

Groundwater modelling in urban areas as a tool for local authority management: Barcelona case study (Spain)

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Abstract Urbanization poses some threats to both the availability and quality of groundwater resources in large cities worldwide, with corresponding significant social, environmental and economic implications. A good knowledge of urban hydrology requires a detailed quantitative analysis of water fluxes, but also of the quality of the resources. In any real case study one has to face at least three aspects: (a) process identification, (b) aquifer characterization and modelling, and (c) water resources management. This three-fold methodology has been applied to the city of Barcelona. The outcome is a groundwater model which among other things may become a management tool, as it allows definition, characterization and quantification of the potential risk to aquifers, as well as to urban structures, with all the implications for the population. This is an important step towards convincing city managers to consider groundwater as one of the topics to be taken into account in city planning.

INTRODUCTION

The study of urban groundwater is motivated by the strong interaction between city socio-economic development and groundwater environmental impacts. Urbanization clearly affects both availability and quality of groundwater resources. This interaction leads to significant social, environmental and economic implications. Problems caused by urbanization are being faced by many cities worldwide, so that researchers and municipal managers have addressed them, although, in general, treating them separately and not in an integrated framework.

A good knowledge of urban hydrology requires a detailed analysis of water fluxes: their magnitude, relative importance, and dependence upon hydrological parameters. The analysis must consider both the quantity and the quality of water, from the moment it enters the system through rainfall infiltration, river water, or other sources, until it leaves through runoff, evaporation or withdrawal.

In this paper the real case study of Barcelona is addressed. We present first the motivation that has moved the local authorities to consider that a full groundwater study needed to be developed. The study addresses three aspects: (a) process identification, including sink/sources characterization, (b) aquifer modelling, including hydrogeological data integration, and (c) water resources management. The work included different steps such as geological study, hydrogeological conceptualization, recharge sources, boundary conditions, and global water balance. The final outcome is a groundwater model. We present its main features and an application to city local water management.

GROUNDWATER IN BARCELONA

Barcelona is located in northeastern Spain, between a mountain range named Serra de Collserola and the Mediterranean Sea. The city is bounded by two rivers, Besòs and Llobregat (Fig. 1). In Barcelona there are different aquifers, characterized by their geological age. A schematic representation of these aquifers is shown in Fig. 1 (city main streets are plotted for location purposes). The Palaeozoic aquifer is composed of shales and granites. Quaternary aquifers correspond to the alluvial and deltaic sediments of the Llobregat and Besòs rivers; in intermediate areas, they correspond to piedmont cones and coarse alluvial sediments.

During the last few years a large increase in seepage into public and private underground structures (the metropolitan subway, sewage network, and underground parking areas) has been observed; e.g. the total amount of water currently pumped from the metropolitan subway is about $12 \times 10^6 \text{ m}^3 \text{ year}^{-1}$. This seepage problem is not restricted to a few areas, but is quite a general problem throughout the city (Fig. 2).

Given the present groundwater situation, the economic impact of reducing the seepage problems by maintaining groundwater below the structure foundation levels is very high. The impact of maintaining the levels high (no external actions) is also very significant; to the need for drainage works, such as impermeabilization, pump installation, and water disposal, one must add the energy cost of continuously pumping the rather high flows that have to be evacuated. It is important to further note that the use of the city sewage system for evacuating all the seepage water is not a very good solution, as it can affect the proper functioning of the system during periods of critical need, such as summer storms.

The reason for the high phreatic levels can be understood by historical considerations. Since the middle of the nineteenth century, the aquifers underneath Barcelona have been supporting heavy water withdrawals. This produced very large drawdowns, leading to hydraulic head values below sea level at certain points, with the associated impacts on the chemical quality of the water due to seawater intrusion.

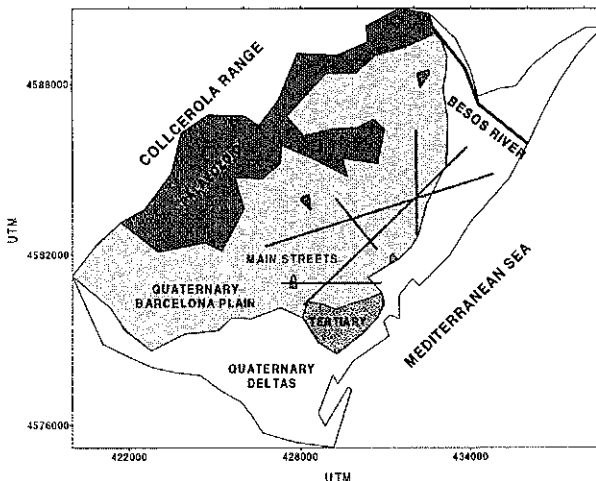


Fig. 1 Hydrogeological scheme of Barcelona.

