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VERIFYING CONCEPTUAL FLOW MODELS IN A RIVER-CONNECTED ALLUVIAL AQUIFER FOR MANAGEMENT PURPOSES USING NUMERICAL MODELING

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Summary. Hydrological relationships between surface water and ground water are relevant for water resources management in alluvial aquifers, as well as to accomplish the objectives of the Water Framework Directive. This paper introduces a numerical flow model that considers a river-connected alluvial aquifer with the aim to investigate stream-aquifer relationships, as well as those of the alluvial aquifer with its surrounding geological formations. Moreover, the geomorphological location of the stream along a fault zone allows investigating its role on the alluvial inflow. The mass-balance shows the dual gaining/losing character of the Santa Coloma River, the relevance of the drains in the wetland area, and the recharge of the alluvial aquifer from the nearby ranges and the fault zone, which provides a significant percentage of the groundwater withdrawn from the alluvial layer.

1 INTRODUCTION

Recent approaches to water management in river basin districts are oriented to fulfill the objectives of the Water Framework Directive (WFD). The Directive 2000/60/CE has established a framework for Community action in the field of water policy is essentially an environmental norm, which aims at reaching 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. As preserving the biological status of streams is a main goal of the WFD, it is important to estimate the hydrological mass-balance. It has to allow an appropriate regulation of the distinct pressures and impacts derived from different water uses.

Alluvial aquifer hydrology is not only related to the stream connection, but as well to their hydrogeological relationship with the surrounding geological formations and structures. Moreover, ground water withdrawal influences subsurface fluxes between geological units and captures stream discharge. The hydrogeological response of alluvial aquifers to human pressures is thus very sensible. Inadequate exploitation regimes may put at risk ground water resources as well as ecological equilibrium.

The Catalan Agency of Water (Agency) is a regional authority responsible for the water management and planning within the Catalan boundaries, and it recognizes the relevance of alluvial aquifer dynamics in the enforcement of the WFD. In this context, Agency has promoted several studies in the Santa Coloma River (SCR) alluvial aquifer in order to define an appropriate mass-balance that assesses the amount of available resources.

A numerical groundwater flow model has been developed as an assessment tool to managers in this issue. Such model integrates the dynamics of the SCR alluvial aquifer with the hydraulically related geological formations and tectonic structures. In particular, regional fault zones are considered as potential recharge elements in this system, and their contribution are considered to maintain stream discharge[1,2]. On the other hand, the occurrence of wetlands ("Estanys de Sils") in the lower part of the basin constitutes a distinct feature of environmental interest that influences the water budget and, therefore, it requires an explicit consideration in hydrological planning. In this paper, we apply a numerical model to simulate such hydrologic system with the aim to estimate the contribution of the components to the overall water budget under present exploitation.

2 GEOLOGICAL CONTEXT

The SCR hydrographic basin is located in the Guilleries Range and in the Selva Basin in NE Catalonia (Spain). Its shape, as well as its main drainage pattern, is defined by the tectonic processes that originated the Selva Basin, as a graben, during the Neogene (Figure 1). The SCR main course follows a main tectonic line; that is, that of the regional fault zone that determines the contact between the Guilleries Range and the Selva Basin.

