GROUNDWATER FLOW AND SALTWATER INTRUSION MODELING OF THE LOW VALLEY AND LLOBREGAT DELTA AQUIFERS

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Abstract

A very large amount of water has been pumped, in particular during the 1970s, from the Llobregat Delta main aquifer (Barcelona, Spain). This caused the salinization of important areas of this aquifer. This contamination process was accelerated by the construction of a new inland dock of the Barcelona Harbor. Since then, big efforts have been undertaken to conceptualize and quantify the groundwater flux and the salt water evolution in this aquifer, and to develop numerical models on the basis of the existing conceptual model. While water level history has been accurately represented in previous numerical models, salt transport results do not completely fit real data evolution. An exhaustive data review was carried out to correctly plan the use of the existing resources and to quantify the available water volumes. All available data, old and new, are often found in a fragmented and disconnected state due to the existence of multiple sources of information. All information from previous works and studies has been integrated. An important effort was devoted to the building of a revised geological model. The review has been carried out within a geological, hydrochemical and hydrodynamic framework. Several aspects that may explain the observed seawater intrusion pattern have been highlighted in the conceptual model. The conceptual model has been translated into an integrated numerical model, calibrated against all compiled hydraulic head and chloride concentration data. The model accurately represents the chloride evolution in the aquifer and can be used as a management tool by water authorities.

Keywords: Llobregat Delta aquifers, seawater intrusion, chloride evolution, inverse modeling.

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Introduction

The Llobregat Delta is a medium-size Quaternary formation located at the SW edge of the densely populated area of Barcelona City, in the NE of Spain. This area, formerly devoted to agriculture practice, now supports important industrial settlements and city suburbs. The high water demand has led to an intense and continuous exploitation of surface and groundwater resources. Intense groundwater exploitation up to the late 1970's caused an important advance of the saline intrusion interface. Nowadays, saline intrusion still affects large areas of the delta.

At present, the Catalonian Water Agency (Agència Catalana de l'Aigua), is trying to correct the actual situation and is developing a groundwater management program to recover groundwater quality and quantity while trying to guarantee sustainable pumping rates. This requires a detailed aquifer characterization. To achieve this goal it has been necessary to do, first, a groundwater review of previous studies along with data recollection and integration, and an exhaustive review of geological information. These two points are necessary to define an improved groundwater conceptual model. Secondly, groundwater modeling is needed to integrate and validate the conceptual model and to obtain a management tool, and thirdly, the simulation of some different scenarios is carried out to allow managers to quantify the effects of different future policies for these aquifers.

The Llobregat delta is a well-known case in classical hydrology and seawater intrusion studies. Since the 1960's a multitude of groundwater studies have been carried out in this area. Among others, the hydrogeological synthesis made by MOP (1966), PHPO (1985) and more recently by Iribar and Custodio (1992) must be remarked. At the end of the 1970's, when salinization problems became increasingly worrying, hydrochemistry works improved the knowledge of the aquifer systems and the mechanisms that cause seawater intrusion in the main aquifer of the Llobregat delta (Custodio *et al.*, 1976; Custodio, 1981; Manzano *et al.*, 1992; Bayó *et al.*, 1977; Domènech *et al.*, 1983, etc.). Some groundwater flow models have been also developed for the Main Aquifer, named Lower Aquifer in previous works, (Custodio *et al.*, 1971; Cuena and Custodio, 1971; Iribar *et al.*, 1997) and, more recently, also for the upper aquifer (UPC, 1998).

Groundwater review

To achieve a detailed characterization it is necessary to recover all the information used to define the conceptual model. One of the most difficult variables to obtain is recharge, which depends on soil use and varies with time, and groundwater extraction. The largest groundwater exploitation was in the 1970s, and reached values of more than 130 Mm^3/y. This period corresponds to the minimum groundwater heads ever reached, with values that went down below 25 m.b.s.l. in the central part of the delta (Figure 1).

Due to this groundwater level decrease and some anthropic modifications of the medium (inland habour dock's enlargement), marine intrusion quickly progressed around the 1980s towards the central part of the delta, where some of the main pumping areas were located. The chloride concentration evolution in time in some selected measurement points is shown in Figure 2, in order to illustrate how seawater intrusion evolved in the main aquifer of the Llobregat delta.