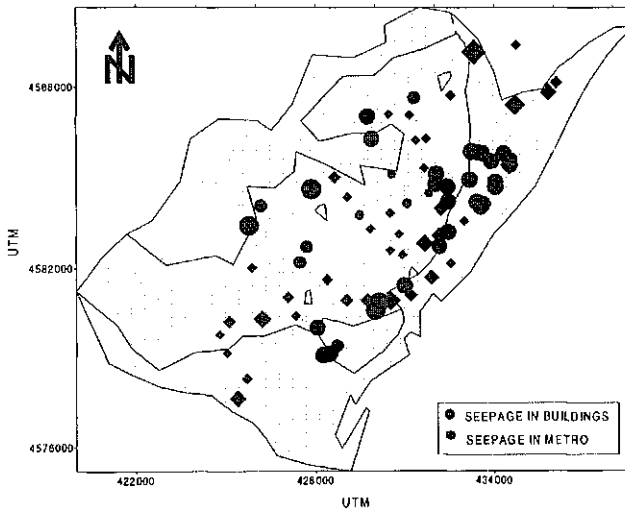


Fig. 2 Seepage problems in Barcelona. Point sizes are proportional to seepage.

Already in this century, and since the 1970s, urban pressure has caused many industries to migrate from the city to other areas. This has resulted in a decrease in total withdrawal and a progressive recovery in the groundwater levels. As a consequence seepage has increased. During the last 30 years, rises from 1 to 10 m in the water table have been observed in certain areas (Fig. 3). The continuous rise in the groundwater levels has become a serious threat to some underground urban structures. Many of them were designed and constructed at times of minimum water levels, and the possibility of water reaching the structure level was never considered.

FACING THE PROBLEM

The municipal authorities were very interested to know the causes of the increasing seepage, what would be the evolution of the problem in the future, and possible

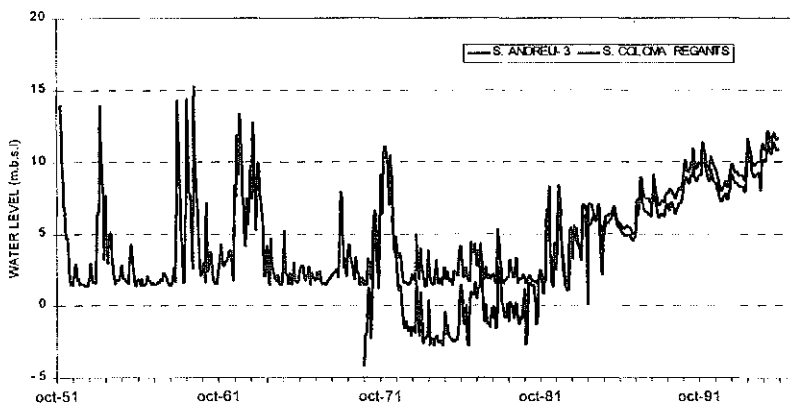


Fig. 3 Evolution of the groundwater table in wells located near the Bésos River.

solutions. The sizeable volume of groundwater beneath Barcelona offers the possibility of exploitation and management, which would help control groundwater levels and would provide an additional water resource for the city. This exploitation might be included in a global hydraulic resources plan in sustainable conditions. The main idea is the progressive substitution of high quality treated water by less quality water in many municipal uses, such as street cleaning, sewage system cleaning, municipal park and garden watering, and also in some industrial uses, whenever technically and economically possible.

In 1995, the local authorities started a huge plan of groundwater development which included: (a) quantification of the total amount of groundwater that could be used in sustainable conditions; (b) possible uses for this water; (c) technical projects for new extraction wells; (d) financial viability studies; (e) groundwater management; and (f) development and installation systems for monitoring hydraulic heads and flow rates.