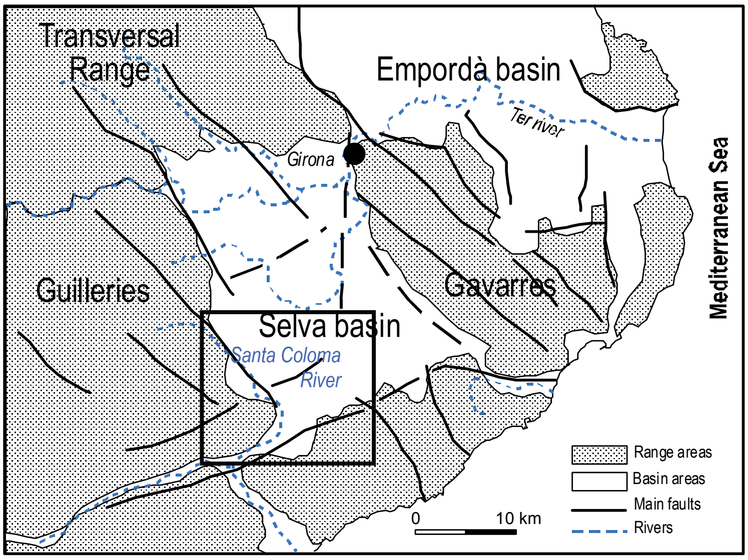

Figure 1 : Geological scheme of the Santa Coloma River Basin. The rectangle indicates the modeled area, which is located in a complex tectonic spot. The Santa Coloma River lays on a NW-SE regional fault zone.

The Guilleries Range is mainly constituted by igneous rocks, with a weathered horizon at the surface, and its porosity is mainly due to fractures except in its most weathered parts. The Selva Basin is formed by the sedimentary infilling of sand and silt that took place during its tectonic evolution. Sedimentary materials may reach a depth of more than 200 m in this area, and it forms a multilayer aquifer with intergranular porosity. Along the 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 eastern branch of the basin drainage network where, due to its tectonic setting and its geomorphological evolution, sedimentary formations with a thickness of 15 m develop flat areas that has permitted the recent development of wetlands.

The hydrogeological behavior of the area consists of local flow systems, which have their recharge areas on the hills within the Selva Basin, and regional flow systems that recharge in the nearby ranges (Guilleries, Transversal) and discharge through the main fault zones[2,3]. A previous study pointed out the fault zone[1] influence on the recharge of the sedimentary infilling in this area.

The model herein described integrates the alluvial formations and the neogene sedimentary materials, as well as some volcanic outcrops (weathered basalts) of reduced occurrence related to Neogene tectonic activity. The igneous rocks of the Guilleries Range and the fault zone effects on the overall flow system are included as boundary conditions.

3 MODELING APPROACH

The numerical model of the SCR basin is based on the existing geological and hydrogeological information derived from previous works. Those include 12 surveys of hydraulic head data starting on 2002. Additionally, two new fiels surveys have been conducted to increase and update potentiometric data in the alluvial and upper neogene formations. Hydraulic head data loggers are used to estimate transmissivity. Monthly rainfall and evapotranspiration rates are calculated based on land-use and crop distribution in the area.

The finite difference numerical model Modflow[4] and the graphical interface Visual Modflow Pro 4.3[5] has been used in this project. A steady-state simulation has conducted to setup the initial conditions, as compared to field data. The transient simulation covers a 7 years period from 2003 to 2009.

3.1 Grid and boundary conditions

The model is constituted by a finite-difference grid of 48,408 active cells, with distinct cell-width along the x- and y-directions (from 40 to 120 m). A refinement of the mesh ($\Delta x=\Delta y=40$ m) has been applied along the main alluvial formations and, also, on the wetland area where a dense network of drains was anciently constructed, and still in use, to keep the water table below the land surface. Because of the steep topographic differences between the upper reaches of the SCR (150 m a.s.l.) and the bottom part of the basin (65 m a.s.l), the entire model is constituted by four horizontal layers of 10 m constant thickness each. Alluvial formations are included in the upper layer and, locally, in the second layer too. Such approach is set to avoid numerical errors due to the wide non-saturated layer and to overcome the gradient of the alluvial formation. Transmissivity and head values are conveniently defined to mend such simplification of the geological structure.

Distinct types of boundary conditions are used in the model. Constant head is defined at the lower reach of the alluvial formation. Constant flux cells are located in the upper reaches of the alluvial formations representing groundwater flow from the upper part of the basin through them. At part of the southwest boundary, coinciding with the tectonic contact with the igneous rocks of the Guilleries range, a third-type boundary condition is applied; i.e., a general head boundary, whose fixed head is given by a representative average value within the mountain area[6], and its conductance is setup using hydraulic conductivity data from the igneous rocks. This type of boundary condition is intended to represent fluxes coming from the weathered granite as well as the contribution of the fault zone to the nearby alluvial formation. A no-flow boundary has been defined upon the neogene materials in the northern hydrographic limit of the SCR basin that acts as water divide with the surrounding basins, and in those limits where the hydraulic conductivity of the materials is very low.

