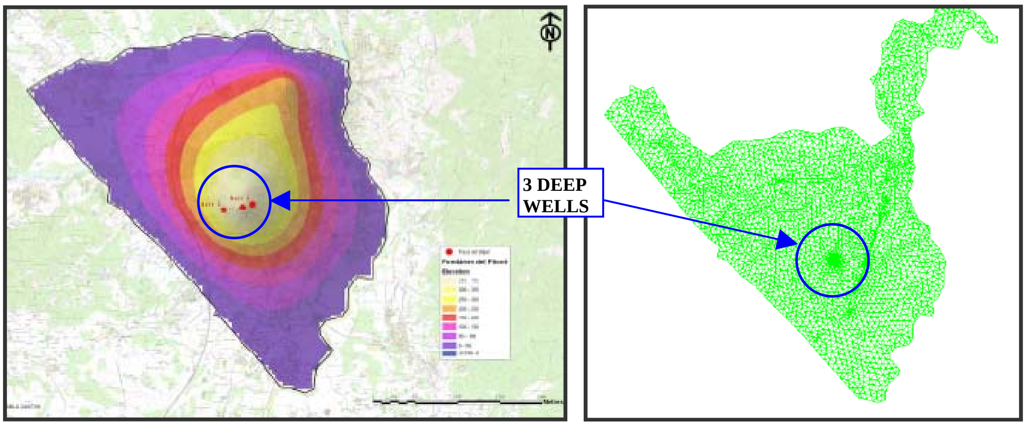


Figure 3: The 3 deep wells in a map showing the thickness of layer 3 (left) and a view of the mesh, refined around them (right).

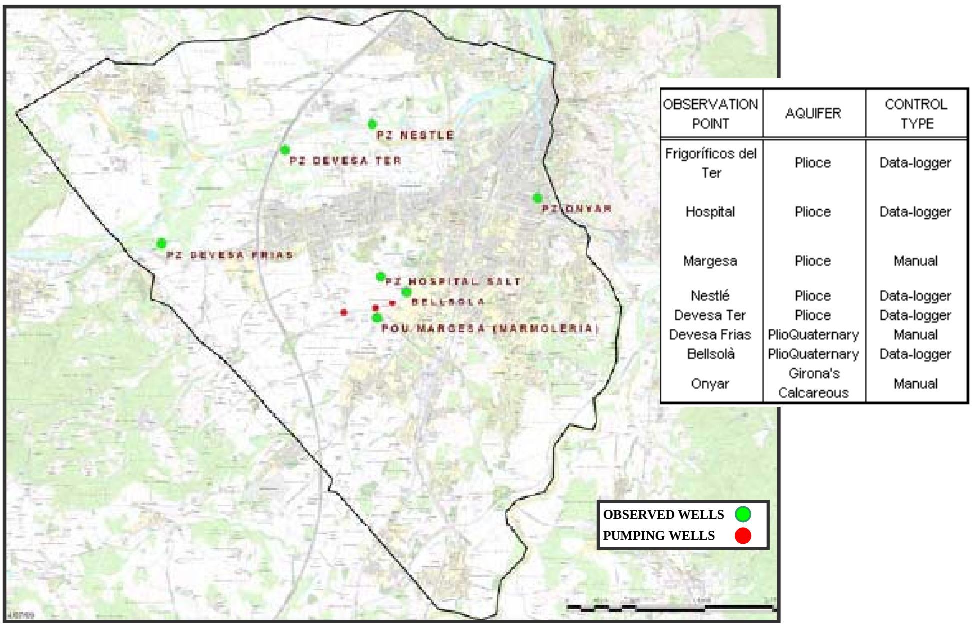
- Defining the boundary conditions: inflow from the Bescano's fault (W limit, Figure 3) and the Ter river and other streams by leakage condition; and outflow to the Girona's calcareous formation (E limit, Figure 3).

Interestingly, when trying to simulate the pumping test with the numerical model, previously to the calibration process, the computed head levels were always between 2-4 m higher than the measured levels. But when a single industrial extraction, quantified at $1,00 \cdot 10^6$ m^3/year and located 3 km far from the pumping and observation wells, was implemented ni the model, then computed heads reproduced the calculated the measurements. This is the classical behaviour of a poor confined aquifer with little recharge, where drawdown may extend at large distances.

