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ESTIMATION OF THE RIVER CONDUCTANCE COEFFICIENT USING STREAMBED SLOPE FOR MODELING OF REGIONAL RIVER-AQUIFER INTERACTION

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Summary. River-aquifer interaction is usually simulated in regional groundwater models using streambed conductance. This is a proxy coefficient that can be estimated from streambed deposits properties, assuming that measurable head losses between river and aquifer are due to the streambed itself. But it is difficult to obtain reliable data on streambed deposits on a regional scale. It is widely accepted that there is a physical relationship between streambed slope, mean flow velocity and deposit characteristics such as thickness, granularity and composition. Adequate groundwater modeling of alluvial aquifers strongly connected to rivers requires methods to use this relationship to quantify streambed conductance.

This was the case when modeling the Abrera Basin, a small alluvial aquifer located in the Lower Llobregat river (Barcelona, NE Spain). The average streambed slope was used to partition the river path in various tracks. According to the average slope of these tracks, a physically realistic range was defined for the calibration of the conductance coefficient. After calibration, this resulted in adirect relationship between slope and conductance coefficient .

The streambed slope turned out to be a useful coefficient to define the river conductance on a regional scale when no data is available on local streambed properties. The original numerical model (with prescribed recharge from the Llobregat river) was modified in order to implement this new boundary condition. This resulted in a rather similar overall mass balance but some very important conceptual, local differences. The model improvement with the more realistic river-aquifer interaction can be used for decision supporting scenario analysis. Especially during periods with stationary river flow regime, the results were satisfying, but further research should be carried out on the influence of peak flows on the relationship between streambed slope and conductance on a regional scale.

1 INTRODUCTION

Numerical modelling is being incorporated as a key tool of integrated resources management by many water agencies around the world. The Catalan Agency of Water (ACA, following its acronym in both Spanish and Catalan languages) started modelling of the most troublesome aquifers in 2001, when an excess of abstraction rates had caused important drawdowns in several regions, where groundwater resources are a support for economical activities as well as for ecological and sociological aspects and surface water bodies.

One of the first study areas of this modelling approach for management purposes was the Abrera Basin, a small alluvial aquifer connected to the Llobregat river (Figure 1). This aquifer is about 10-km long and 10-m thick, and plays a significant role in water supply to different municipalities and industries of the Barcelona Metropolitan Area, BMA. This basin comprises relevant groundwater pumping fields that withdraw around $15 \cdot 10^6$ m^3/yr (15 Mm^3/yr) only for potable uses, and individual wells that provide around 7 Mm^3/yr for industries. The estimated storage capacity of the aquifer is 11 Mm^3/yr, equivalent to half the overall annual extraction volume. Besides groundwater abstraction, there are two main river uptakes for urban water supply of the BMA, consuming over 80 Mm^3/yr. In total, more than 100 Mm^3/yr are withdrawn from the Abrera Basin by means of both wells and surface water catchments.