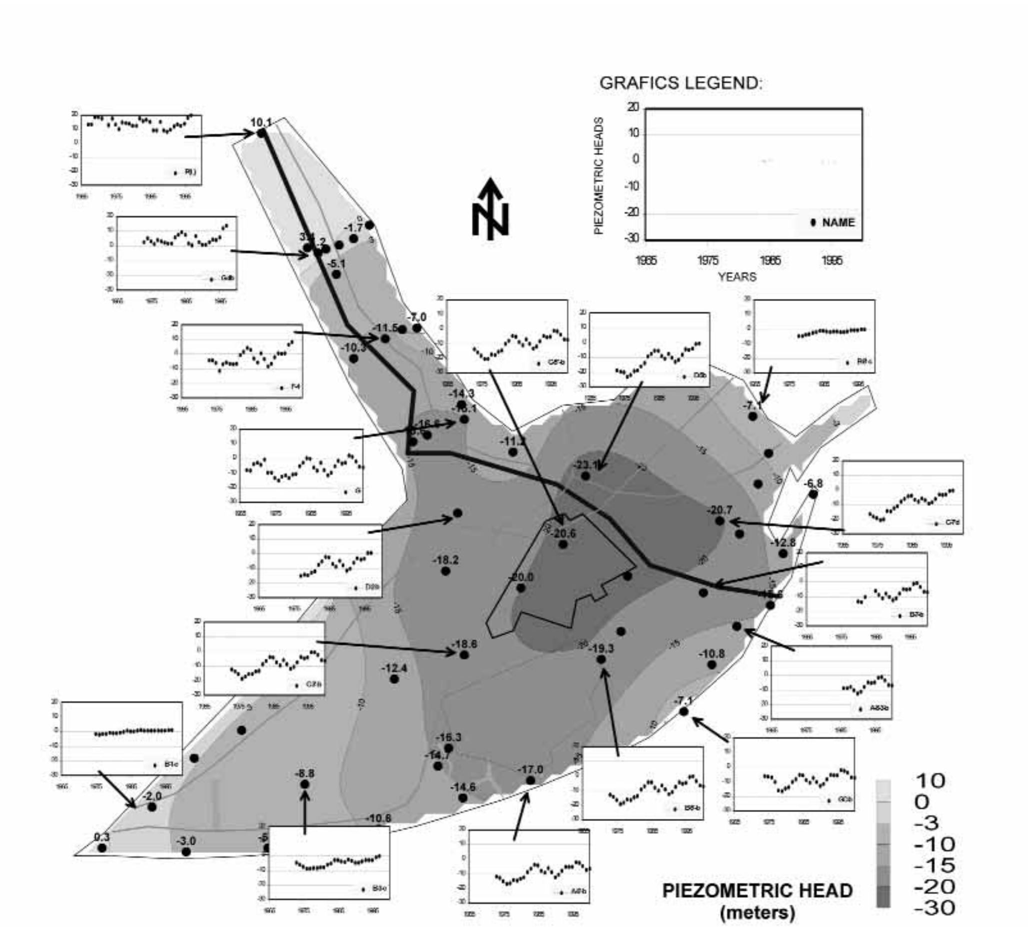

Figure 1. Piezometric surface corresponding to the Main Aquifer in 1976, year of maximum depression. Hydrographs in several points of the aquifer show the complex evolution of the hydraulic heads.

The actual delta is a relatively young formation. Some archaeological findings have shown that in Roman times, the shoreline was almost 2 km inland and that in the Middle Ages, Barcelona's harbor was placed at the shelter of the Western side of Montjüic Mountain, some 1.5 km landwards from the present coast line.

The general guidelines of the Llobregat Delta geology were established by Almera (1891), Llopis (1942, 1946) and Solé-Sabaris (1963). For hydrogeological purposes, the cross-sections proposed in the late 1960s and early 1970s in the framework of the project "Estudio de los recursos hidráulicos de la cuenca del Llobregat" and some other reports published at that time, are still used today (MOP, 1966; Llamas and Molist, 1967; and Bayó, unpublished). Since then, additional geological information has become available thanks to the continuous constructions (related to civil works) that are carried out in the delta area. This