3. HYDRAULIC TEST

The Agency decided to plan a one week pumping test[2], in order to validate the model response and to gain insight into the following processes:

- ✓ Hydraulic connections between shallow and deep aquifers.
- ✓ Lateral connections in the deep aquifer.
- ✓ Outflow to Girona's Calcareous formation.
- ✓ Other mass balance terms: small direct recharge from precipitation, shallow streams and lateral inflow to the deep formation.
- ✓ Behaviour of the Plioquaternary aquifer.



OBSERVATION POINT	AQUIFER	CONTROL TYPE
Frigoríficos del Ter	Plioce	Data-logger
Hospital	Plioce	Data-logger
Margesa	Plioce	Manual
Nestlé	Plioce	Data-logger
Devesa Ter	Plioce	Data-logger
Devesa Frias	PlioQuaternary	Manual
Bellsolà	PlioQuaternary	Data-logger
Onyar	Girona's Calcareous	Manual

Figure 4: Location of the 3 deep wells and the 8 observation points involved in the hydraulic test. The table gives information about the screened aquifer and type of measurements taken.

The pumping was done between April 27th, 2009 and May 4th, 2009. The regime was increasing: first, pumping out from well # 3, then adding well # 2 and, finally, also well # 1 (Figure 5). After 24 hours, the three wells worked with a global extraction of 240 L/s. However, the average rate was 229 L/s (Figure 5)

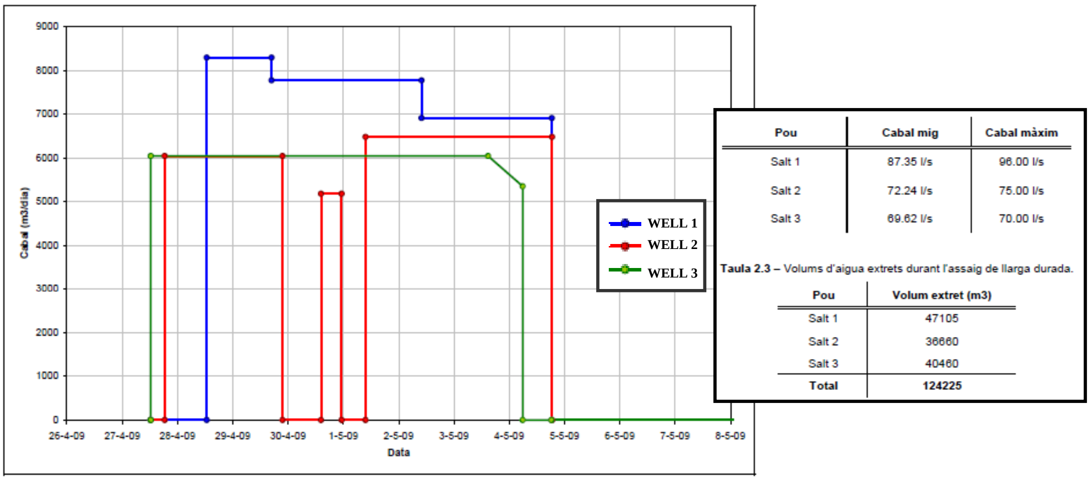


Figure 5: Pumping regime adopted for the test carried out for the 3 emergency reserve wells. The table shows the average flowrate and the cumulative abstraction for each well.

Measurements were taken in 8 observation points, 5 of them equipped with dataloggers and 3 with manual measurements (Table 1).

Table 1: Different scenarios simulated to verify the wells use viability.

Observation point	Water use	Aquifer	Distance to Wells (km)	Maximum drawdown (m)	Recovery (after stopping the test)
Frigoríficos del Ter	Industry	Deep	1.400	7.0	Interference with own wells
Hospital	Piezometer	Deep	0.700	6.2	0.48 m drawdown alter 35-days
Nestlé	Piezometer	Deep	2.500	1.4	0.15 m drawdown after 35-days
Devesa Ter	Piezometer	Deep	2.400	3.6	2.00 m when test stopped
Bellsolà	Domestic	Shallow	0.260	Not affected	Not affected
Margesa	Abandoned	Deep	0.125	27.0	2.00 m drawdown after 11-days
Devesa Frias	Abandoned	Shallow	2.220	Not affected	Not affected
Onyar	Piezometer	Carbonate	3.200	0.13 (increase)	Fast stabilization

4. MODEL CALIBRATION USING THE HYDRAULIC TEST

After analyzing the results, it was decided to use the best four observation points within the Pliocenic aquifer: Hospital, Nestlé, Margesa and Devesa Ter piezometers. Recharge and lateral flows variations were not considered because the pumping test lasted one week only.

