

Hydrogeological studies previous to the artificial recharge of *Los Arenales* aquifer, Duero basin (Spain)

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ABSTRACT: The intensive rate of groundwater exploitation in several areas of “*Los Arenales*” aquifer (Duero Basin, Spain) during last four decades has originated a remarkable descent of water heads. As a consequence of this problem, the ministry of agriculture of Spanish government (MAPA) began several studies and inquiries based on artificial superficial recharge in order to minimize environmental impacts.

The main aim of this writing is to describe the employed methodology based on three-dimensional palaeogeography reconstruction of the wind-sand detrital aquifer employing topographical and geophysical methods, carrying out hydraulic tests in boreholes, etc, in order to find out the behaviour of the aquifer and its response to artificial recharge. Complementary studies allowed accurate *Modflow* modeling, which uses quantitative data about the volume of water involved and the most adequate recharge method and facilities in each area. The results suggest that this aquifer is appropriate for artificial recharge application, the methodology is feasible and useful to other similar aquifers, and the consequences of its application should be profitable in agriculture benefits, environmental alterations and social acceptance.

1 INTRODUCTION

Artificial recharge of aquifers in Spain is increasing in importance, as a consequence of the prevailing dry climate in most of the country and the abrupt physiography. A rising trend is also expected if this activity is combined correctly with the objectives of the National Hydrological Plan, that emphasizes the water transfer between different watersheds, and the construction of new damming.

Numerous studies and experiences have been developed during the last 30 years, prevailing a main goal: availability of water resources in the framework of Spanish agrarian policy that has prevailed during the second half of the 20th century.

One of the best documented examples of artificial recharge is located in several areas of *Los Arenales* aquifer, *Duero* Basin (NW of Spain), as a consequence of the phreatic levels falling due to the intense irrigation-use pumping. The considered sites are the “*Cubeta de Santiuste*” where some recharge input devices are being built at present time (Fig. 3), and *Carracillo*, where previous viability studies are almost finished and the execution of the building project will be scheduled in the very next future. They are located in Segovia and Valladolid provinces.

2 GENERAL CONTEXT

Arenales aquifer is located in the southern sector of Duero Basin. Its surface spreads over 7,754 km² and includes a part of the provinces of Salamanca, Valladolid, Segovia and Avila. The main rivers that run across this aquifer are Duero, *Zapardiel*, *Adaja*, *Eresma* and *Voltoya* (Fig. 1).

3 RECHARGE ACTUATION

The *Santiuste* basin is a small aquifer with 85 km² in extension, that is limited by the Voltoya and Eresma rivers to the East, and low permeability Tertiary outcrops to the West. Despite its reduced size, it is considered an important irrigation area depending on groundwater. The projected artificial recharge actuation will be carried out making use of a small stream watercourse called *arroyo de la Ermita*, that gets partially interrupted by labor fields and where important land movements have been performed during the drought periods happened in Spain during the last 20 years. These actions have almost made it completely disappear.

Despite its poor entity this stream presents a very well developed system of fluvial terraces constituted by alluvial gravel deposits that gets intercalated inside the Quaternary sandy aquifer. According with geophysics the stream trace gets orientated along the SSE-NNW tectonic trend, detected in the 500 metres

deep basement. Several outcrops of the Tertiary aquitard acting as impermeable basement of the Quaternary aquifer appear along the stream trace.

The recovery of the old watercourse and the construction of the recharge devices is based on the construction of a small dam that taps the Voltoya river, directing the water from a altitude of 817 m above sea level, by gravity down to a transferring station sited at 814 m above sea level. A 10 km long pipeline starts from this station, directing the water down the slope to a 36 m³ deposit. The main recharge ditch, dug out through the 20 per cent of the old watercourse of the *Ermita* stream, starts from this deposit to the surroundings of the Eresma river, where the irrigation area ends. The trace of the ditch goes down 30 m of height difference and 0.28% slope through a 10.7 km distance. This ditch is 1.5 m high and 1 m wide, with 1/1 banks, and it has 53 stopping devices with the aim of facilitate the infiltration and decant processes. It has, as well, 32 transit devices. A parallel service road is being built 4 m away from the ditch that gets elevated 50 cm above the terrain height and will serve as a barrier against possible overflows.

