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## A method to estimate the artificial recharge capacity of the Crestatx aquifer (Majorca, Spain).

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**Abstract** This paper presents a method for the feasibility of an artificial recharge scheme in a limestone aquifer. A 3D digital groundwater flow model was developed and calibrated to gain a better understanding of the aquifer dynamics and to estimate its capacity for artificial recharge. Several scenarios, based on different pumping alternatives, were tested over a 30 year period. The results were then analysed by yearly input-output balances. Worst case scenario model output suggests that implementing the scheme might ensure a sustainable use of the aquifer in the future.

**Keywords** Artificial recharge · Groundwater modelling · Sustainable groundwater use · Majorca

### Introduction

Majorca's tourist industry has experienced a spectacular growth in the last decades, becoming the island's main source of income and employment. Seasonal water demands have in turn increased, and now place a significant degree of stress upon the island's scarce water resources. Sustainable management of Majorca's aquifers is currently perceived as a pressing need. Among other initiatives, an artificial recharge scheme for Crestatx limestone aquifer has been proposed.

The aim is two-fold: first, to ensure a sustainable use of the aquifer; and second, to contribute to stop or slow down seawater intrusion in the Sa Pobla plain. Both could be achieved by taking advantage of sporadic heavy rainfall to replenish the aquifer, when possible, with excess runoff that is currently lost to the sea.

Artificial aquifer recharge is widely recognised as a valuable tool for the sustainable management and conservation of groundwater resources (United Nations 1998). Examples of different artificial recharge techniques such as infiltration ponds and injection wells are well-documented in scientific literature (Murillo et al. 1999, Bouwer 2002, Han 2003).

Previous groundwork was carried out jointly by researchers of the Complutense University of Madrid, the Geological Survey of Spain (IGME) and the Water Resources Direction of the Balearic Regional Government (Gelabert 1998, IGME-DRHGB 1998, Murillo and Lopez Geta 2000, IGME 2004). These provide a better characterization of the aquifer and of the available resources for artificial recharge.

Estimating Crestatx actual capacity for artificial recharge, and thus the feasibility of the scheme, remains a source of controversy among professionals (as well as a

limiting factor from a technical point of view). This paper presents a methodology for the feasibility analysis based on the implementation of a calibrated numerical 3D groundwater flow model.

**Methodology**

Conceptual model

*Aquifer characterization*

The Fangar limestone aquifer system spans a surface of about 30 km<sup>2</sup> in the Tramuntana Mountains of Majorca, Spain, about 40 km northeast of the island’s capital (Fig 1). The aquifer is divided in two hydrogeologically independent units, roughly equal in size: Maria-Casells and Crestatx. Given the topographic complexity the former, only the latter offers an appropriate setting for groundwater development.

The area is subject to a typically Mediterranean climate, with short, mild winters and hot dry summer periods. Monthly average temperatures range from 15 to 25 celsius, while average rainfall in the area of study is 600–700 mm/year (Guijarro 1995). Heavy precipitation

takes place sporadically, and results in flash floods associated with the discharge of the Ufanes springs (about 3 km west of Crestatx). Runoff flows eastward along Sant Miquel creek and discharges into the sea.

By means of two geological cross-sections (Gelabert 1998), the aquifer was found to have an average thickness of about 500 m. Total aquifer volume can therefore be estimated at 1300 Mm<sup>3</sup>. As pumping tests suggest the efficient porosity of the aquifer ranges between 1% and 3%, the aquifer’s total storage capacity must be between 13 Mm<sup>3</sup> and 38 Mm<sup>3</sup> approximately. The average hydraulic conductivity of the aquifer is between 0.5 and 2 m/d.

Under natural conditions, Crestatx aquifer (“Crestatx” or “the aquifer” from now on) discharges along its southern border into a different system: the adjacent detritic aquifer of Sa Pobra plain (“Sa Pobra” or “the plain”). This discharge, together with water from a series of abstraction wells and small karstic galleries (usually dry), accounts for Crestatx total outputs. The aquifer’s sole source of natural recharge is rainfall.