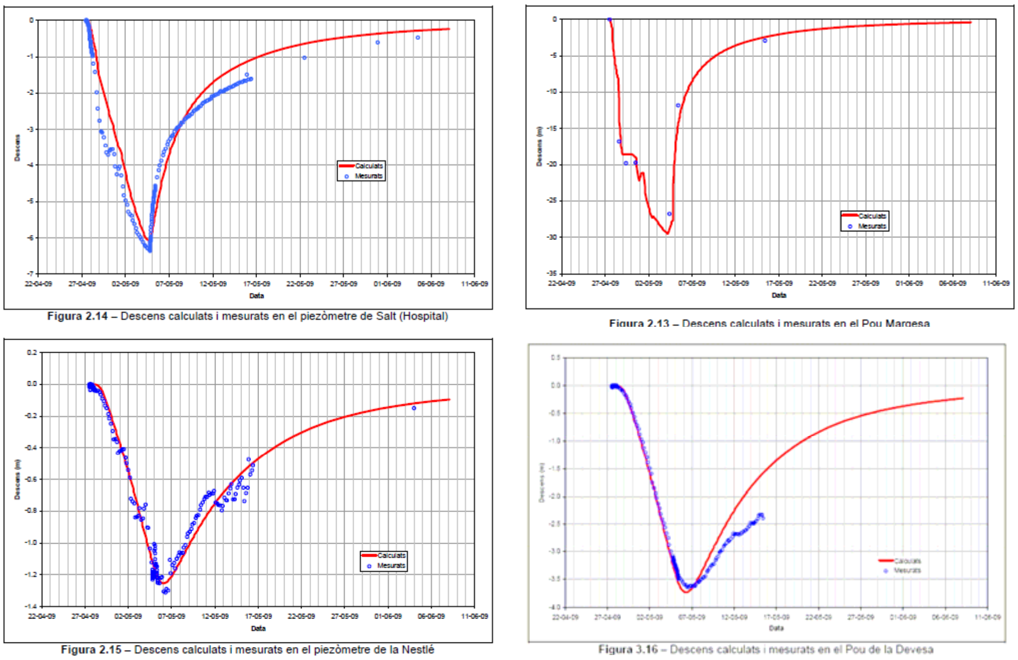
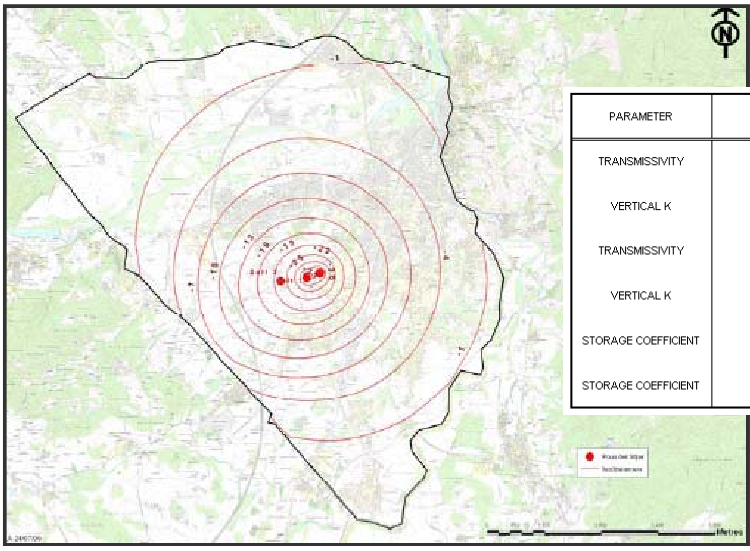


Figure 6: Measured data (in blue) versus calculated data (in red).



PARAMETER	LAYER	VALUE	UNITS
TRANSMISSIVITY	2	0.658	m^2/day
VERTICAL K	1 - 2	0.77×10^{-5}	m/day
TRANSMISSIVITY	3	100.75	m^2/day
VERTICAL K	2 - 3	0.77×10^{-4}	m/day
STORAGE COEFFICIENT	2	0.0000065	-----
STORAGE COEFFICIENT	3	0.0003	-----

Figure 7: Maximum drawdown during the hydraulic test. Hydraulic parameters calibrated are displayed in the lateral table.

The heads adjustment (Figure 6) can be considered very good. In addition, the behavior of non-recovery levels is represented. Figure 7 shows the heads associated with the layer 3 by the end of the pumping test and the hydraulic parameters of layers 2 and 3 after the process of calibration. The test results confirm some previous conceptual aspects. For instance, the deep aquifer is fairly disconnected from the shallow aquifer, but the large contact area between them (more than 28 km^2) may lead to significant vertical flows.