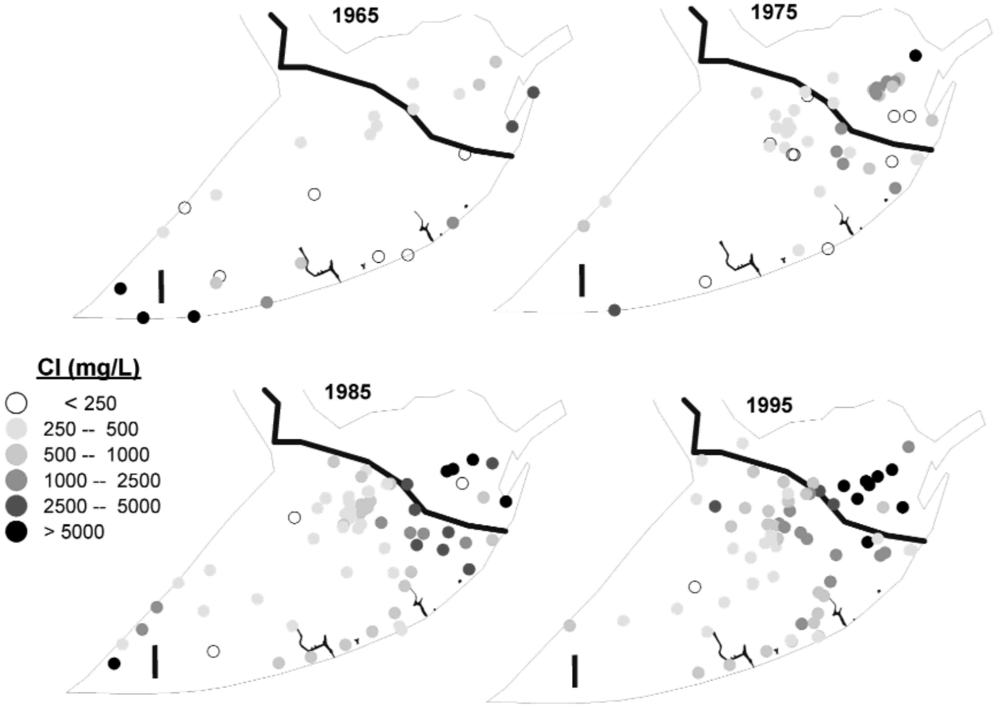

Figure 2. Chloride concentration data evolution in the main aquifer of the Llobregat delta. Two fingers of high salinity can be observed advancing towards the main pumping fields in the center of the Llobregat delta.

additional information helped in defining a more accurate geological model. The motivation of the review of the model comes from the need to account for medium-scale heterogeneities that would control the contamination transport processes taking place in the Llobregat delta aquifers. This is especially true when there is a need to account for mass transport studies, moreover when remediation measures are to be designed or planned. A thorough sedimentological study was carried out to define in detail the three-dimensional geological structure. As an example, well-logs have been reviewed under a sedimentological point of view and it has been possible to redefine aquifer units, their geometries, and lateral connections, both between units and with the sea. The final geological model is presented in figures 3a and 3b.

All collected data were compiled in a dedicated data base, compatible with GIS (ArcInfo and ArcView).

Modelling

The **Visual Transin** code has been used for calibration of the numerical model (UPC, 2003). The code does not take into account the effect of variable density, however, the seawater density is implemented in the boundary conditions, where equivalent freshwater head is prescribed.

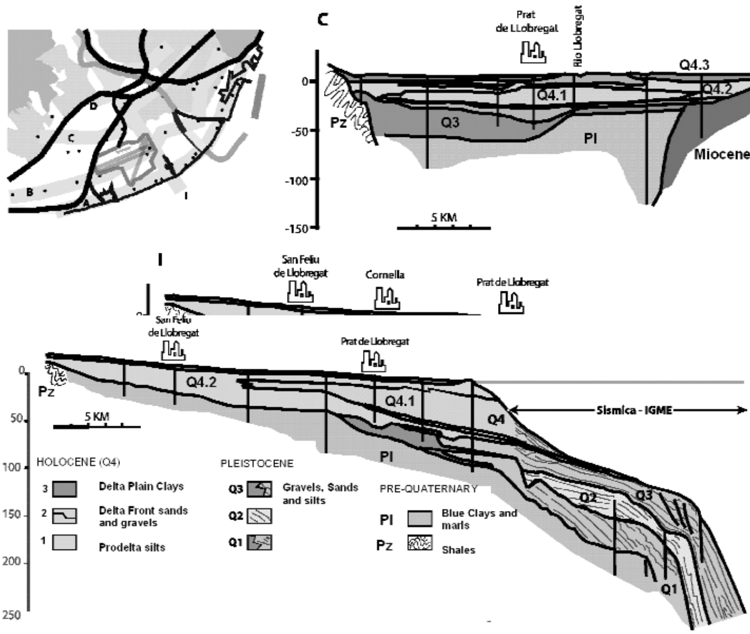

Figure 3a. Geological cross-section of the emerged and submerged delta based on old MOP data and from a reflexion seismic survey performed by IGME. Vertical scale in meters. The silt wedge separates the upper and main (lover) aquifers. Other old Quaternary deltas (Q1-Q3) are part of a hydrologically unknown lower aquifer system. The modern delta (Q4) was formed about 18000 years ago, although its progradation took place during the last 6000 years.