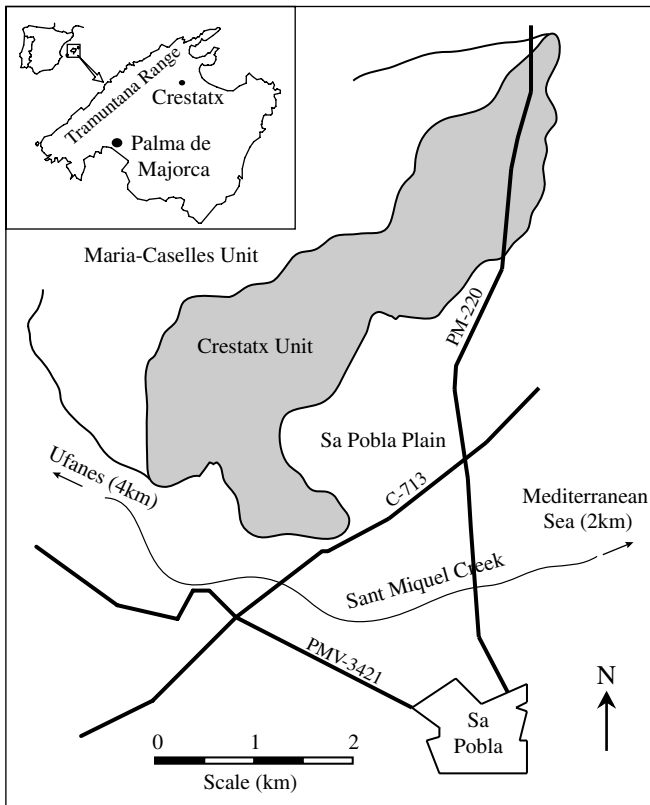


Fig. 1 Geographical setting of the Crestatx aquifer

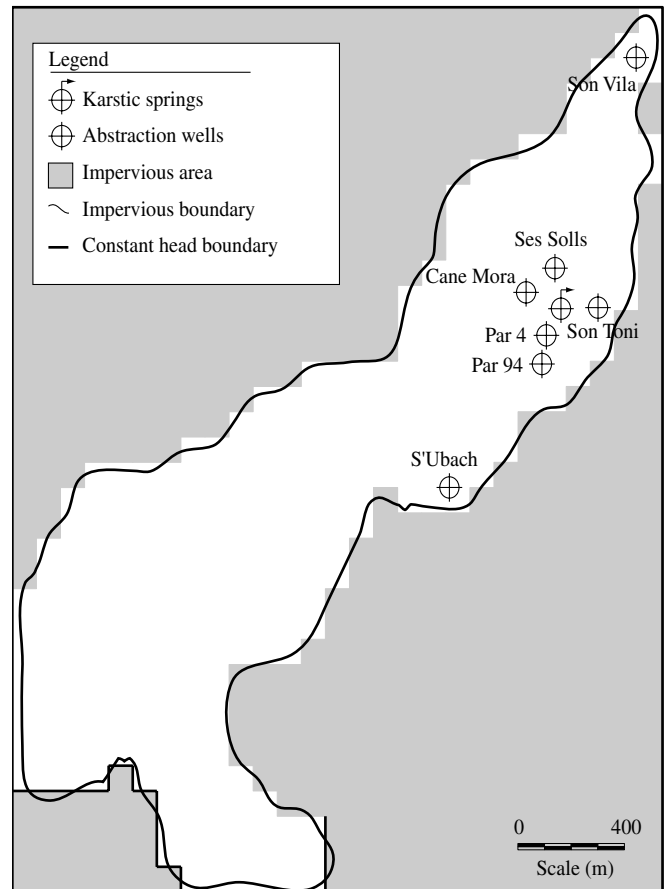


Fig. 2 Overview of aquifer discretization

### Boundary conditions

For modelling purposes, the aquifer surface was divided into a matrix of 100×100 m cells (Fig 2). A single unconfined layer about 500 m thick represents the permeable unit in the vertical dimension. The software package used was Visual Modflow 2.8.