In order to address these different points, a groundwater model of the whole city was built. The model included the reinterpretation of geology in a hydrogeological context, the evolution of heads and extraction rates, a geochemical study, and a quantification of the water balance. This led to the definition of a sound conceptual model (Vázquez-Suñé *et al.*, 1997).

THE GROUNDWATER MODEL

The conceptual model thus obtained was implemented in a numerical model with multiple purposes: integrating different historical data, accounting for the present situation, validating the conceptual model, quantifying groundwater flows (water balance), and finally, being able to predict the future evolution of the groundwater levels under different scenarios. In addition the integration effort helps to reduce uncertainty in the hydraulic parameters. The aim is to include the numerical model as a management tool for water decision making in the city of Barcelona.

The initial task in the modelling process was to build a database which was fed with all available information, including geological, hydraulic head, hydraulic parameter, and quality data from more than 1000 wells and boreholes drilled since 1900.

The next step in the modelling process is discretization. Spatially, it consists of defining a zonation of the hydraulic parameters based upon geological considerations and available data; a two-dimensional (2-D) finite element mesh consisting of 1762 triangular elements is then superimposed. Temporally, the model starts in 1900, with observation times of one year, until 1960, and of three months from then on (until 1997).

An important feature is the way underground structures are treated in the model. Water inflow is considered as a linear relationship between the water level at the aquifer and the foundation level of the structures. In any case the inflow must be null until the time structures were constructed (independently of water level evolution).

Calibration was performed using TRANSIN-III (Galarza *et al.*, 1996). This is a finite element code that allows automatic calibration of the non-linear hydraulic parameters. The calibration process accounted for 414 observation points (where head measures were available). The fit between computed and observed heads (Fig. 4) is remarkable.

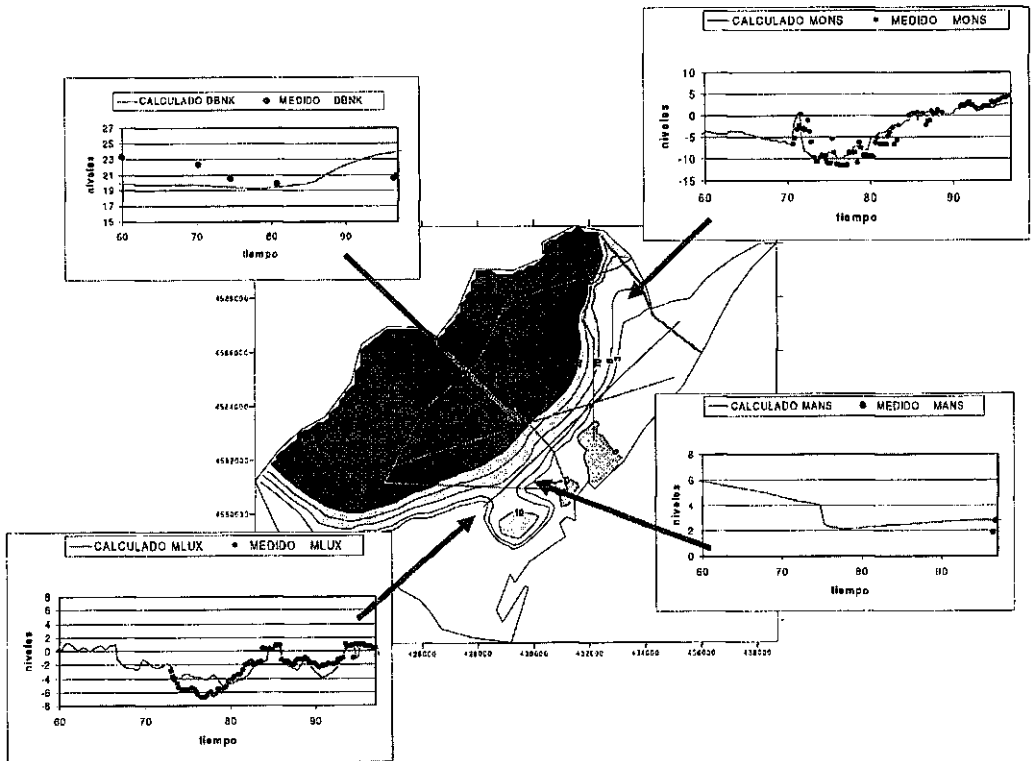


Fig. 4 Groundwater level fit obtained from calibration at selected locations.