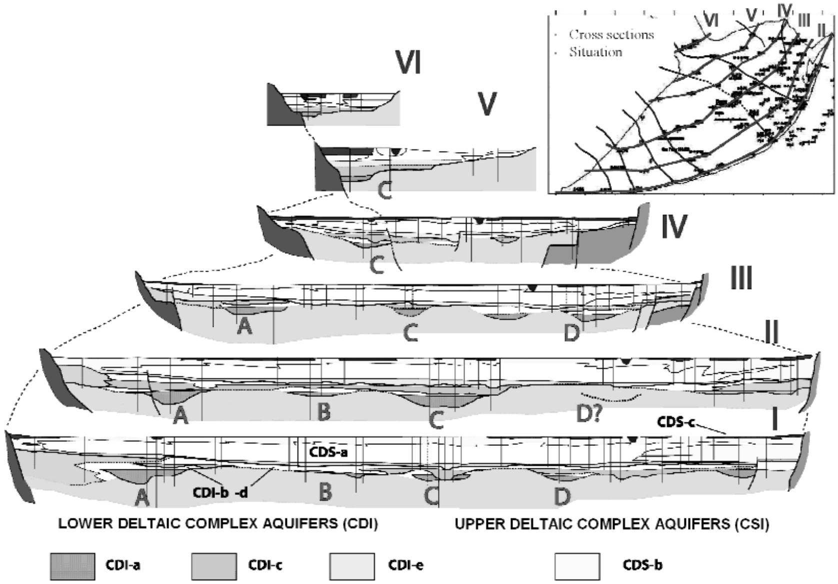

Figure 3b. Conceptual model of the incised systems of the called Lower Detritic Complex. Gravels and conglomerates represent the different incised systems. Between the coarse sediments there are silts and sands are found. The lower grey area represents the Pliocene Blue Marls, and the dark-grey the Miocene and pre-Miocene basement.

As a result of the geological characterization, the model was divided into two layers, corresponding to the Upper aquifer and the Main aquifer. Spatial discretization (Figure 4) is very fine, especially near the main pumping areas, and the mesh is adapted to the main geographical features. The average size of each element is about 200 m. Simulation time steps are set to monthly frequency, from 1965 to 2001.

