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title: **Managing groundwater resources linked to perennial and non perennial streams: Santa Coloma River Basin, Girona, Spain**

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SUMMARY

Hydrological relationships between surface and groundwater are crucial in alluvial aquifers, both for management purposes and with the aim of accomplishing the objectives of the Water Framework Directive. This paper presents a numerical flow model that considers a river-connected alluvial aquifer in Catalonia, NE Spain. The model mass-balance shows the dual gaining/losing character of the Santa Coloma River and the relevance of the drains in a wetland area, which account for a significant percentage of groundwater withdrawn from the alluvial aquifer. The model also points out the role of "extraction" associated with phreatophytic plants in reducing surface flow rates, especially during summer and droughts. A good understanding and quantification of the river-alluvial relationship helps to determine the best actions in order to promote conjunctive use (groundwater-surface water) whilst preserving fluvial ecosystems.

INTRODUCTION

The Water Framework Directive (WFD, Directive 2000/60/CE) is essentially an environmental norm, which seeks the good ecological status for all European waters. Among the distinct groundwater bodies, managers are especially concerned with alluvial aquifers because of their relationship with stream hydrology and ecology. Given the objective of reaching the good ecological status for surface streams, hydrogeologists claim that assessing the hydrological stream-aquifer mass-balance should be a must.

In order to accomplish with some of the requirements of the WFD, the Catalan Agency of Water (the Agency), as a regional authority responsible for water management and planning, has drawn up the Environmental Flows Plan in the Inner Catalan basins (PSCM, 2006). This plan establishes the necessary environmental flows to fulfill a good development of fluvial ecosystems and imposes restrictions on water users. In this context, the Santa Coloma River (SCR) poses a challenge to PSCM's implementation due to the difficulty to guarantee ecological flows in the latest dry periods.

According to the importance of groundwater in river-connected systems, the Agency has carried out several studies in SCR alluvial aquifer in order to reverse the current trends and to meet environmental goals as well. Probably, the main step consists of estimating the system water budget, including the details of stream-aquifer fluxes. This is far more necessary in dry seasons when the availability of water resources is lower and water demand higher, and it exists a lack of external water supplies.

A third factor to be considered is the need to ascertain the most appropriate conceptual model of the stream-aquifer system. Issues such as a difficult geological context, the lack of information on hydrogeological flows, the historic construction of draining channels, the uncertainty about some pumping rates, and the inherent complexity of stream-aquifer interactions explain some of the discrepancies found in the preliminary studies performed up to now.

All these reasons explain the decision taken by the Agency, in collaboration with other institutions, to build-up a reliable conceptual model of the SCR aquifer that has been translated to a numerical model capable of quantifying groundwater flows between the stream and the aquifer. Our final goal is to identify the factors, and their magnitude, that control such processes as a mean to improve water management in these locations within the WFD goals of environmental preservation and sustainability.

GEOLOGY AND HIDROLOGIC CONTEXT

The SCR hydrographic basin (270 km²) is located in the Guilleries range, within the Selva basin (Catalonia, NE Spain) in a range-and-basin setting formed during the Neogene period (Fig. 1). In particular, the SCR main course follows a main tectonic line, i.e. the regional fault zone in the geological contact between the Guilleries range and the Selva basin.

The Selva basin aquifer systems presents a sedimentary infilling that took place during its tectonic evolution. Sedimentary materials (mainly sand and silt layers) may reach a thickness of more than 200 m in this area, and behave as a multilayer aquifer with intergranular porosity. Along its course, the SCR shows a quaternary alluvial belt with an average width of 1.3 km and a depth of 15-20 m. In its lower part, the SCR joints the Sils channel, which collects the eastern drainage network of the basin. Due to its tectonic setting and geomorphological evolution, the Sils channel sedimentary formations are about 5-m thick and develop in flat areas that have permitted the recent recovery of part of the original wetlands. The Guilleries range is mainly constituted by igneous rocks, with a weathered horizon at the surface. Its porosity is due to fractures except in its most weathered parts.