5. SIMULATION OF FUTURE (EMERGENCY) SCENARIOS

The Pliocene deep aquifer is currently subject to little extraction. However, the 1997-1998 drought period promoted the construction and recovery of wells in order to reinforce urban water supply in the future. This is the case of the 3 deep wells built in the Plioquaternary Girona Plains aquifer, which will be able to contribute to Girona's supply if required. But the model has been used to determine the best extraction regime for these 3 wells (Table 2).

Table 2: Different scenarios simulated to assess the optimum pumping regime for the 3 emergency wells drilled next to Girona city.

SIMULATION	CONTINOUS EXTRACTION	EXTRATION TIME	TOTAL EXTRACCION
A	164 L/s	6 Months	2.59 x 10^6 m^3/a
B	240 L/s	3.5 Months	2.20 x 10^6 m^3/a
C	240 L/s	6 Monts	3.79 x 10^6 m^3/a

All three simulations meet the following assumptions:

- ✓ Natural recharge replicates the period between January 1st, 2007, and March 31st, 2008, i.e. under extraordinarily dry weather conditions.
- ✓ Industry wells would keep pumping from the deep aquifer at the same rate as in year 2007 ($1.3 \cdot 10^6$ m^3/year)
- ✓ The 3 emergency wells would pump at relative rates of 41.6% for well # 1 and 29.2% for wells # 2 and # 3.
- ✓ For all scenarios, the 3 wells would start pumping on April 1st, 2007 and would last the period indicated in Table 2.
- ✓ Ter river is always receiving water from the surface aquifer.

The results obtained (Figures 8 and 9) can be summarized as follows:

- A Scenario: Head stabilizes in well # 1 by late May (2007), after a fall of 69 m (without head losses). At the beginning of a new pumping cycle (April 1st, 2008) there is a 1.1 m piezometric deficit in layer 3 and 2.5 m in layer 1 (Figure 8), which means 99.4% total recovery. The drainage evolution of Ter river (Figure 9) presents fluctuations associated with episodes of recharge and always receives water from the aquifer.
- B Scenario: The behavior is similar to the previous scenario but the peak flows are higher. In well # 1 level stabilizes, in late May (2007), after a fall of 100 m. At the beginning of a new pumping cycle (April 1st, 2008) there is a 1.0 m piezometric deficit in layer 3 and 1.7 m in layer 1 (Figure 8), i.e. 99.8% total recovery. The drainage evolution of Ter river (Figure 9)is similar to the A scenario.

- <u>C Scenario</u>: The behavior is very similar to the previous scenario but increasing the pumping time. Well # 1 stabilizes by late May after a fall of 100.5 m. Deficits on April 1st, 2008 would be 1.0 m in layer 3 and 1.7 m in layer 1 (Figure 9), i.e. 99.1% total recovery. The drainage evolution of Ter river is similar the other scenarios (Figure 9).