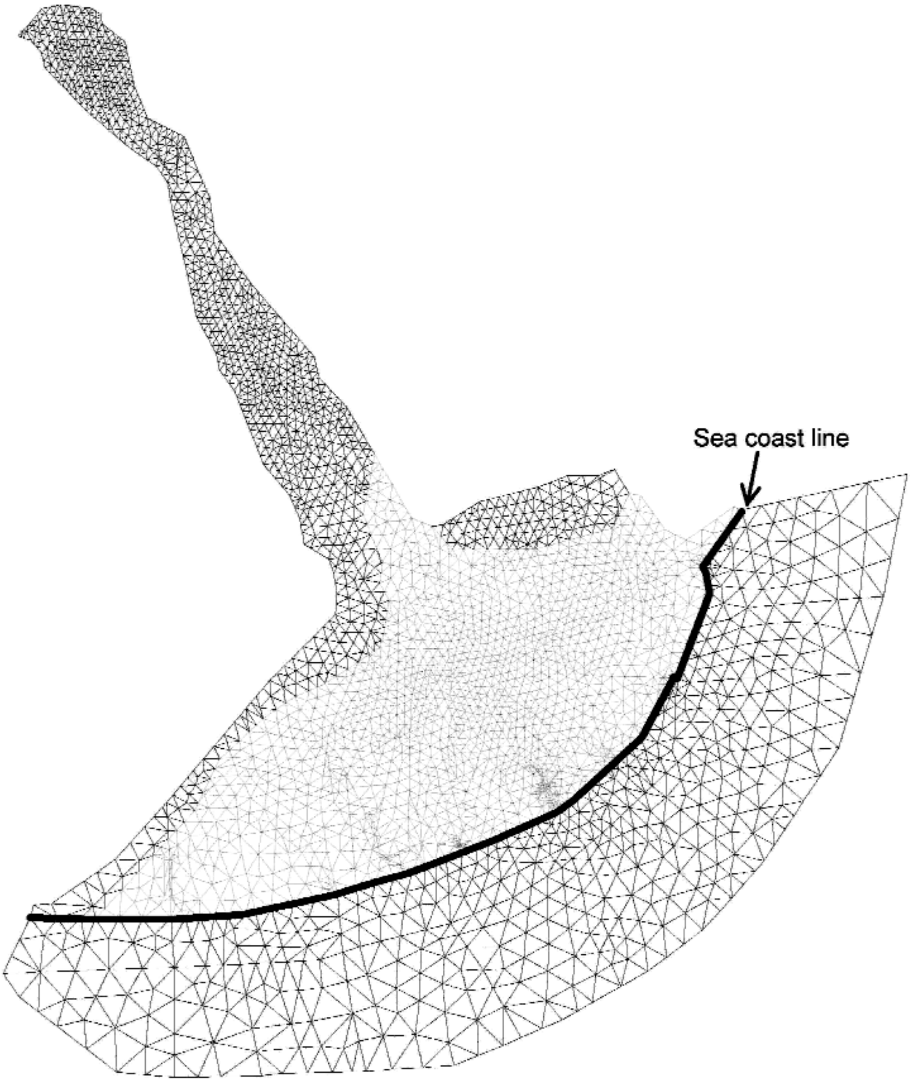

Figure 4. Finite element mesh divided into two layers (grey and black) connected by 1D elements. The complete mesh is composed of 4411 nodes and 9848 elements.

The main parameters used in the model were estimated after data integration and completing the geological review. As an example, it was possible to define 101 transmissivity zones, defined according to aquifer thickness, lithofacies description and values obtained in hydraulic tests. The transmissivity zone map is shown in Figure 5, which also shows the aquifer thickness isolines above it.

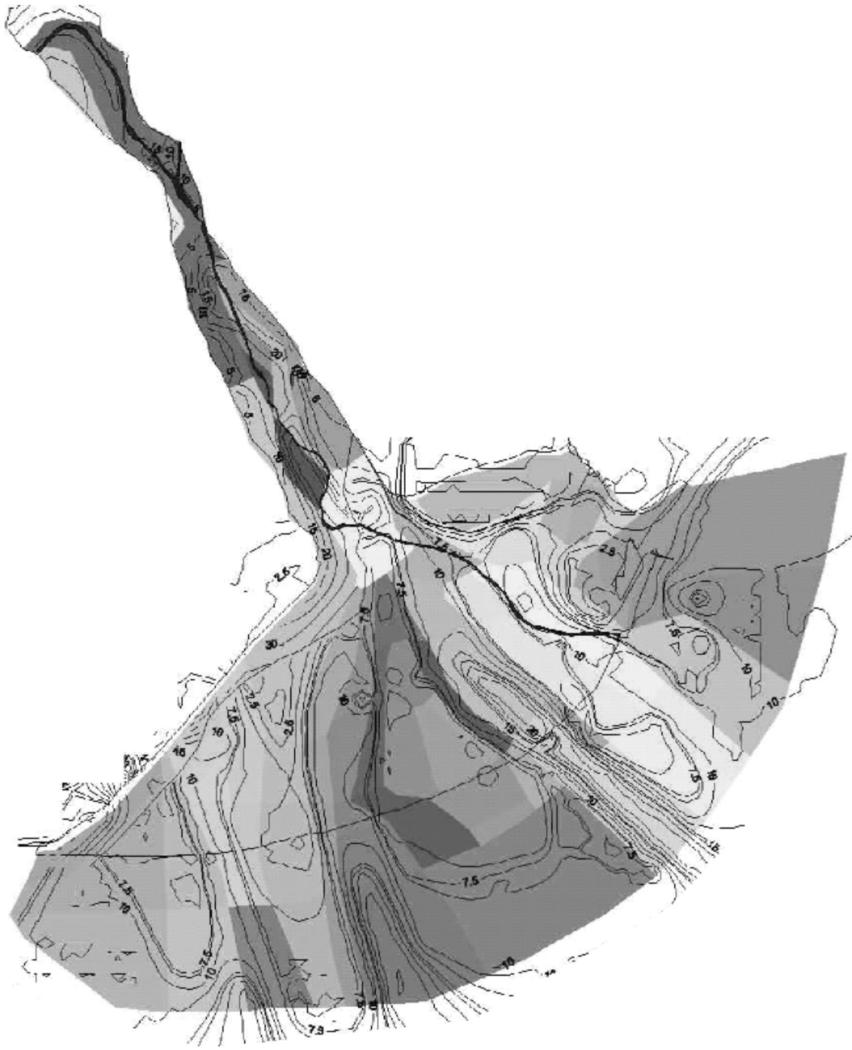

Figure 5. Map of transmissivity zones. 101 constant transmissivity zones are defined, based on several criteria: aquifer thickness, lithofacies, hydraulic tests and sediments grain size distribution of the sediments. Aquifer thickness isolines (in meters) are plotted over the map.