The infiltration surface is close to 33,300 m². The maximum directed flow of water surplus from the Voltoya river is expected to be 1 m³/s between November and March, although it may decrease or even get stopped according with the river flow. The maximum directed flow may reach 8 hm³ per year, although it will depend on the characteristics of the considered hydrological year. The sheet of water inside the ditch will range between 50 and 100 cm in height but it will tend to be 80 cm.

The traces of the Voltoya river, to the east, and the *Ermita* stream, to the west, are shown in Figure 2 where it can be seen that the stream flows through an area that connects some small basins filled with Quaternary eolic sediments developed over an abrupt Tertiary palaeorelief.

Carracillo site is located about 40 km to the east of *Santiuste Basin*. It spreads over 150 km² and is located in the interfluent of Cega and Pirón rivers. It has a labeled irrigation culture, where at least 2,700 ha are irrigated with groundwater. The definitive recharge devices have not been defined yet.

The progressive exploitation increase of the superficial Quaternary aquifer has caused the falling of the water table down to 10 m, and led salinization and contamination processes in both zones.

The simplified geological profile, valid for both sites, is formed by a regulation Quaternary aquifer, composed by fine sand dunes, alluvial river deposits and clays. Its average thickness is about 20 meters, with a maximum registered value of 57 m. Below those, alluvial deposits were deposited, altogether with altered Tertiary materials up to 4 m of thickness, and a Tertiary aquitard constituted by clays,

sands and marls. A new aquifer composed by arkose sludges and carbonates was found at 100 m in depth.

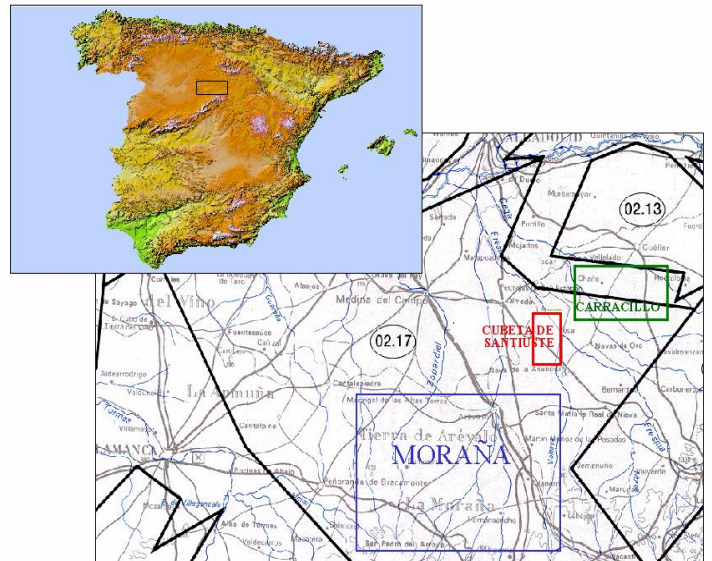


Figure 1. Geographical location of *Los Arenales* aquifer (scale map 1:200,000) and the position into the Iberian Peninsula.

The assigned budget to studies and projects in the last stage (after being declared as works of general interest by the national Decree Law 9/1998) ascends to 374,000 € for the basin of *Santiuste*, and 741,600 € for *Carracillo basin*, independently of the costs of the previous studies.

Previous studies were carried out in successive stages through the decade of 1990, when water deficit kept on rising in both contexts. Although most of those studies present several common features, there are important differences that require the use of different methodologies, due to *Santiuste* is a restricted basin, while *Carracillo* presents an open surface limited by riverbeds in one side, and political limits in the other one.