The boundary conditions common to both permanent and transient regime simulations were defined as:

- A constant head boundary of 11 m, corresponding to the piezometric levels in the Sa Pobla plain, along the aquifer southern border (Cardoso 1997). This was assumed constant as the plain aquifer presents a much larger size.
- A drain condition at 30 m above sea level to represent the karstic gallery area.
- Impervious boundaries surrounding the rest of the aquifer.
- A hydraulic conductivity of 0.5 m/day everywhere except in the karstic gallery area, where it is defined as 2 m/day (according to pumping test data).
- Natural recharge equivalent to 30% of rainfall levels for the 1996–2003 period (Fuster 1973, Cardoso 1997).

Three further conditions were added for transient regime simulations:

- Quarterly time steps.
- Initial heads taken from the results of the permanent regime simulation.
- Seven pumping/observation wells to represent the multiple exploitations of Cane Mora, Son Toni, Ses Solls, Par 4, Par 94, S'Ubach and Son Vila.

### Permanent regime simulation

A first simulation was carried out in permanent regime (without pumping wells), in order to replicate the aquifer's natural conditions. The aquifer was found to discharge both through the karstic galleries (at a rate of about 0.05 Mm<sup>3</sup>/year) and along the southern border into the plain (about 0.9 Mm<sup>3</sup>/year). The sum of these two values equals the aquifer recharge from rainfall. The equilibrium potentials range between 30 m (near the karstic gallery area) and 11 m (in the discharge area to the plain). These potentials were taken as the initial head values for ensuing transient-regime simulations.

### Model calibration

Two transient-regime simulations, for efficient porosities of 1% and 3% were carried out to calibrate the model.

An 8-year period (1996–2003), modelled in quarterly time steps, was deemed appropriate in view of the available data.

Natural recharge was estimated as 30% of rainfall (Fuster 1973, Cardoso 1997). The average annual rainfall for the period under consideration was about 600 mm, although it fluctuated between 350 mm (2000) and 960 mm (2003). While these values place the average rainfall slightly on the dry side, the variation allows for the calibration of the model under a wide range of conditions.

Pumping is the main system output. For the 1996–2003 interval, yearly pumping rates for urban supply range between 1 and 1.5 Mm<sup>3</sup>. Almost 75% of pumping takes place during the warmer months (April to September), while approximately 23% occurs from January to March, and only 4% during the last quarter of each year.

Cane Mora and Ses Solls were identified as the main abstraction facilities (see Table 1), with pumping rates between 0.3 and 0.45 Mm<sup>3</sup>/year for the 1996–2003 period. Par 4 proved the least significant with an abstraction volume of 0.05–0.06 Mm<sup>3</sup>/year. While Son Toni's wells have been working since the 1960s, Cane Mora, Son Vila and S'Ubach did not begin until the mid-1990s. Thus, the 1996–2003 period provides an accurate reflection of the aquifer's current situation.

Table 1: Range of yearly abstractions via pumping wells for the 1996–2003 period (Mm<sup>3</sup>/year).

Figure 3 shows the model calibration results. Overall, the model seems to replicate the aquifer's piezometric trends accurately, particularly the 1% efficient porosity simulation. Outliers can be observed due to the daily nature of head observation wells (in contrast with the quarterly nature of pumping data). However, the calibration was deemed satisfactory in view of the existing information. Pumping measurements are currently being carried out at a daily scale, and will be available for future enhancement of the model.