Three main points have to be taken into account while calibrating the model. Firstly, a good consistency between a priori information and calibrated parameters must be pursued; secondly, we must ensure a good fitting between measured and computed data, both in terms of piezometric heads and concentrations (figures 6a and b), and thirdly, the water and chloride mass balances should be coherent with the conceptual model and previous calculations. A synthesis of the water mass balance is shown in Figure 7.

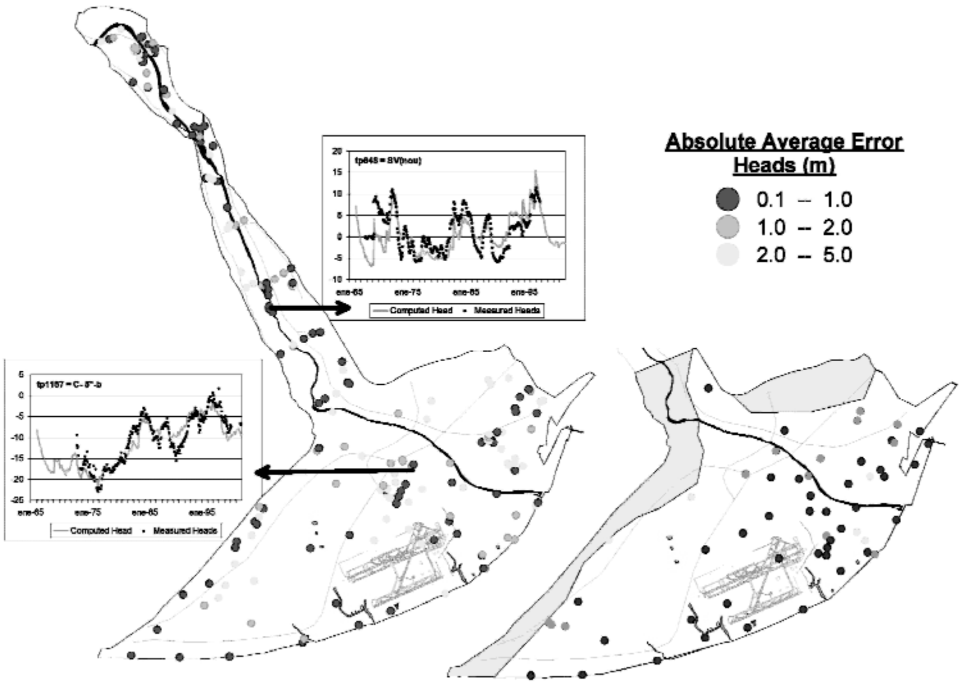

Figure 6a. Head calibration errors, defined as the mean difference between the calculated and the measured head data at a given observation point. The dark dots represent wells whose mean difference is less than a meter. The time evolution of calculated and measured heads in two wells is also shown. The main aquifer is displayed on the left, while the upper aquifer is on the right.