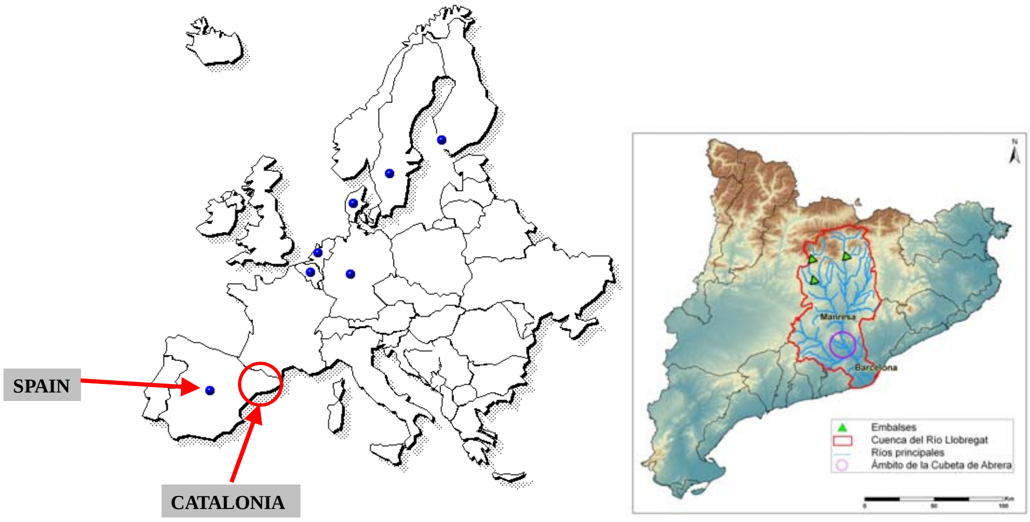

Figure 1. Abrera Basin located 20 km NE of Barcelona (Catalonia, NE of Spain). The red circle (left-hand figure) shows its position within Spain. The purple circle (right-hand figure) shows the position within Catalonia and the Llobregat river basin (red line).

This paper reviews the main features and assumptions of the first numerical model, which was built up with the aim of settling a quantitative basis for groundwater management (ACA, 2004). The need to develop a tool capable of simulating realistic future scenarios led to a modification of the former model, focusing on aquifer-river relationship (ACA, 2009). Both approaches and results are discussed in this article, mainly with regard to the river boundary.

2 FIRST MODELLING OF THE RIVER-AQUIFER INTERACTION

The first numerical model of the Abrera Basin was developed to quantify the mass balance of the aquifer and its dependence upon surface flowrates in order to improve the overall water resources management of the area (ACA, 2004). The Abrera Basin is a, relatively small, alluvial aquifer well connected to the Llobregat river, except for some areas with high abstraction rates where piezometric head is depressed. Groundwater flow is N-S, following the direction of the river itself (Figure 2), even though some tributaries contribute to (generally, non-perennial) surface water and also to the main aquifer.

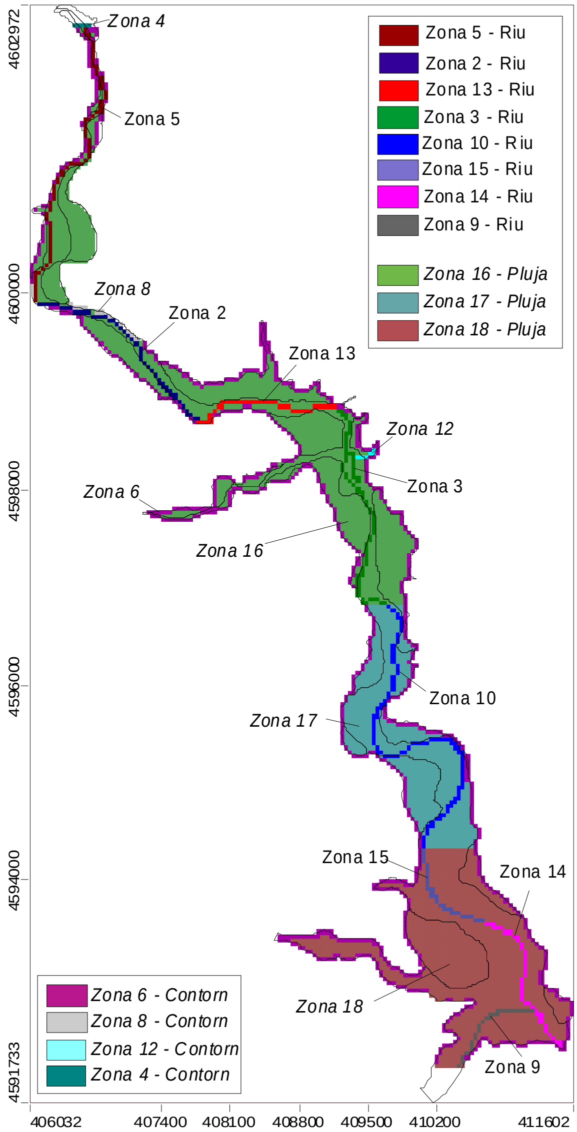

Figure 2. Zonation of the aquifer-river relationship with the former 2004-model, when the river was represented by 10 prescribed recharge zones (coefficients). Aerial rain recharge and lateral flows are also displayed.