The Modflow boundary condition known as "River" is applied to the SCR main stream. Moreover, the so-called "Drain" boundary condition is selected for all the main drains located across the wetland area. Final conductance values at the base of the river and drains are obtained through calibration.

3.2 Groundwater exploitation rates

Agricultural demand is estimated using the specific coefficients for the distinct crop types in the area. Total water volume needed for each crop is uniformly distributed among the cells with the same type of harvest. In this sense, pumping wells are uniformly distributed in the crop areas where groundwater exploitation occurs. A total amount of 2.3 hm^3/year (10^6 m^3/year) is distributed on wells situated in 137 cells. Cattle-rising water demand is based on the cattle stock (0.06 hm^3/year), and assigned to 51 cells corresponding to the farm locations. Industrial demand (0.34 hm^3/year) is attributed to 39 cells matching to the industrial areas.

Water supply for urban uses is relevant in the three main villages in the area (Santa Coloma de Farners, Riudarenes and Vidreres) that have some of their wells located in the alluvial formations. They withdraw a total amount of 1.30 hm^3/year. Other domestic supply wells are sparse in the area, with small pumping rates, or they are located in the deepest neogene sedimentary layers that are not represented in the model.

3.3 Recharge

The term of recharge is estimated as the difference between the monthly rainfall rate and the crop reference evapotranspiration. This soil mass-balance considers the soil water storage that depends on its retention capacity, the wilting point, the soil depth, field capacity, and the runoff threshold. These parameters have been spatially mapped using GIS, and the infiltration rate estimated for each cell.

Returns from waste water treatment plants (3.5 hm^3/year) are included as injection wells in the cell nearby the stream (modeled as river and/or drain) where the facility is located.

3.4 Hydraulic parameters

Hydraulic parameters were initially defined using data from previous studies. Nevertheless, these values have been modified through the calibration processes according to specific local lithological features and the simulation results in observation wells. The model presents a set of 20 different hydraulic conductivity (K) zones: five for the neogene sedimentary materials, with a range of K values, from 0.2 to 0.8 m/day; seven for the alluvial formations, three along the SCR as the main alluvial, and the rest on some minor tributaries (from 15 to 80 m/day), including the wetland area (15 m/day); four zones for the igneous outcrops in the area, distinguishing fractured rock, and distinct levels of weathering (from 0.02 to 0.20 m/day, and up to 5.0 m/day where the cell joined weathered granite and alluvial materials). Finally, four zones are also differentiated for volcanic materials and their special appearance in the field or in boreholes (from 0.03 to 0.50 m/day). Igneous and volcanic rocks present a larger variability as a result of their distinct degrees of fracture that force to vary their K values to obtain a better fit of the simulated head nearby their locations. In all cases, K_x=K_y, and a certain degree of anisotropy was allowed with K_z, within a ratio of one-half to one-fourth of K_x.

Specific storage is defined through calibration for each lithology. They are set to 4.0×10^{-3} to 1.5×10^{-3} m^{-1} for the alluvial formations depending of their silt content, to 3.0×10^{-3} m^{-1} for the neogene sediments, to 1.0×10^{-4} to 3.0×10^{-2} m^{-1} for igneous rocks, and to 1.0×10^{-2} to 5.0×10^{-2} m^{-1} for volcanic rocks. Values assigned to the sedimentary formations are lower than expected. Drain conductance is set to 50 to 100 m^2/day, and river conductance to 500 m^2/day.