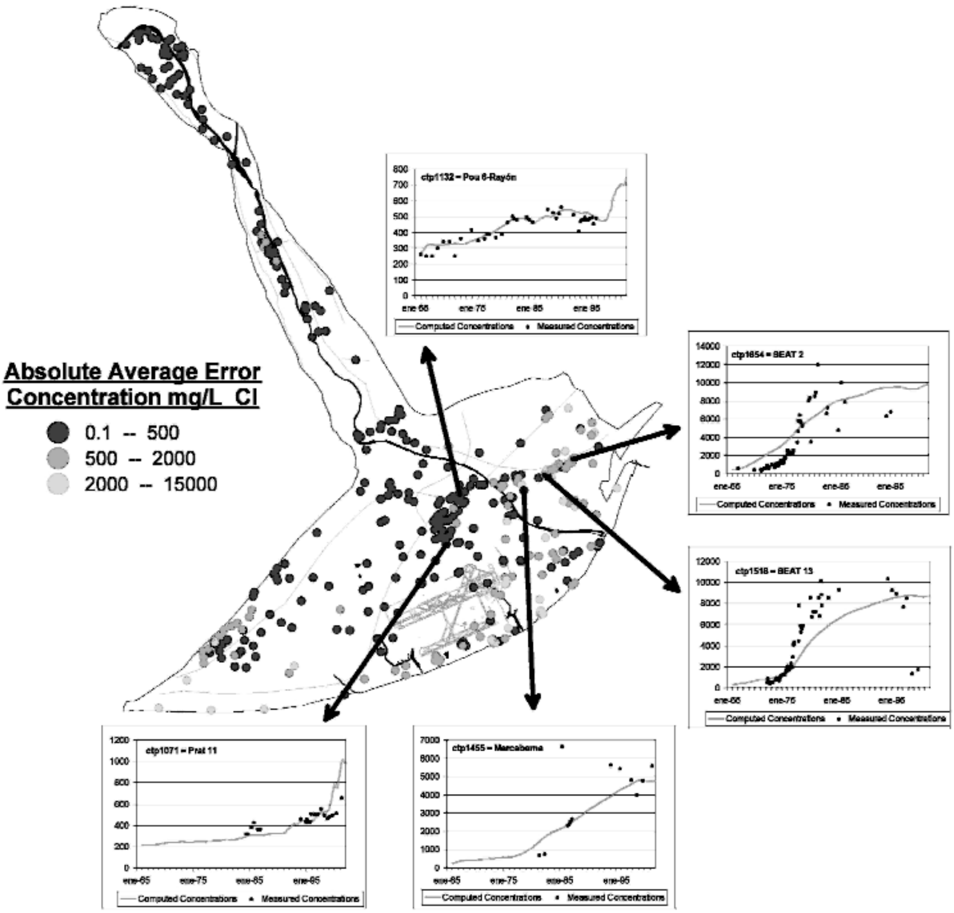

Figure 6b. Chloride calibration errors in the main aquifer, defined as the mean difference between the calculated and the measured concentration data at any given observation location. The dark dots represent wells whose mean difference is less than 500 mg/L of chloride. The time evolution of calculated and measured concentration in several wells is also shown.

From Figure 7 several relevant aspects arise, e.g. the recharge from the river during floods is the most important contribution to aquifer recharge, while groundwater abstraction is the main term in aquifer discharge. The most significant contribution of the model is its ability to simulate the evolution of seawater intrusion and to define a path for it.

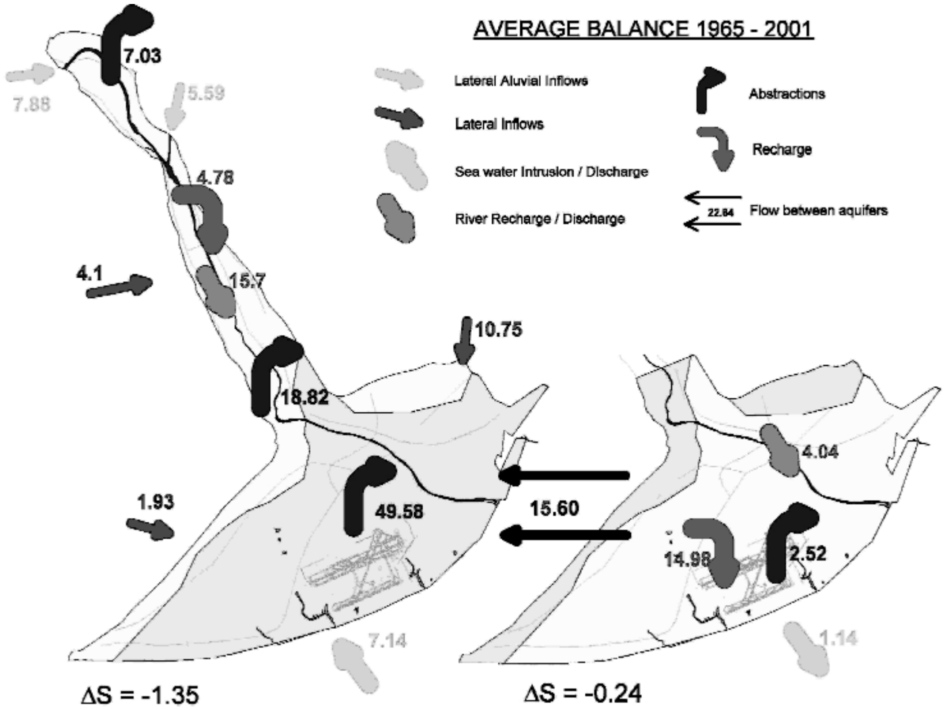

Figure 7. Water mass balance scheme for the Llobregat delta aquifers expressed in Mm^3/y. The mass balance for the main aquifer is shown on the left side and for the upper aquifer on the right. The black arrows show the flux from the upper to the main aquifer.