The model assigned prescribed head conditions to the Northern model boundary (entrance to the Basin along the main river path) and Western boundaries (contribution of the Anoia river and associated alluvial). Areal surface recharge was not considered to be relevant, although it was implemented in the model. The main input to the model was river infiltration, which was calibrated by means of a recharge-boundary type, i.e. dividing the domain into different zones each with the same coefficients and time distribution (Figure 2). Outflow was mainly caused by pumping, which amounts up to 21.5 Mm^3/yr; a smaller fraction was due to downstream groundwater flow across the SE-boundary. Calibration was done for the period 2000-2003 because due to the lack of older data.

The resulting mass balance after calibration is shown in Table 1. Approximately 23.1 Mm^3/yr water is involved in the total aquifer budget. The main components of the water balance are river infiltration (15.3 Mm^3/yr) and groundwater withdrawal (-21.5 Mm^3/yr).

Table 1. Mass balance after calibrating the 2004 numerical model.

Input	Concept	Mm^3/yr
	Llobregat river recharge	15.3
	Lateral groundwater flow	4.5
	Rain recharge	0.6
	Flow through N-boundary	1.0
	Flow through W-boundary	1.8
Output	**Concept**	**Mm^3/yr**
	Wells abstraction	21.5
	Flow through SE-boundary	1.6

This first model yielded consistent results from the point of view of the estimated mass balance and also from the calibration standpoint, since computed heads fitted very well to the measured values. However, serious concerns arose as for its predictive capabilities, since an increase in (any) wells pumping led to a severe drawdown all along the model domain, even for those scenarios where only a small increment was considered. Figure 3 shows the predicted heads for a 20-years simulation with an additional 3 Mm^3/yr pumping at the so-called radial-wells, placed to the south of the domain: the drawdown would be generalised and in some cases would cause the piezometric head to reach the bottom of the alluvial aquifer. This is why the ACA decided to improve the conceptual and numerical model for future work.

