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title: **Integral approach to manage saltwater intrusion in a Mediterranean aquifer (Tordera's delta)**

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INTRODUCTION

The Catalan Agency of Water (the Agency) is the organism in charge of water control, management and planning in Catalonia. One of the main tasks consists of meeting the environmental objectives of the Water Framework Directive and, at the same time, ensuring water supply for different uses. This may be a quite difficult objective in Mediterranean semi-arid areas which support a high density of human activities, where urban and industrial supplies require important amounts of water that is obtained from small, heavily exploited coastal aquifers. This was the case of Tordera's Delta: a tiny alluvial aquifer close to Barcelona city, in NE of Spain (Fig. 1).

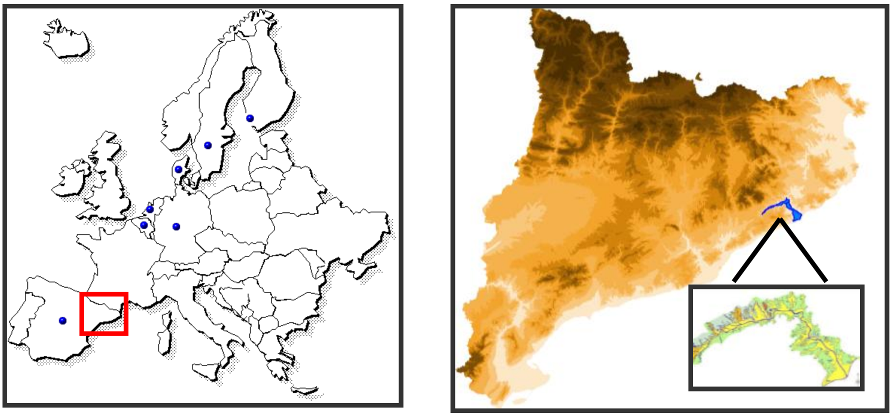

Figure 1. Location of Tordera's Delta aquifer, 70 km NE Barcelona, in NE Spain.

Between 1997 and 2002, the intensification of groundwater extractions, mainly in summer, gave rise to a serious marine intrusion problem (Figure 2) that affected the viability of urban, industrial and irrigation wells.

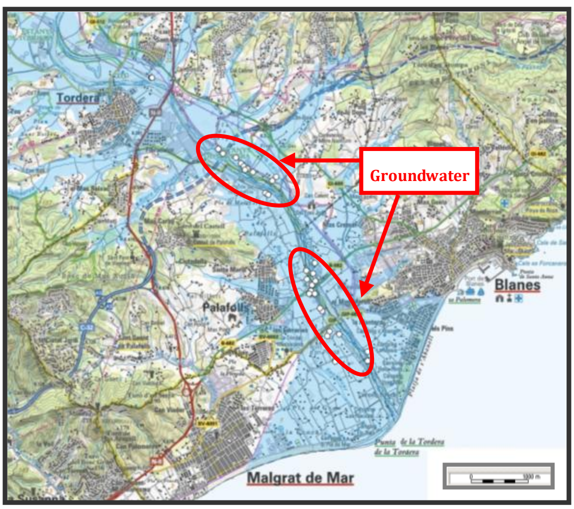

Figure 2. Identification of main group of extraction for supply uses.

In 2002 chloride concentrations reached values as high as 2,500 ppm 2.5 km inland and peak electrical conductivities of 14,000 μS/cm (Figure 3).

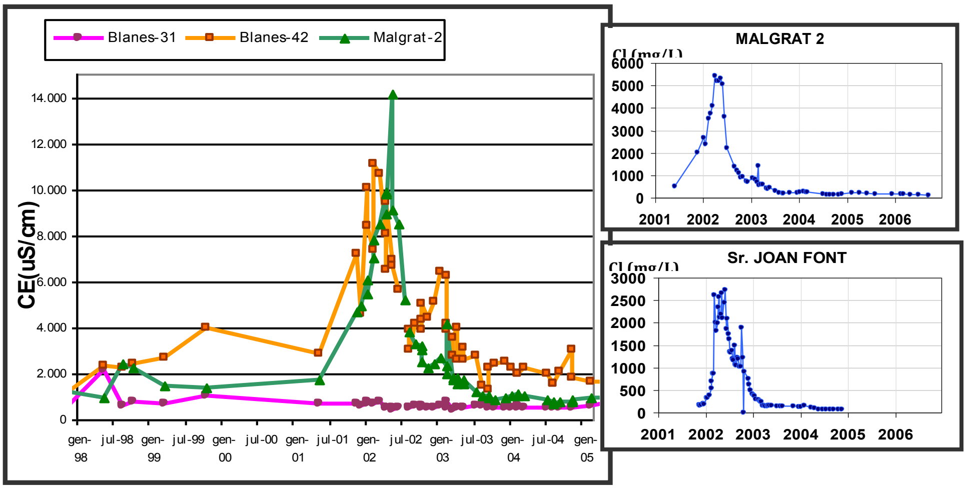

Figure 3. Electrical conductivity evolution at three points in Tordera's Delta (in left) and Chloride concentrations in two points at the same area (in right).