### Simulation hypotheses

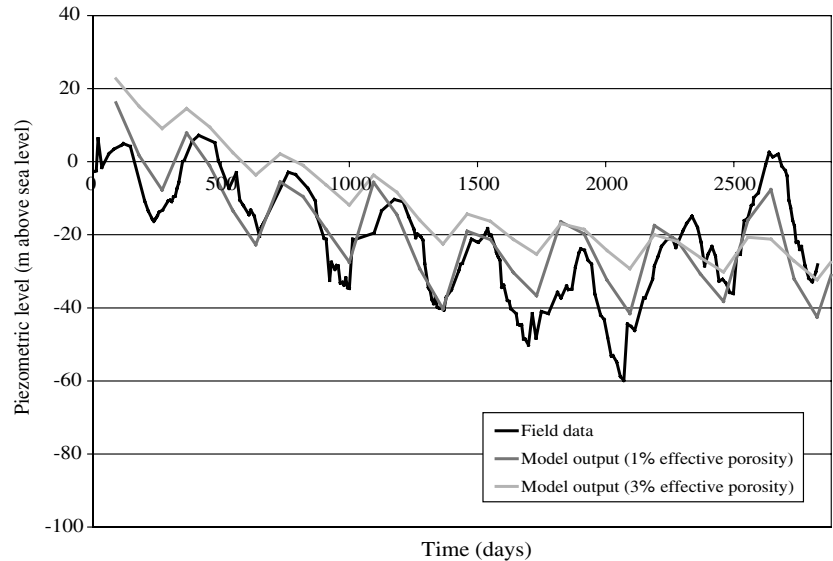
The model was applied to different potential scenarios in transient regime. Aside from the mentioned assumptions, others were made:

- A 30 year simulation period for each simulation hypothesis (quarterly time-steps).
- Rainfall recharge values correspond to those observed in the last 30 years.

**Table 1** Range of yearly abstractions via pumping wells for the 1996–2003 period (Mm<sup>3</sup>/year)

SON TONI	SES SOLLIS	C. MORA	PAR 4	PAR 94	S'UBACH	SON VILA
0.10–0.11	0.32–0.45	0.31–0.45	0.05–0.06	0.07–0.08	0.11–0.12	0.19–0.26

**Fig. 3** Calibration results for 1% and 3% efficient porosity



- Pumping wells are assumed to reach the aquifer bottom.
- A representative observation point was placed near the Par 4 well (due to its geographical location, towards the centre of the pumping cone).

To observe the evolution of the available volume for artificial recharge in time, the yearly input-output balance for the aquifer was simulated. This is done according to the balance equation:

$$\text{Inputs} - \text{outputs} = \text{change in storage}$$

Which, for the case under consideration, is equivalent to:

$$R + R_p - (P + D_p) = \Delta S$$

Where  $R$  is rainfall recharge,  $R_p$  is potential recharge from the plain into the aquifer,  $P$  is the total volume pumped from all abstraction wells,  $D_p$  is the discharge from the aquifer into the plain and  $\Delta S$  the change in aquifer storage.

Thus, the following management scenarios were tested:

- Current pumping regime for the next 30 years.
- A two-fold increase in pumping regime (for 30 years).
- A three-fold increase in pumping regime (for 30 years).
- A four-fold increase in pumping regime (for 30 years).
- An artificial recharge simulation for three-fold pumping conditions (for 16 years corresponding to the existing data on available runoff for artificial recharge).

## Results

Numerical model output was processed and analysed in the following sequence:

- Elaboration of equipotential head and drawdown graphs to observe the influence of increased pumping upon these levels and the potential impact of drawdowns on the existing abstraction wells.
- Evaluation of the relationship between the Sa Pobla plain and the aquifer to establish its variation over time.
- Yearly input-output balance to estimate the cumulative distribution of available aquifer volume in time. This volume constitutes the aquifer capacity for artificial recharge.
- Comparative interpretation of results, discussion and conclusions.