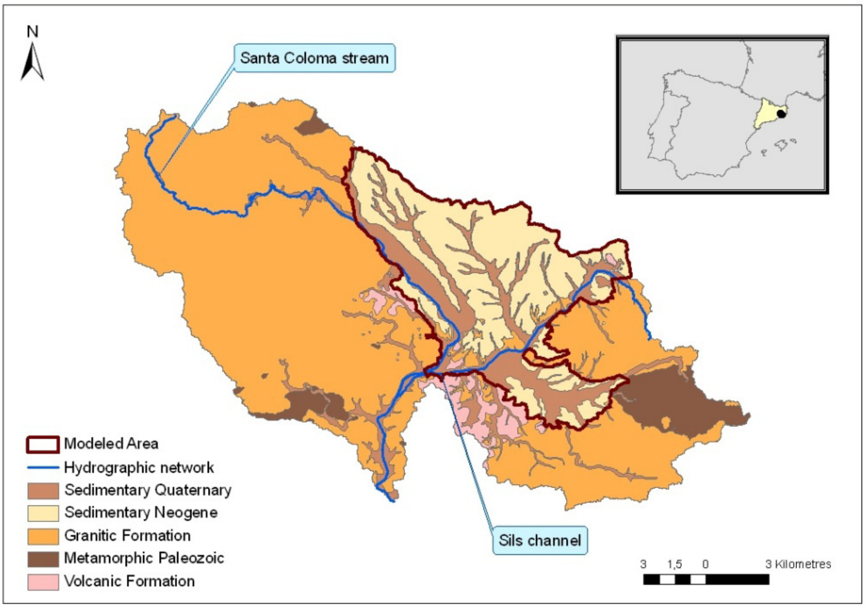

Figure 1. Aquifers of the Santa Coloma river basin and modeled area.

The hydrogeological behavior of this system is complex and characterized by both local flow systems, whose recharge areas are on the hills within the Selva Basin itself, and regional flow systems, which are recharged in the nearby ranges in the NW (Guilleries, Transversal mountains) and discharge through the main fault zones (Folch, 2010; Menció, 2006). A previous study pointed out the fault zone (Folch, Mas-Pla, 2008) influences on the recharge of the sedimentary infilling in this area.

The SCR is an affluent of Tordera River. The fixed measuring gauge is just at the end of the basin, before their confluence. The average flow is 1.26 m³/s during the period comprised between January 2003 and May 2009 (Fig. 2). Surface discharge varies much seasonally, and often is well below the defined environmental flow (0.243 m^3/s) in summer. The lack of minimum flows was particularly serious during the last drought (spring of 2007 until summer 2008), when measured mean discharge was under 0.304 m^3/s and 0.365 m^3/s in autumn and winter, respectively (PSCM, 2006).

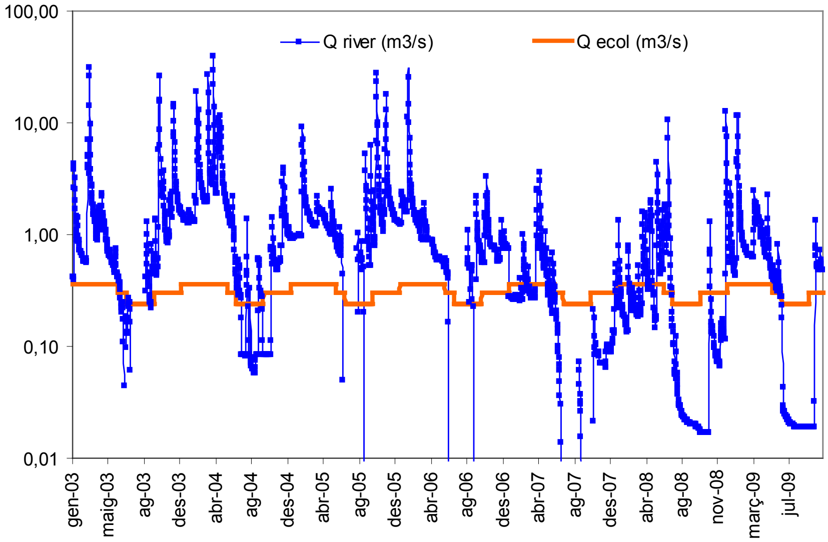

Figure 2. Measured SCR flows (Q river) and calculated environmental flows (Q ecol), in m^3/s.

Apart from the two perennial streams called SCR and Sils channel, there are also non-perennial streams that contribute to the surface drainage.

METHODOLOGY

The conceptual model has been based on existing geological and hydrogeological information derived from previous work, including 12 hydraulic head data surveys starting on 2002. Additionally, two new field surveys were conducted in the framework of this project to increase and update potentiometric data of the alluvial and upper (< 30 m deep) neogene formations. Hydraulic head data loggers were used to estimate transmissivity parameters. As hydrological data, the difference between monthly rainfall and evapotranspiration rates (calculated from land-use and crop distribution) was estimated.