4 RESULTS

4.1 Steady-state simulation

A steady-state simulation disregarding groundwater withdrawal for human uses is used to conduct a first calibration of the hydrogeologic parameters, and to obtain an estimate of the magnitude of the mass-balance terms in a pre-development stage (Figure 2). Inputs to the model come mainly from effective rainfall recharge (15.4 hm^3/year; recall that rainfall recharge already includes crop evapotransporation), the headwaters of the alluvial formations (0.15 hm^3/year), and stream infiltration (1.06 hm^3/year). Water outputs are estimated as base flow to the SCR (1.99 hm^3/year), and groundwater flow out of the system at the lowest point of the SCR (0.51 hm^3/year). Drained water volumes in the lowland and wetland areas account for a total contribution of 14.14 hm^3/year. Following steady-state simulation under pumping conditions has been carried out to determine the initial heads of the transient simulations.

4.2 Transient simulation

The transient simulation reproduces the time evolution of human influences upon the hydrogeologic system. Once withdrawal rates are included in the model, some parameter adjustment has been necessary to obtain a better fit between observed and simulated data. Values are only amended in those areas where there were an appropriate number of observations wells. Circa a 70% of the simulated head data corresponding to May 2009, after seven years of simulation with a maximum time step of 15 days, differed less than ±3.7 m from observed data. The average difference between observed and simulated heads is of 0.92±0.51 m (Figure 3a). Alluvial areas, that have endorsed a more intense calibration effort, show the lowest head differences. Most of the largest discrepancies are found in the neogene sedimentary formations; in particular, in observations wells located in these areas where, because of the multilayered character of the aquifer, calibration can not be entirely successful. Notwithstanding, these results are considered satisfactory given the assumptions related to the modeling of the uppermost layer.

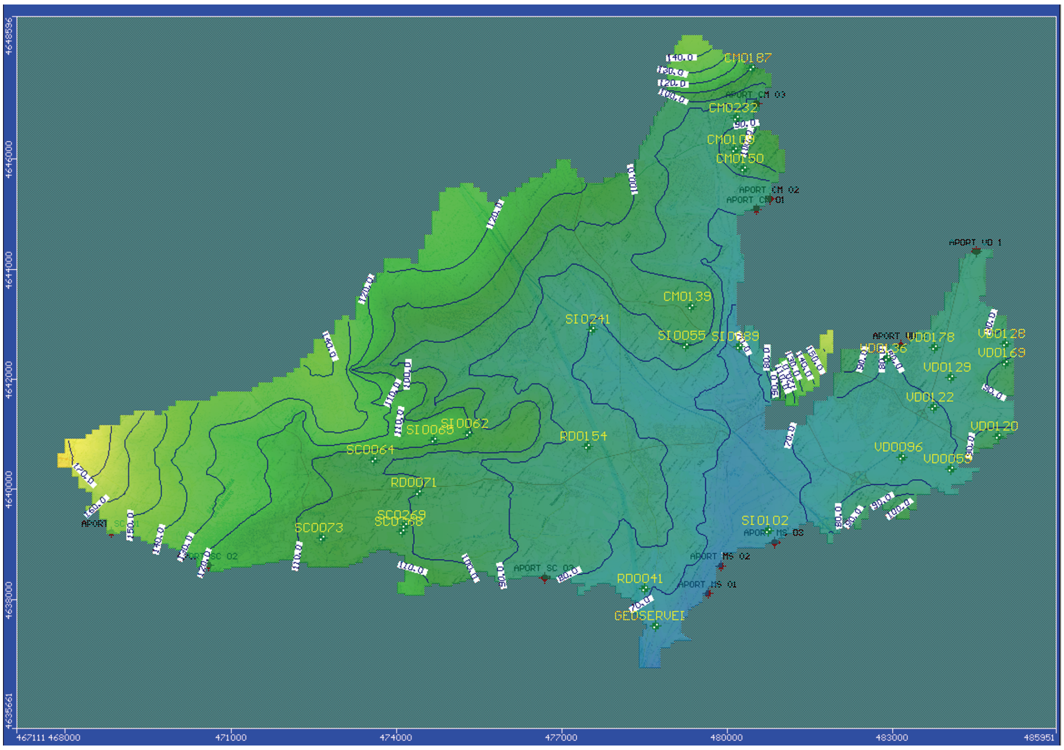

Figure 2: Simulated potentiometric map under pre-development stage. Equipotential lines plotted every 10 m.