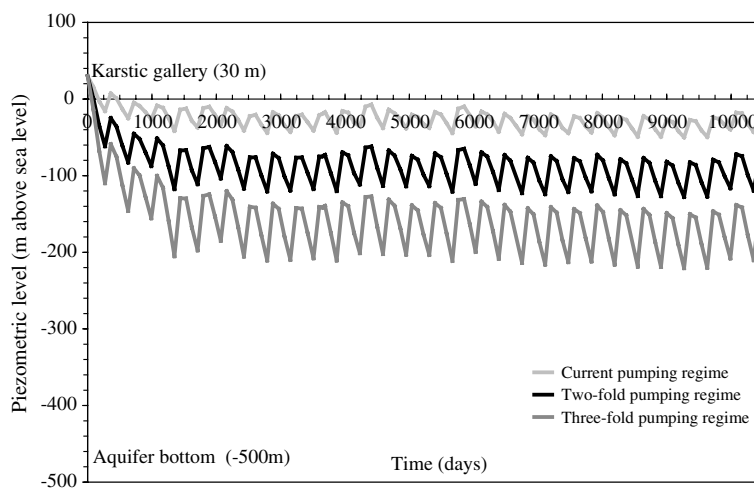
## Discussion and conclusions

Figure 4 shows the relative evolution of piezometric levels depending on the pumping regime. This implies drawdowns between 40 and 250 m from the natural conditions, depending on the simulation hypothesis. It must be noted that a four-fold pumping increase would lead to drying of several wells. Thus a three-fold increase would constitute the system limit.

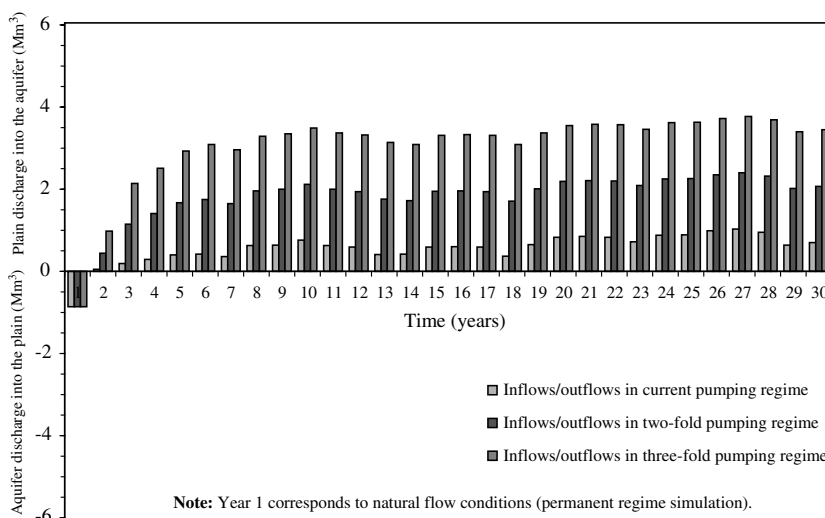
Figure 5 shows the flow relationship between the aquifer and the plain for each pumping regime. The main feature of this graph is the flow inversion that takes place with regard to the natural conditions. Notwithstanding the pumping alternative, it would take less than a year for the aquifer inflows to the plain to stop. Thus, under severe pumping and with no artificial recharge, inverted flows from the plain into the aquifer might reach a maximum of nearly 4 Mm<sup>3</sup>/year.

Figure 6 provides an overview of the cumulative “void” induced by pumping, or the “artificially rechargeable” volume. For the given modelling condi-

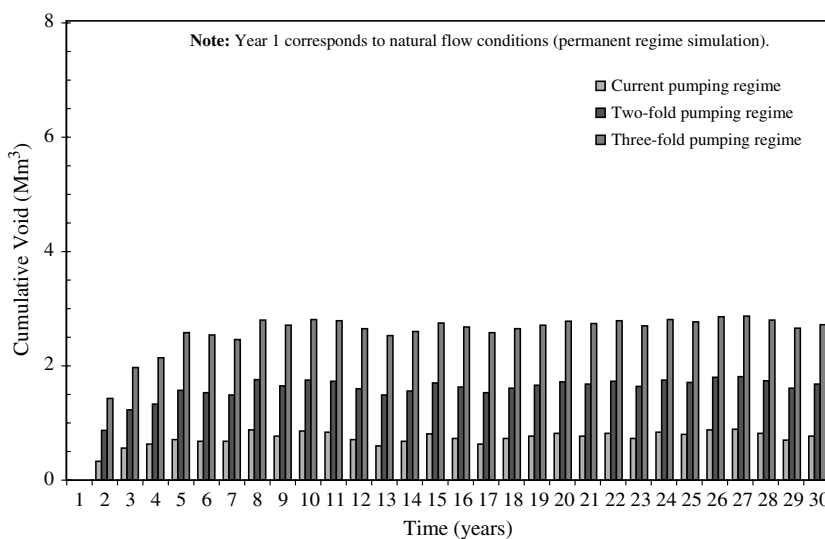
**Fig. 4** Piezometric evolutions for each pumping alternative