In order to investigate flow relationships between the uppermost hydrogeological units (up to 30 m depth) and the stream-connected alluvial, as well as assessing the water mass balance, a groundwater flow numerical model was developed using the Visual Modflow 4.3 platform (Schlumberger Water Services).

Quantifying groundwater abstraction is usually a hard task. In this model, pumping from the superficial aquifers has been estimated at 4.00 hm^3/yr: 1.30 hm^3/yr for urban water supply; 2.30 hm^3/yr for agricultural demand, which was obtained by means of specific coefficients for the distinct crop types in the area; 0.06 hm^3/yr for cattle-rising water demand, and 0.34 hm^3/yr

for industrial demand. Also, evapotranspiration due to phreatophytes was considered in the model, and included as negative recharge (-1.21 hm^3/yr). Finally, returns from waste water treatment plants (3.50 hm^3/yr) were included as injection wells at the nearest cells of the drainage network.

Distinct types of boundary conditions were implemented in the model, as follows: 1) prescribed head at the lower reach of the alluvial formation; 2) prescribed flow to cells located in the upper reaches of the alluvial formations representing groundwater flow from the upper part of the basin; 3) general head boundary (GHB) at part of the southwest boundary, coinciding with the tectonic contact with the igneous rocks of the Guilleries range, in which a head representing an average value within the mountain area is prescribed[7], together with a conductance parameter that can be approximated using hydraulic conductivity data from the igneous rocks. This GHB condition intends to account for fluxes coming from the weathered granite as well as the contribution of the fault zone to the nearby alluvial formation; 4), a no-flow boundary has been defined upon the neogene materials in the northern hydrographic limit of the SCR basin that acts as a water divide with the surrounding basins, and also on those limits whose hydraulic conductivity is very low; 5) the Modflow "River" boundary condition was applied to the SCR main stream; 6) the so-called "Drain" boundary condition was assigned to the Sils channel, to non-perennial streams as well as to all the main drains in the wetland area. Final conductance values at the base of the river and drains were refined through calibration.

A steady-state simulation was conducted to set-up the initial conditions, as compared to field data. The transient simulation covers a 6.5 years period, from January 2003 to May 2009.

RESULTS

Results from different simulations are consistent with the observed head distribution and give acceptable water balance error (<0.003 %). Simulations also point out the relevance of rainfall recharge, which is especially evident during the dry years of 2006 and 2007. It is significant that the output flow from the aquifer layers (including alluvial and neogene formations up to 30 m deep) is linked to groundwater discharge to perennial (3.27 hm^3/yr) and non-perennial (14.92 hm^3/yr) streams, and only with a minor proportion to pumping wells (3.35 hm^3/yr). Nevertheless, wells have strong impacts on environmental flows in summer or droughts, which is of upmost relevance to meet the WFD goals (Tab. 1). Besides, considering phreatophytic evapotranspiration (-1.21 hm^3/yr) has an effect on groundwater-to-river discharge (0.1 hm^3/yr), yet it also reduces surface water flows by 0.9 hm^3/yr (0.3 hm^3/yr in the SCR and 0.6 hm^3/yr in drains), and also groundwater withdrawal by 0.1 hm^3/yr from aquifer storage. The influence of phreatophytes, which mostly transpire in summer, causes a 1.0 hm^3/yr reduction in surface water flow just in this period (i.e. almost 0.130 m^3/s, which is a 54% of the proposed environmental flow, 0.243 m^3/s).

Table 1. Mass-balance results for the transient simulation, in hm^3/yr.

	2003	2004	2005	2006	2007	2008	2009*	Mean
Recharge In	24.21	20.85	16.32	9.31	2.87	11.36	5.89	14.15
GHB In	0.96	0.97	0.96	0.96	0.96	0.97	0.40	0.96
River leakage In	2.21	2.01	2.26	2.32	2.67	2.63	0.91	2.35
Drains In	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wells In	5.64	5.73	4.62	3.94	3.33	4.60	3.45	4.64
Constant Head In	0.44	0.42	0.44	0.44	0.46	0.45	0.18	0.44
Total Input	***33.5***	***30.0***	***24.6***	***17.0***	***10.3***	***20.0***	***10.8***	***22.6***
Recharge Out (**)	1.24	1.06	1.25	1.25	1.25	1.23	0.25	1.21
GHB Out	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
River leakage Out	3.90	4.78	3.38	3.32	2.04	2.19	1.44	3.27
Drains Out	15.84	19.14	15.48	15.66	11.64	11.78	6.79	14.92
Wells Out	3.54	2.98	3.20	3.63	3.68	3.07	0.68	3.35
Constant Head Out	1.11	1.14	1.11	1.11	1.07	1.09	0.46	1.10
Total Output	***25.6***	***29.1***	***24.4***	***25.0***	***19.7***	***19.4***	***9.6***	***23.9***
Storage Variation	***7.8***	***0.9***	***0.2***	***-8.0***	***-9.4***	***0.7***	***1.2***	***-1.3***