In order to improve the three-dimensional knowledge of the aquifers structure and their hydrogeological behavior, many tasks were accomplished, as geoelectrical prospecting works with a total amount of 147 vertical electrical logs in *Santiuste* and 607 in *Carracillo*, and respectively 14 and 34 investigation mechanical parametric boreholes drilled (employed later as observation piezometers), 10 and 18 pumping tests (where slug and bail interpretation method has been considered the most convenient), 6 and 12 *in situ* infiltration tests, 16 and 18 in laboratory, there were inventories of 234 and 452 water points in order to update the hydrogeological mapping, and were measured the current river flows at 2 and 19 stations. Digital Terrain Models were generated, reconstructing the palaeogeography of the final Tertiary.

Additionally and with the aim of controlling the evolution of the aquifer behavior, several monitoring nets have been designed: piezometry monitoring nets constituted respectively by 41 and 111 water

points, hydrochemical nets composed by 28 and 48 points and Artificial Recharge nets with six and 24 piezometers located on both sides of the recharge ditch.

At present, new studies are being accomplished focused on the exhaustive knowledge of the physical environment willing to its integration in a numeric modeling (*Modflow*), that will be operative in 2003 year in Santiuste, while it is already operative in *Carracillo*.

4 DISCUSSION

In this paper it was intended to define a methodology based on the empirical experience obtained in several studies of surface artificial recharge in two regions of a sandy regional aquifer. After analyzing the resulting experiences at a first stage, and applying the “*trial and error*” method, it is concluded that a study of these characteristics requires an exhaustive knowledge of the environment, what, at least, precises the three-dimensional reconstruction of the palaeogeomorphology of the Quaternary aquifer (Fig. 2) through the elaboration of detailed mapping, use of microtopography data of the present surface and reconstructing the palaeorelief employing specific accurate interpolation tools (good results were obtained using triangulation with linear interpolation). This aim requires the application of direct techniques (continuous core borings) and indirect (geophysical exploration, choosing the most suitable method according to the highest behavior contrast of the materials). It always results convenient to accomplish some indirect techniques (logs) with well-known parametric boreholes, in order to obtain an accurate calibration.

Hydraulic tests in wells are necessary to determine the heterogeneity and anisotropy of the aquifer with the greatest precision, and to calculate the “*optimum recharge rate*” in every zone. It is also necessary to detect the location of the fossilized fluvial gravel deposits since they may work as drains. Up to five days long recharge tests in infiltration ponds have been carried out, although monitoring some test pilot areas during one hydrological year it is expected to be done with the purpose of determining an infiltration optimum rate similar to that of the real recharge conditions. Short period laboratory or in situ tests have resulted to be of inappropriate magnitude since they differ even two orders with respect to the longtime tests results.

Water balances should be referred to some given space-time conditions, and it is preferable to elaborate several balances in small watersheds what will allow to tickle the problem in different points at the same time. Due to the application of an aggregation technique some zones may be scantily recharged while other get waterlogged at the same time. For this reason, it seems to be necessary to establish ho-

mogeneous units from a hydrological and hydrogeological point of view as well as to apply a runoff-rainfall modeling. The models *HELP* and *Témez* are providing good results. This technique requires the support of GIS tools, what allows to determine high over flood risk areas and to design structures against the effects of the surface runoff. It is also necessary to know the distribution of the pumping areas according to their rate of exploitation.

The aquifer drainage analysis requires sequential flow tests in different points of the river involved in the aquifer behavior, enhanced with complementary techniques. For instance, the study of the intersections cutoffs between chemical isolines or major ion composition ratios with riverbeds and isopiestic lines appears to be a technique that provides accurate qualitative results. The zonal water balances must be contrasted with the results of the modeling applied, defining some zone-budgets and elaborating determined mass balances, especially in the sectors which behavior is directly conditioned by the rivers flow regimes.