Management program

The calibrated groundwater model becomes a tool for aquifers management. The model is used to define future evolution trends, depending on possible scenarios. The methodology consists on:

1. Defining a future reference scenario for the next 35 years. Some assumptions are needed to define this scenario:
   - The meteorological evolution will be the same as in the previous 35 years (same recharge and boundary inflows)
   - Present abstraction rates are maintained all throughout the period
   - Implementation of civil structures (extension of the airport drainage network, new subway tunnels, harbor enlargement, etc.)

2. Defining aquifer indicators for:
   - Maximum and minimum admissible piezometric levels
   - Acceptable salinity values in selected points of the aquifers

3. Optimization of abstraction rates, based on previous indicators and its implementation in the numerical model.

As a result of this optimization, it is observed that seawater intrusion will be very significant, and probably irreversible, if the current situation is not corrected in the immediate future. Simulation results of one of the hypothetic scenarios in which pumping well fields migrate, as the salinity in the wells increases, is presented in Figure 8 (left). Another hypothetical situation, in which corrective measures are implemented, and the quality of the aquifer is recovered in 35 years, is also shown in Figure 8 (right).

The possible corrective measures considered are:

1. Positive Recharge Barriers with regenerated waters, between abstraction areas and seawater intrusion paths.

2. Artificial Recharge by:
   - Wells
   - Surface ponds
   - River bank and urban runoff infiltration
   - Induced recharge from controlled river floods

Depending on different possible solutions, the necessary inflow to reduce seawater intrusion and maintain the actual abstractions rates in the aquifers can be quantified. As it turns out, this can be used by water authorities for management purposes.

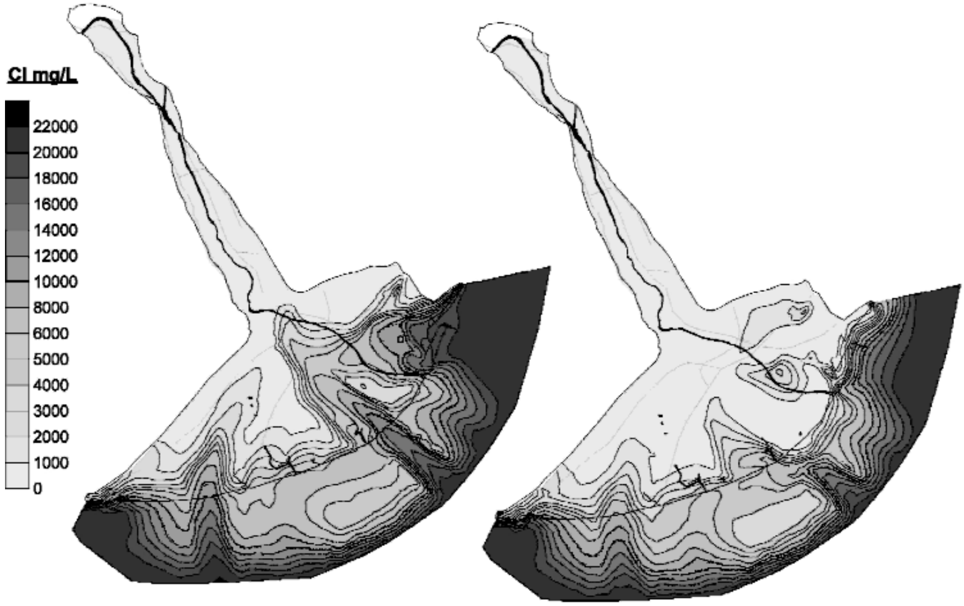

Figure 8. Left: simulation of the future evolution of salinity in the main aquifer of the delta (year 2037) if the pumping wells move inland as a consequence of salinity making the pumped water undrinkable. Right: Hypothetical situation in year 2037 if the current situation is remediated with some additional measures such as an injection barrier and recharge ponds.

Discussion and conclusions

A hydrogeological review of the Llobregat delta aquifers has been carried out. Additional data have been added to the previous works information to conform a large GIS based data base. The geological model has been improved thanks to the new information obtained from recent civil engineering works.

The geological and hydrological conceptual model has been tested and calibrated. The final model accurately reflects the spatial and temporal variability of available data from 1965-2001, both in terms of heads and chloride concentrations. This model has been properly modified to be used as a tool for management policies. Different future scenarios have been studied because of the uncertainty of the future prognosis. As a result of all the simulated scenarios, it is concluded that the actual situation is not sustainable for a long term, as seawater intrusion is approaching the main extraction zones. Some alternative measures have been tested to restore the aquifer quality without modifying the present extraction rates. The pumping rates and the amount of water that might be introduced in the system through the corrective measures have been optimized by a linear programming code together with the flow and transport model. The most effective measure according to the optimization process is the seawater intrusion barrier.

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