For these reasons, the Agency decided to (1) build a seawater treatment plant capable of producing $10 \cdot 10^6$ m^3/yr of drinkable water in order to reduce groundwater extraction, and (2) develop a groundwater flow and transport numerical model (2002) without calibrating the transport. In 2009, some aspects of the previous model have been notably revised and the resulting numerical model has been calibrated also with regard to chloride transport, both for management purposes.

THE NEW MODEL TORDERA'S AQUIFERS MODEL

The original model (year 2002, Figure 4) has been revised in order to update the conceptual model and to calibrate the transport problem based on chloride measurements from the Agency's network. The new conceptualization aims at improving the initial assumptions, mainly in the Delta. Improvements include:

- New data on geology, review of the geometry of the layers and hydrologic interpretation through the definition of new and justified permeability areas.
- Improving hydrologic factors such as recharge, head levels, extractions and numerical model conditions.

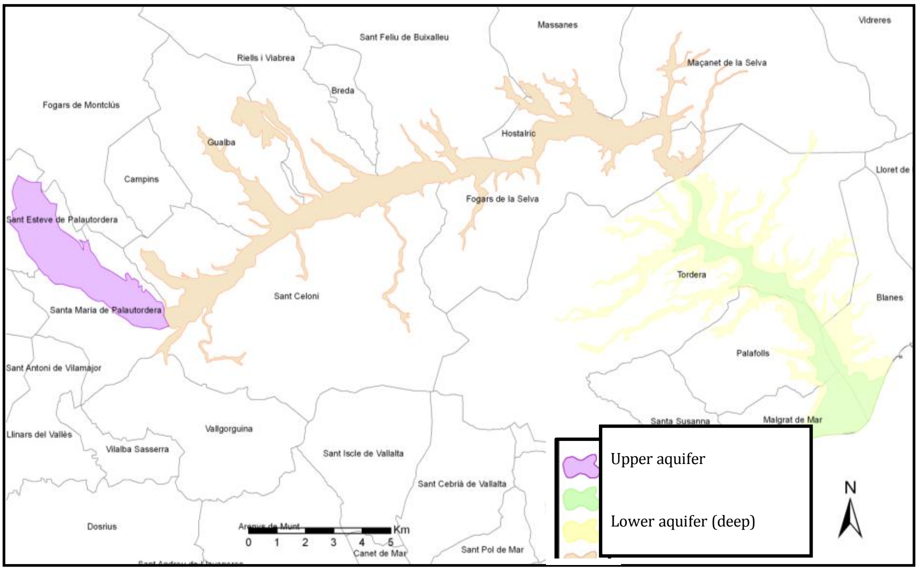

Figure 4. Tordera alluvial aquifer domain where each color represents a part of the aquifer.

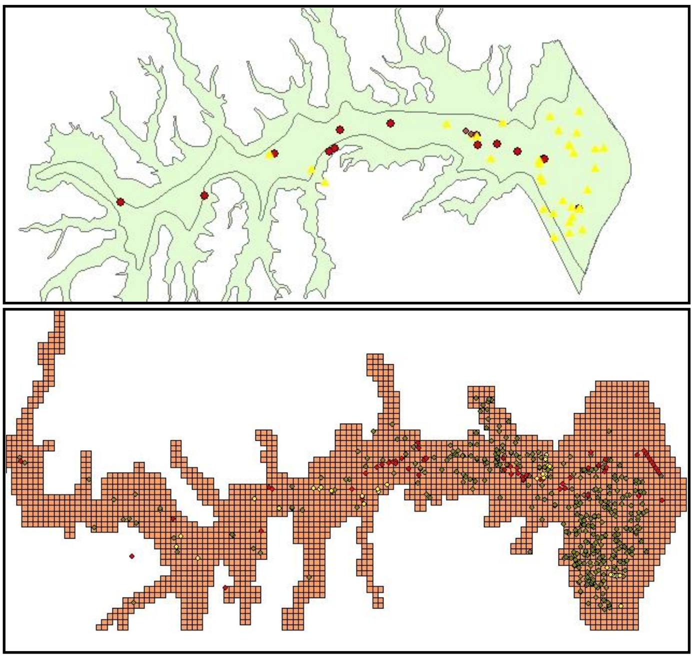

Figure 5. Points of the Agency network used to calibrate chloride concentrations (up): wells in shallow aquifer in yellow and deep aquifer in red. Wells situated at Tordera's delta (down): supply in red, industrial in yellow and irrigation in green.