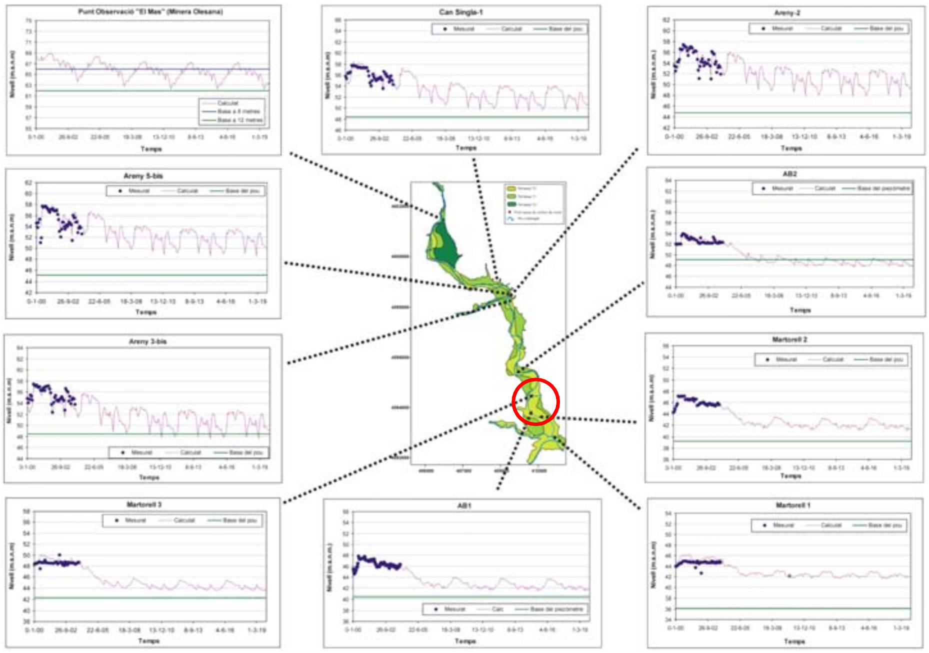

Figure 3. Scenario S2 with the 2004-model: additional groundwater abstraction in the lower sector of 3 Mm^3/yr. The green line represents the alluvial aquifer bottom. Blue dots stand for measurements, whilst the thin purple line gives the simulated heads.

3 IMPROVEMENT OF THE RIVER-AQUIFER INTERACTION IN ABRERA

The need to achieve a more robust model that is not only capable of reproducing measured data and giving a consistent mass balance, but also of providing reliable predictions, was one of the reasons to improve both the conceptual and numerical models of the Abrera aquifer. This task has been conducted within the framework of the "Management Plan for Water Uses" (*PDU, from the Catalan and Spanish acronym*) for the Abrera Basin, undertaken by the ACA in an attempt to integrate surface, reclaimed and groundwater.

Most effort has been dedicated to improve the river boundary condition in the model by means of a Neuman relationship-like: infiltration takes place when groundwater head is below the river stage and is proportional to the head difference, but the flux no longer increases when aquifer disconnects from the stream. This representation assumes that the stream stage is specified and is not a function of the amount of ground-water inflow or outflow.

Calculating the flow between river and aquifer is usually done using a proxy coefficient that represents the streambed conductance. This coefficient, termed C_e (L^2 T^{-1}) in equation (1), is estimated from streambed deposits properties, since it is assumed that all measurable aquifer-river head losses are due to the streambed itself:

$$C_e = \frac{K_e(L)W}{M} \tag{1}$$

where K_e ($L\,T^{-1}$) is the hydraulic conductivity of the bed material, M (L) is the river bed thickness and L (L) and W (L) define the length and width of the river cell for the calculation node. Since these are geometrically defined by the mesh, calibration of the aquifer-river interaction focuses on the factor K_eM^{-1}.

Given that no reliable data on streambed deposits was available in the study area, a novel approach was developed based on work from Dade & Friend (1998) that relates channel slope, s (-), with the grain size of the channel bed trough the following equation:

$$s \approx \theta_i R\, d\, M^{-1} \tag{2}$$

where θ_i (-) is the Shields parameter depending on the mode of transport (suspended load, mixed load and bedload), R (-) is the relative excess density of sediment particles, and d (L) is median grain size of channel bed material. This equation confirms that steeper slopes lead to courser average grain sizes in the channel bed, and thus a lower resistance to flow between river and aquifer.

When equations 1 and 2 are combined, a linear relationship between channel slope and the river coefficient is obtained. The modified model has used this relationship to divide the stream in three different zones along the river path, depending on the slope (Figure 4).