An important outcome of the model is the groundwater balance displayed in Table 1. Quantification of the different terms involved in the water balance are critical for two reasons: (a) knowing which are the main points to be stressed when managing the groundwater resources, and (b) suggesting corrective measures.

Some considerations arise from the water balance presented. The model allows more precise quantification of urban recharge (see Vázquez-Suñé & Sánchez-Vila, 1997 for previous estimates). Recharge is conditioned by the losses in the water supply and sewage systems, which account for a very large part of the water entering the aquifers. Additional inflows are excess watering in green zones and direct infiltration of rainfall. The latter has been decreasing due to progressive urbanization.

Table 1 Global water balance for different years ($\text{hm}^3 \text{ year}^{-1}$).

Year	Recharge	Outflow to sea	Lateral inflows	Extractions: wells+others	Extractions: subway	Water storage
1960	27.6	-17.2	4.1	40.2	0.04	0.4
1970	35.7	-17.8	-4.0	56.3	1.3	-0.1
1980	36.3	-7.8	-3.2	42.7	2.4	2.2
1990	34.6	-4.2	-5.2	36.4	6.0	1.7
1995	27.5	0.8	2.4	14.6	6.0	3.7
1996	27.5	2.2	4.6	9.6	7.1	3.9

Water flowing from/to the sea is important as a potential source of pollution. Excessive groundwater extractions during the 1960s and the corresponding drawdown, led to significant seawater intrusion, with loss in water quality. Table 1 reflects the relationship between total extraction and seawater intrusion, with a maximum close to $20 \text{ hm}^3 \text{ year}^{-1}$. From then on, a decrease in water inflow from the sea is observed; as a consequence the groundwater has recovered part of its initial chemical quality.

Regarding seepage to the subway system, it seems that some of the water entering the system does not correspond to groundwater seepage, but to leakage in water systems or to surface water infiltration. In any case the problem associated with seepage is still important and it is increasing with time.

The final column in Table 1 is water storage. It is clear that in recent years the net balance is positive, which corresponds to increasing phreatic levels. The minimum historical levels correspond to the period 1960–1980. This was a time of economic expansion in Barcelona and many buildings were built during these two decades. At that time few people could suspect that groundwater levels would ever recover their historical values so many buildings were constructed without impermeabilization measures. This is now the main reason for seepage. Note that in such cases seepage could result in concrete or steel damage, leading to structural failure.

The economic considerations associated with groundwater levels should be included in a management context. The groundwater model can be integrated in this context. We have to distinguish between global and local management. In a global framework, a piezometric observation network has been defined. It consists of a total of 30 measuring points, distributed throughout the city, where heads are measured and water samples are taken for quality analysis periodically. The application of the model to this network helped defining the potential risk areas and, in particular, where to locate a system of wells that could optimally control water level rises if necessary.

In a local framework, the model is used to define local actions that use groundwater as an additional resource in selected areas and, mainly, to predict the outcome of such exploitation. An example is presented in the next section.

THE MODEL AS A MANAGEMENT TOOL IN A REAL PROBLEM

The numerical model has recently been used as the managing tool it was designed for in a number of cases. We outline the particular motivation, the different parts involved, how the model was used, the main results, and the political decisions finally taken in one of such cases. The selected case is that of the new Fluvial Park that is being constructed at the Besós River.

Until recent times environmental issues were typically neglected in city planning. At present most big projects in large cities in Spain are trying to recover part of the urban space for the citizens. Following this idea, in Barcelona a project under construction aims at recovering the riverbed of one of the major rivers that marks the city limit. After recovering the chemical quality of the surface water, some grass areas will be planted both in the riverbed and in a nearby urban park. All these areas are planned for leisure purposes. The new area is called the Besós River Fluvial Park and its main importance is that it is located in an area with a large historical deficit in green zones.

We focus here on water management for this new area. A total amount close to $1 \text{ hm}^3 \text{ year}^{-1}$ must be supplied to the area in order to maintain the green areas and an artificial lake. The first idea was to use water from the local drinking water supply system. An alternative is to use groundwater from wells located nearby. Using water from the river was discarded for quality reasons. The final decision was cast in a global management concept where the model presented above was a key tool.