The final groundwater model was implemented in the well-known Visual Modflow code, which is a pre- and post-process system based on code Modflow.

In general, the heads adjustment can be considered very good. Furthermore, the represented heads of the deep aquifer in Tordera's Delta were even better, area that belongs to the transport model domain.

As for chloride transport, the calibration process (Figure 6) is much more affected by heterogeneities presents in the aquifer. This adds a difficulty in reproducing peak concentrations produced in a very short time, as it occurs with some wells of the shallow aquifer. However, the deep aquifer results are considered to be correct. In short, the model is robust and is well calibrated with current hydrological information.

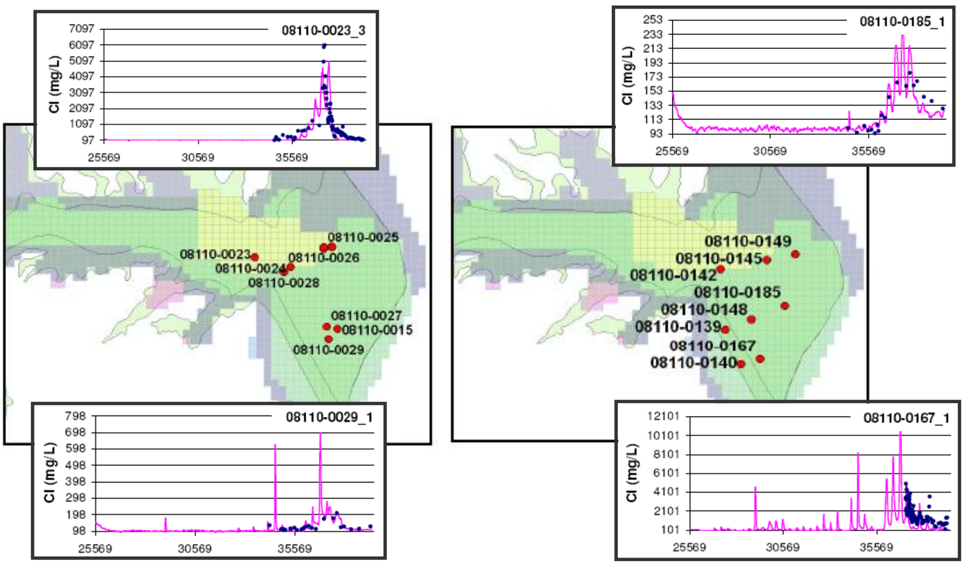

Figure 6. Examples of the transport calibration process. The blue points are measured values of chloride concentrations and red are simulated. Points with _1 suffix belong to shallow aquifer and _3 suffix to deep aquifer.

FUTURE ACTIONS IN THE TORDERA'S AQUIFERS: MODEL SCENARIOS

The new numerical model can be used as a groundwater management and planning tool suitable to simulate future, potential scenarios. The Agency was conducted different actions during the last years in Tordera's basin which now allow envisaging changes in future water resources management. Among these, the following steps must be remarked: joint use surface water-groundwater, reclaiming water to replace wells, passing more-sustainable aquifer's exploitation rules, promoting artificial recharge (e.g. the construction of a tertiary treatment of a wastewater plant for recharge purposes) and improving the quality of flowing waters by means of better treatments and control on discharges.

The analysis of future scenarios has been done with both the original and the updated models in order to assess their robustness for predictive purposes. Increasing the pumping regime yields quite different results between them (Table 1).

Table 1. Comparison between 2002 (1) and 2009 (2) Tordera's aquifers model from the perspective of sustainability (viability to support an increase in pumping from wells of +2, +4 and +6 Mm^3/yr, expressed as Hm^3/a below).

	CALIBRATE FLUX	CALIBRATE TRANSPORT	PUMPING + 2 Hm3/a	PUMPING + 4 Hm3/a	PUMPING + 6 Hm3/a
MODEL 1	Y	N	VIABLE	**VIABLE**	UNVIABLE
MODEL 2 (new)	Y	Y	VIABLE	**UNVIABLE**	UNVIABLE

Model 1 only yields small piezometric head variations (-0.5 m) in wells close to the shoreline when pumping is increased by $4 \cdot 10^6$ m^3/yr, whilst the new model (2) results in chloride concentrations increased by a 2-3 factor. Both models agree on the non-sustainability of increasing withdrawal by $6 \cdot 10^6$ m^3/yr.