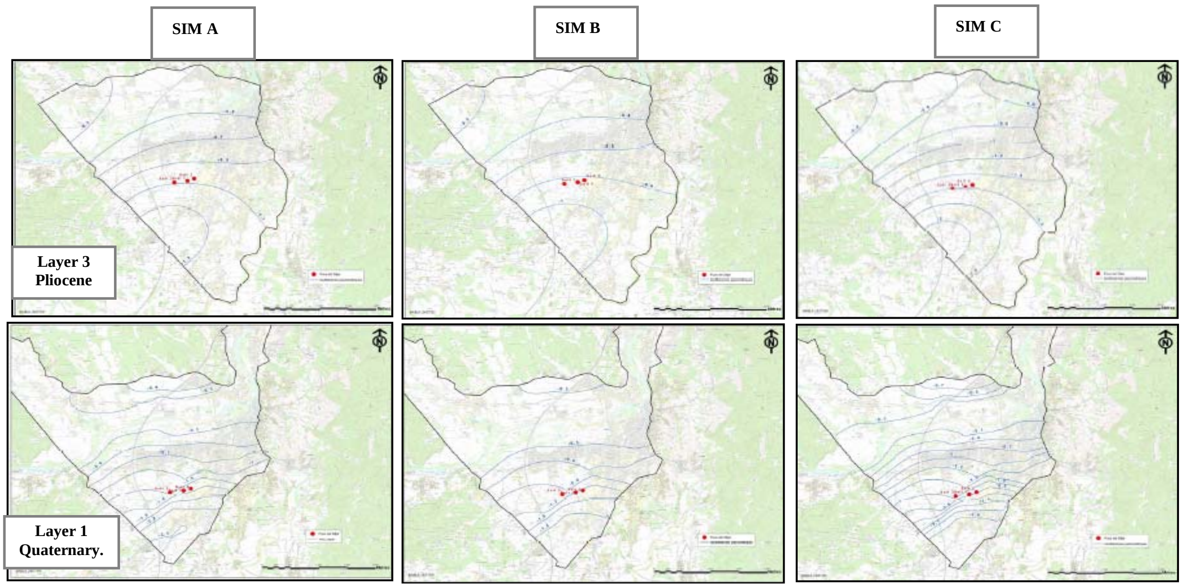


Figure 8: Differences between no-pumping and each pumping scenario (up, layer 3; down, layer 1)

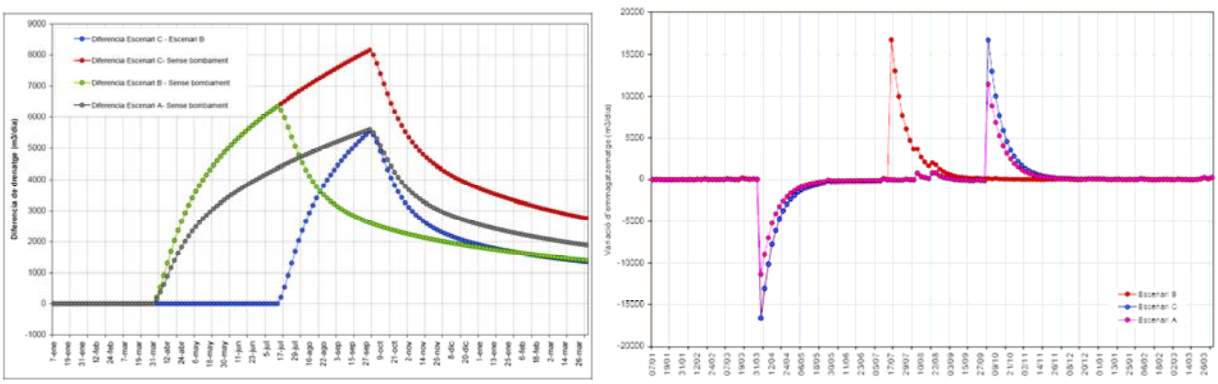


Figure 9. Comparison of Ter river discharges for the 3 simulated scenarios.

According to these results, the following conclusions can be drawn:

1. The Ter river tends to compensate declining piezometric heads generated by delayed drainage caused by the pumping.
2. Extraction in deep wells gives raise to an important delayed drainage effect, which in turns has an impact on the Ter river flowrate: up to 8,000 m^3/dia for scenario C (Figure 9)
3. At the beginning of a new pumping cycle, there is a circulating flow deficit in Ter river:

up to 3,000 m^3/dia in the worst case.

4. In terms of resource availability, the proposed pumping causes a significant decrease in aquifer storage that affects the shallow aquifer and the contribution to the river.
5. The aquifer needs periods of intense recharge to recover, such as delayed infiltration of precipitation and recharge through rivers (tributaries of the Ter river).
6. The recommended pumping regime for the emergency wells is presented in Table 3.

Table 3: Recommended pumping regime from the 3 supply reserve wells after the hydraulic test and model simulations, depending on the hydraulic state ('scenario') of global water resources.

Scenario	Mensual Extraction (hm^3)	Duration (Months)	Total Extraction (hm^3)
Normalitat	Maintenance	-----	-----
Alerta	0.18	6	1.08
Excepcionalitat	0.26	6	1.56
Emergencia	0.44	6	2.64

6. CONCLUSIONS

This paper presents the unusual sequence followed (integrating data – formulating a preliminary numerical model – conducting a field test to verify numeric results – simulating future scenarios for water resources planning) to built a groundwater numerical model that has proven to successfully predict real observations at the regional scale.

The hydrogeological functioning of the Plioquaternary aquifer, can be summarized as follows:

- ✓ In general, the shallow and deep aquifers are quite disconnected.
- ✓ The deep Plioquaternary aquifer only has an important recharge area (SE).
- ✓ The system behaves as a multilayer aquifer system under confined condicionts, which causes important drawdown at kilometric scale.
- ✓ There is a delayed drainage of Ter river to the upper superficial layer and from this to the deep formation that can be significant due to the surface involved despite the low permeability of confining units.

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