The different authorities and companies that provided input to be used in the decision process were: (a) the contractor, who had to provide the installation for whatever alternative was selected; (b) the City Council, who wanted to include this action in the context of using groundwater for non-drinking purposes; (c) the subway managing company, which is having seepage problems in the subway line that passes under the Besós River, amounting to $0.8 \text{ hm}^3 \text{ year}^{-1}$ (note that another alternative considered was direct use of the seepage water from the subway system); (d) the water supply company, with a project for groundwater abstraction, up to 500 l s^{-1} , in the Sant Andreu wells (these wells were used for supply purposes until 1980, and then abandoned due to the decrease in water quality); and (e) private people who are having problems with seepage in several underground parking areas in the zone.

The numerical model presented previously was used to analyse a number of pumping scenarios. The main scenario studied was the compatibility of pumping $15 \text{ hm}^3 \text{ year}^{-1}$ in the Sant Andreu wells plus $1 \text{ hm}^3 \text{ year}^{-1}$ in an abstraction well located beside the Baró de Viver (BVIC) subway station (Fig. 5). Compatibility is measured in terms of admissible drawdowns. We could also determine the effect of pumping upon the groundwater levels along the subway line as an outcome from the model.

The effects on the groundwater levels can be seen in Fig. 5, where equal drawdown lines are plotted. Maximum drawdowns are located near the Sant Andreu wells, as expected. The effects along the subway line are quite significant, as phreatic levels show a decrease of around 2.9 m in the right margin and around 2.3 m in the left margin. This results in an important decrease in seepage which is now around $0.3 \text{ hm}^3 \text{ year}^{-1}$; furthermore, the length of the area affected by seepage is reduced to 200 m.

These results helped in the decision making, as finally the City Council decided to implement the full groundwater option as it was technically feasible, economically competitive and was of some benefit to the subway managing company and to the city in general, because the pressure on good quality water decreased.

This is not the only case where the model has been applied for decision making process. Recently there was another opportunity to use groundwater for watering the botanic garden, located in Montjuic (the Olympic Mountain). Water will be abstracted from the City Plain, carried inside the subway tunnels and pumped up to the mountain. The model was used in this case to evaluate the amount of water that could be abstracted with acceptable drawdowns.

DISCUSSION

The study of urban groundwater is motivated by the strong interaction between city socio-economic development and groundwater environmental impacts. This interaction is generally neglected in real cases. A global analysis of the impact of groundwater in a

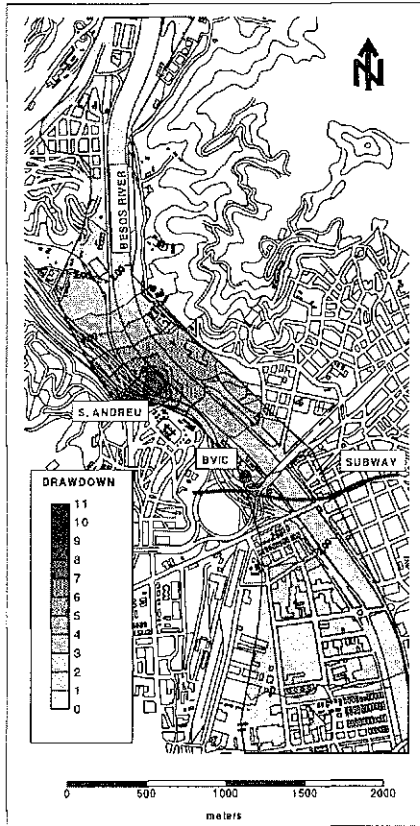


Fig. 5 Calculated drawdowns.

city must include both aquifer characterization (done by hydrogeologists), water resources management (public or private companies), and city planning (politics).

An integrated framework involves the use of groundwater models that can be understood by decision makers. Models of this type must be based on certain criteria that allow definition, characterization and quantification of the potential risk to aquifers and natural systems associated to them, as well as to urban structures, with all the implications for the population. This should allow city managers to consider groundwater as one of the topics to be taken into account in city planning. In this context, water can be considered either as an alternative resource (for park irrigation, street cleaning, secondary distribution networks, water supply, etc.), or as a nuisance (protection of existing structures, precautions and/or permissions for future developments).

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