The design and monitoring of the observation networks results necessary to feed the mathematical model, basic tool to optimize the design of the distribution nets, in order to spot the position of the recharge devices, to determine the future recharge regimes, as well as to aboard the temporary planning and management of the recharge facilities. In light of the experiences obtained during the accomplished studies, it has been observed that the application of a constant head boundary gives to the model a very high degree of dependency, resulting more realistic, although it is also more difficult to use limits of the kind General Head Boundary or general phreatic level when calibrating the conductance or simulating a battery of wells with a tantamount negative and variable flow rate.

In the same way, the periodic analysis permit to prove if the scheduled processes of interaction between infiltrated water and soils or rocks applying hydrochemical modeling or codes are fulfilled after one period of recharge, and also, concerning to their interaction with pollutants, if it is adjusted to the anticipated model (decrease of groundwater quality at an initial stage of at least two years, to progressively reduce afterwards the pollutants concentration). Anyhow the superficial aquifers recharge is an activity suitable to walk towards the “good state of the waters” that imposes the community guideline 2000/60/CE as objective to reach in 2015 by all the state members of the European Community.

The quantitative control must also be boarded with very frequent measurements or even to be continuous, in order to adjust the infiltration optimum rate of all the devices (ditches down stream gates and ponds) with a distributed treatment.

Some of the objectives that will be reached during the recharge task will be the facilities design in order

to minimize the head losses, to accomplish labors of aquifer clogging, to reduce costs in transportation, storage and pumping, that may have a high enough useful life to obtain a high profitability. Furthermore they will have to consider some systems of recharge water treatment, employing filters, decant devices, etc.

Another objective to carry out during the artificial recharge stage will be the elaboration of a manual of practical procedures related to the design of a following and alertness program linked to the artificial recharge system, the adoption of parameters that permit adequate water management and the elaboration of a planning program which considers the employment of groundwater and surface water.

5 CONCLUSION

Current investigations indicate that the mentioned zones are auspicious for superficial artificial recharge. The preliminary applied methodology and the design of the recharge devices show that this activity is perfectly viable and applicable to other aquifers with similar characteristics. The application would result beneficial in agrarian productivity, environmental impact and social acceptance and any performance should take into account the involved regulation and the traditional inhabitant customs.

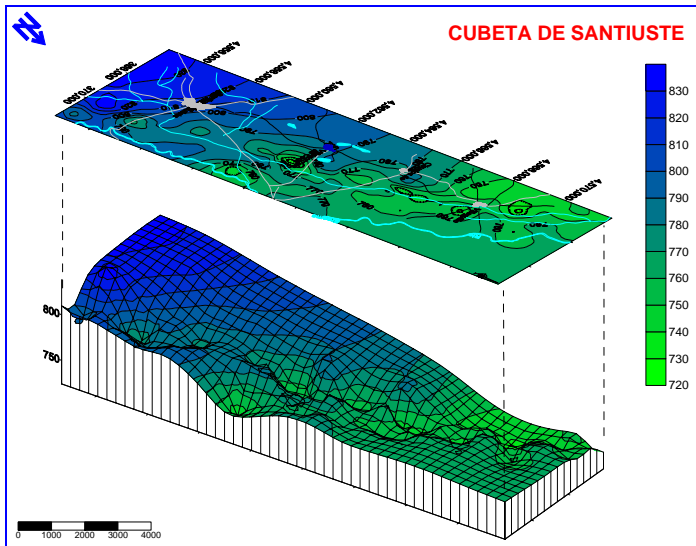


Figure 2. Palaeorelief reconstructed of the geomorphology of the Tertiary aquitard. The upper map shows the trace of Ermita stream, to the west, and the Voltoya river, to the east.



Figure 3. Initial building works of artificial recharge ditches at Santiuste basin, Segovia, Spain.

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