Figure 3b shows head variations in a piezometer located at the SCR alluvial formation, in an area of maximum interest for management purposes. Simulated head can fairly reproduce the observed head evolution; nevertheless, observed data need to be added a difference of 1.2 m, which has been attributed to an error on the topographic leveling of the piezometer. Another location of interest is the wetland in the southeastern limit of the modeled area. Because of the drain control and the lack of severe groundwater withdrawal, simulated potentiometric variations are smaller in the wetland than in the alluvial formations. Such features require a detailed calibration of the hydraulic parameters, giving evidence of the geological heterogeneity and the limitation of the model to reproduce small-scale flow details.

4.3 Mass-balance

One of the purposes of the SCR basin flow model is to provide information about the relationship between the stream (and drains) and the alluvial aquifer, as well as that of the alluvial with the underlying formations, especially with tectonic structures such as fault zones.

A summary of the yearly amounts of water estimated for each component of the water budget during the transient simulation is shown in Table 1. One of the main aspects is the variability of the recharge, as previously described, along these years, including the rigorous drought of 2007.

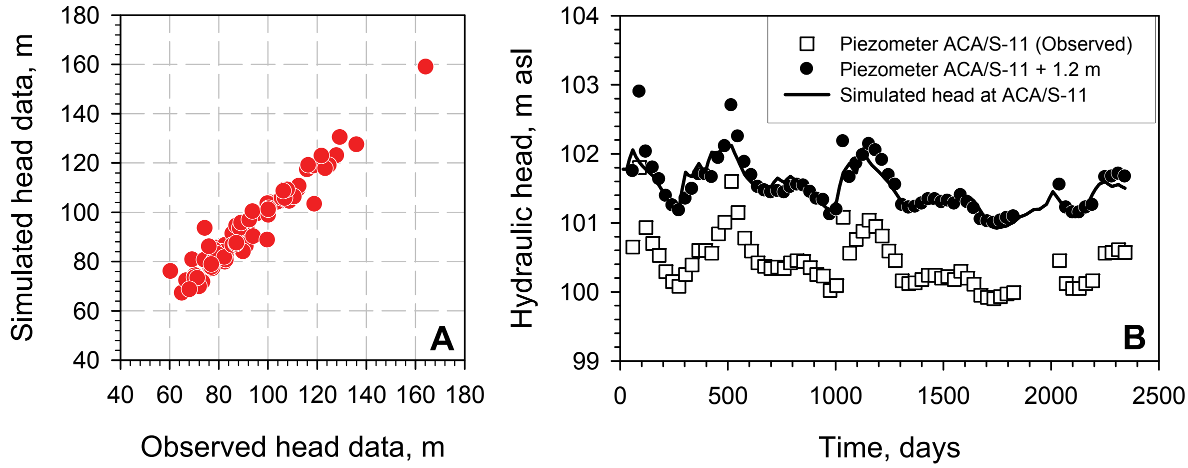

Figure 3 : A) Observed hydraulic head versus simulated hydraulic head data in the transient simulation at 2009; and B) Hydraulic head observed data, head data plus a topographic leveling of +1.2 m, and simulated evolution in piezometer ACA/S-11 in the SCR alluvial aquifer.