Besides, the model can face more complex scenarios. For instance, it would be possible to increase groundwater abstraction by $6 \cdot 10^6$ m^3/yr as compared to current pumping provided that an adequate (reclaimed water) recharge scheme was adopted. Figure 7 shows the three configurations analysed, depending on the location of recharge wells.

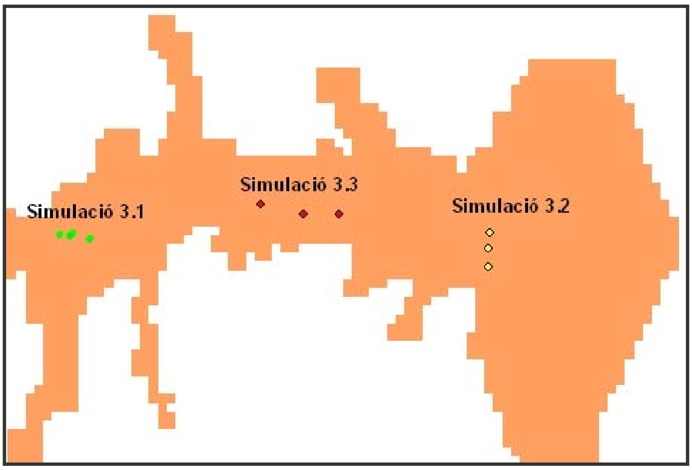

Figure 7. Three possible options considered to drill reclaimed water recharge wells in Tordera's Delta in order to allow increasing pumping for human supply by $6 \cdot 10^6$ m^3/yr.

The simulation 3.1 shows that recharging 2 10^6 m^3/yr would have almost no effect on piezometric heads and chloride concentracions. This is probably due to the fact that recharged water would be discharged to surface streams.

The simulation 3.3 consists of recharging 15,000 m^3/day since year 2012, which would noticeably improve head levels and also would cause a substantial reduction of chloride content within the aquifer; however, marine intrusion would not be completely prevented. However, if the same recharge is done through wells parallel to the shoreline, then results improve remarkably, showing around 2-m rise in heads in nearest wells and a complete removal of chloride concentration to the base or reference level (Figure 8).

Therefore, after evaluating the 3 simulations, it can be stated that pumping may be increased in Tordera's Delta aquifer if an adequate recharge configuration is implemented. The new model helps identifying the best management alternative.

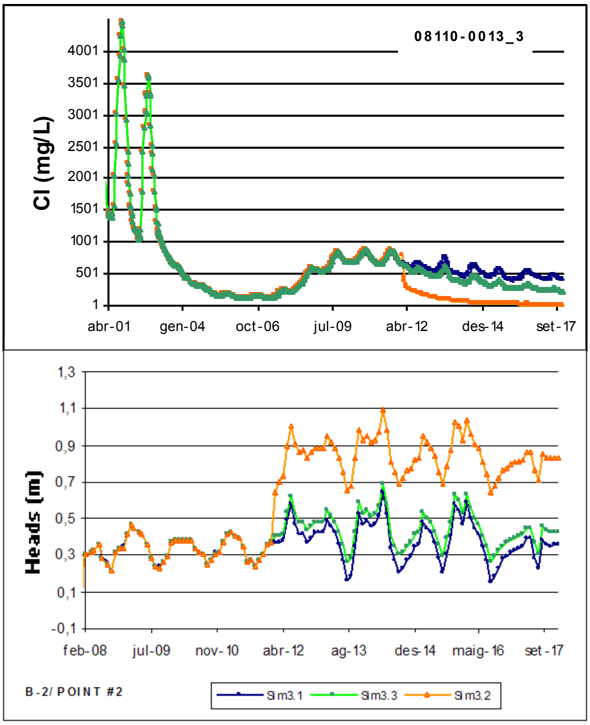

Figure 8. The new model allows to analyze more complicated scenarios, such as the best choice for artificial recharge facilities.

CONCLUSIONS

Numerical modelling is a key to achieve the Water Framework Directive goals and, at the same time, to meet the needs of water users. This is definitely the case of coastal aquifers, provided that the conceptual model is right and that both flow and transport are properly calibrated, which requires improving both our conceptual and numerical approaches. This has been done for the Tordera's aquifers, in NE Catalonia, Spain: the revised model is now far more robust than the original one and can be wisely used for integrated water resources management needs.

The implementation of several actions by the Agency and other stakeholders has reversed the situation in Tordera's Delta aquifers, as both its quantitative and chemical status are nowadays good, contrarily to the dramatic marine intrusion episode that took place just in the beginning of this century. Future plans preview now scenarios in which aquifer pumping will be moderately increased provided that adequate artificial recharge facilities are implemented.

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