*.- 2009: data up to May,ç

**.- Estimated evapotranspirtaion by phreatophyte vegetation.

Calibrated conductance value is of 500 m^2/day for the SCR main stream. A sensitivity analysis for this parameter is shown in Fig. 3 for a wide range of conductance values.

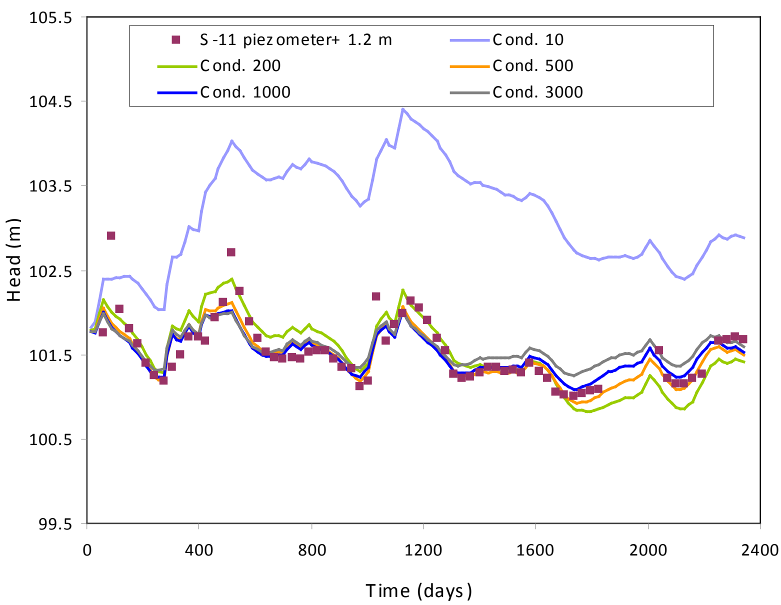

Figure 3. Evolution of piezometer S-11 (after topographic levelling in m) with different values of river conductance during the transient simulation.

The drain's conductance values vary between 5 and 80 m^2/day for the smaller and bigger drains, respectively. Drains are responsible for a 67% of the total rainfall recharge. This result suggests that both, underlying quaternary alluvial formations and neogene sedimentary layers, may contribute to the loss of groundwater resources as surface discharge.

It is also significant that, according to our conceptual model, some reaches act as "loosing stream" or "gaining stream" along the SCR. This suggests a complex behavior of the stream-aquifer relationship that needs to be locally considered. Nevertheless, drains always act as output flow boundaries which indicate an effective drainage in the flat wetland zones.

Finally, the model quantifies at 0.96 hm^3/yr the contribution of lateral and/or deep flows that are necessary to fit the observed groundwater heads and stream discharge flows. This is roughly a 3% of the total inputs to the system, but a significant percentage (74%) of the urban groundwater withdrawal which it mainly takes place in the alluvial aquifer close to this tectonic contact.

CONCLUSIONS

The numerical model shows the response of the surface (< 30m-deep) aquifers of the Santa Coloma river basin under the hydrological pressures given by groundwater withdrawal and phreatophyte plant crops. In particular, quantitative estimations of the model indicate the dual "gaining"/"loosing" character of the main stream course (SCR) and emphasize the role of drains; both river and drains account for most of the groundwater outputs. The models specifies the local effects on stream discharge, specifically in those reaches where a "loosing" stream-aquifer relationship will require detailed management strategies to minimize the impact on surface discharge. The extraction due to phreatophytes concentrates in summer, causing a 1.0 hm^3 reduction in surface water flows, i.e. more than 50% of the environmental flow. This evidences that integrated (surface-ground water) management actions should be undertaken to maintain ecological flows in the SCR basin. Moreover, urban water supply may be guaranteed, even during droughts, although further measures are needed to attain a good ecological status of the surface drainage network.

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