	2003	2004	2005	2006	2007	2008	2009*	Mean
RECHARGE IN	24.29	21.11	16.36	9.35	2.88	11.39	5.91	14.23
HEAD DEPENDENT BOUNDARIES IN	0.96	0.97	0.96	0.96	0.96	0.97	0.4	0.96
RIVER LEAKAGE IN	2.13	1.94	2.17	2.23	2.56	2.51	0.87	2.26
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	4.6	3.45	4.64
CONSTANT HEAD IN	0.43	0.42	0.43	0.43	0.45	0.45	0.18	0.43
TOTAL INPUT	***33.45***	***30.17***	***24.54***	***16.91***	***10.18***	***19.92***	***10.81***	***22.52***
RECHARGE OUT	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
HEAD DEPENDENT BOUNDARIES OUT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RIVER LEAKAGE OUT	4.18	5.15	3.7	3.62	2.28	2.49	1.56	3.57
DRAINS OUT	16.29	19.79	16.15	16.37	12.33	12.49	7.02	15.57
WELLS OUT	3.54	2.98	3.2	3.63	3.68	3.07	0.68	3.35
CONSTANT HEAD OUT	1.12	1.15	1.12	1.12	1.08	1.09	0.46	1.11
TOTAL OUTPUT	***25.13***	***29.07***	***24.17***	***24.74***	***19.37***	***19.14***	***9.72***	***23.6***
STORAGE VARIATION	***8.32***	***1.10***	***0.37***	***-7.80***	***-9.19***	***0.78***	***1.09***	***-1.08***

Table 1: Mass-balance results, in hm^3/year, for the transient simulation. * data up to May 2009.

River leakage refers to the SCR reaches, where such boundary condition is defined. It shows that it may act as a gaining (leakage out) or losing (leakage in) stream. Furthermore, the drains are responsible for a significant loss of groundwater resources: about a 67% of the total rainfall recharge. It shows an effective action of such historical drains on the wetland.

The head-dependent boundary condition ("General Head Boundary", in Modflow terminology) represents the contribution of the Guilleries Range (fault zone and weathered granite) to the alluvial formation, which are in geological contact (fault zone and weathered granite) in the southwestern limit of the model. It provides a total volume of 0.96 hm^3, which 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. It confirms that the flow from the Guilleries range plays a significant role in the water balance within the alluvial formation, and it is an important element in the conceptual model of the SCR basin.

Finally, water contributions from storage are equilibrated in the "in" and "out" terms in most of the years. Differences are more evident during the dry years of 2006 and 2007.

5 CONCLUSION

The numerical flow modeling of the SCR basin provides some interesting contributions to its water management. The model has tested the relationship between the stream and the alluvial aquifer, and that of it with the surrounding geological formations. In particular, the model points out 1) the dual "gaining"/"losing" character of the main stream course (SCR), 2) the draining efficiency, considering altogether drains and river, accounts for most of the outputs from the system, 3) the contribution of rainfall to recharge, and 4) the significance of the flow from the Guilleries range which is attributed to the influence of the fault zone and weathered granite. Both, the corroboration of a conceptual model and the magnitude of each hydrological component given by the mass balance, provide sound information to set criteria for the assessment of the SCR basin hydrological planning under the WFD objectives.

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REFERENCES

[1] A. Folch and J. Mas-Pla. Hydrogeological interactions between fault zones and alluvial aquifers in regional flow systems. *Hydrological Processes*, 22(17): 3476-3487 (2008).

[2] A. Folch. *Geological and human influences on groundwater flow systems in range-and-basin areas: the case of the Selva Basin (Catalonia, NE Spain)*. Ph.D. Dissertation. Universitat Autònoma de Barcelona (2010).

[3] A. Menció. *Anàlisi multidiciplinària de l'estat de l'aigua a la depressió de la Selva*. Ph.D. Dissertation. Universitat Autònoma de Barcelona (2006).

[4] M.G. McDonald and A.W. Harbaugh. *A modular three-dimensional finite difference ground-water flow model*. USGS Open-File Report 83–875. Washington. 1988.

[5] Schlumberger Water Services. *Visual Modflow v4.3 Pro*. Waterloo Hydrologic Software.

[6] Agència Catalana de l'Aigua (ACA). Model de gestió del sistema hidrològic de naturalesa granítica del sistema Montseny-Guilleries. Generalitat de Catalunya (2002).

[7] Water Framework Directive (WFD). Directive 2000/60/CE.