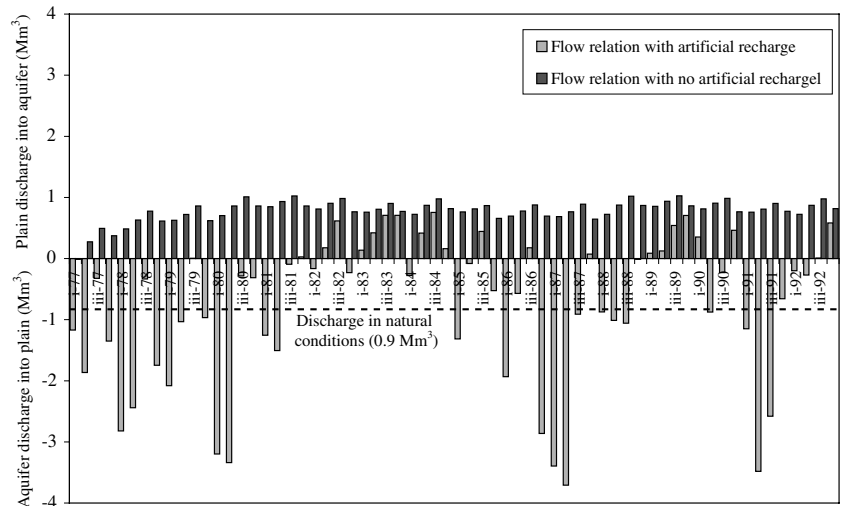
**Fig. 5** Flow relationship between Crestatx aquifer and Sa Pobla Plain for each pumping alternative



**Fig. 6** Cumulative volume available for artificial recharge



**Fig. 7** Flow relationship between Crestatx aquifer and Sa Pobra Plain with and without artificial recharge (for a three-fold pumping regime)



tions, such volume would reach a maximum every seven or eight years (just under  $1 \text{ Mm}^3$  under the current pumping conditions and almost  $3 \text{ Mm}^3$  for a three-fold pumping regime). However, should this void be recharged completely at any given time, the system could be assumed to go back to initial (natural) conditions.

The last simulation hypothesis included artificial recharge inputs under the most severe pumping conditions. This would imply a worst case scenario setting, as the available water for artificial recharge would only be available after sporadic precipitation phenomena. For modelling purposes, these were obtained from the estimates of Murillo and Lopez-Geta (2000). Figure 7 shows the flow relation between the aquifer and the plain with and without artificial recharge.

Artificial recharge would prevent the flow inversion about two thirds of the time under the most severe pumping alternative. In fact, in 11 out of 16 years, artificial recharge would result in the aquifer yielding to the plain a volume higher than in natural conditions ( $0.9 \text{ Mm}^3/\text{year}$ ). Finally, model output shows that for about 25% of the time, excess water would discharge through the galleries.

These results present two main implications. Firstly, given the potential resources calculated by Murillo and Lopez-Geta (2000), the artificial recharge scheme seems a feasible option from the hydrological point of view. Second, excess artificial recharge of the Crestatx aquifer would mostly end up recharging the plain aquifer. This might prove a valuable aid against the sea water intrusion problems currently being experienced by the latter (Manzano et al. 2002, Galimont et al. 2003). However, a more detailed assessment of the actual significance of such barrier will not be available until a joint model of the aquifer and the plain is implemented.

Finally, the value of these results is acknowledged to be limited. As pointed out before, the model presents a series of restrictions which stem mostly from the quality of available data. Particularly, given the sporadic nature of rainfall precipitation, both artificial and natural recharge should be dealt with on a daily scale. In addition, this reveals the need for further field campaigns to deal with both aquifers (Crestatx and Sa Pobra) in a joint manner. Thus, while the accuracy of the current results is likely to be enhanced, the outlined methodology appears a valid tool for future works.

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