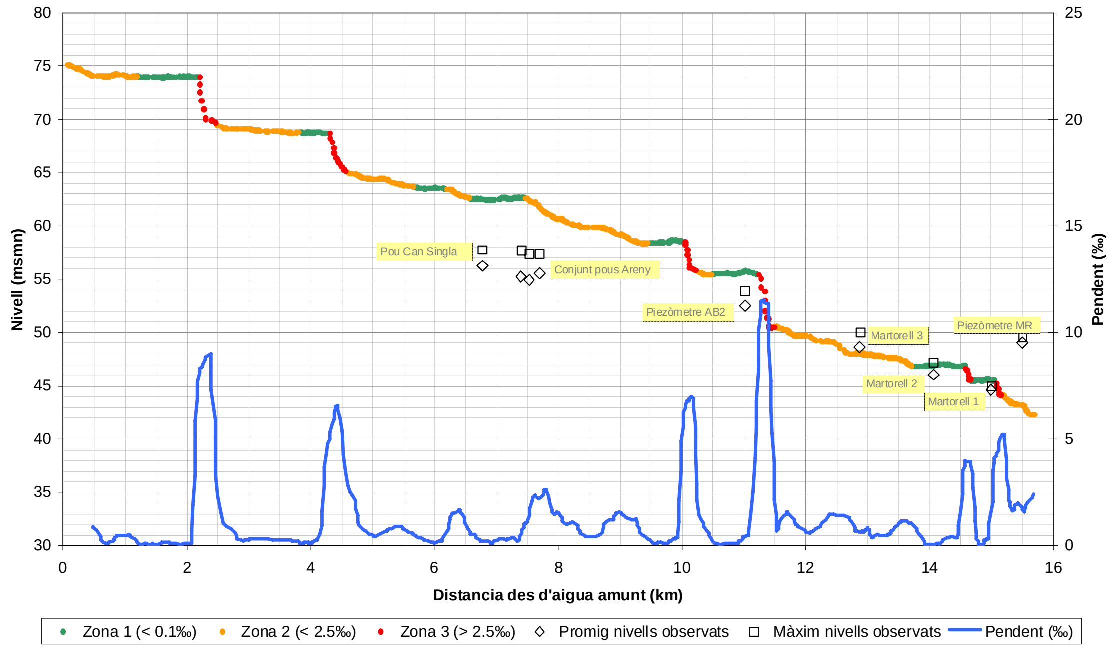

Figure 4. Zonation of the river coefficient depending on the river slope.

For each of these three zones, both an upper and lower limit for the river coefficient were defined to limit the calibration parameter space. The results of the calibration process for the ratio K_eM^{-1} (it defines the value of the river coefficient, $C_{e,}$) are shown in Table 2 and the implications as concerns mass balance in Table 3.

Table 2. Values of the ratio K_eM^{-1} before (initial parameters) and after the calibration process. This ratio yields directly the river coefficient parameter, equation (1).

Zona	**Pendents** (‰)	$K_e M^{-1}$ (s^{-1}) ***initial***	$K_e M^{-1}$ (s^{-1}) ***final***
1	0 – 0.1	0.10	0.09
2	0.1 – 2.5	0.50	0.40
3	> 2.5	1.00	0.80

Table 3. Mass balance with the improved 2009 model: a significant conceptual difference arises when avaluating the aquifer-river interaction, since there are zones where river infiltrates water to the aquifer but the lower Llobregat river receives water from the aquifer.

Component	**Input (Mm^3/yr)**	**Output (Mm^3/yr)**
Lateral inflow + Effective rain	**4.79**	**0.00**
Aquifer-river interaction	**20.38**	**4.44**
Well injection / pumping	**0.00**	**21.40**
Prescribed head boundary condition	**2.40**	**1.42**
Storage variation	**1.51**	**1.80**
Total	**29.07**	**29.07**

4 DISCUSSION

Calculated drawdown exhibit a completely different behaviour with the 2009 improved model as compared to the former version. Figure 5 shows that an increment of groundwater extraction (3 Mm^3/yr in the southern part of the study area) combined with an identical decrease in the central part has an effect on drawdown but it does not extend to the whole domain. Instead, this scenario gives more realistic results.

Comparing the outcomes of both modeling approaches it becomes clear that the yearly water balances are similar (Tables 1 and 3), except for the river recharge component. The improved model with dynamic river-aquifer interaction gives the in- and outflow components as well as the net inflow component (approximately, 16 Mm^3/yr). As a result, the total water balance sums up to approximately 29 Mm^3/yr using the flexible modelling approach. The segregation of in- and outflow confirms the existence of recharge and drainage zones, whose extension varies in time as a function of the river discharge regime.

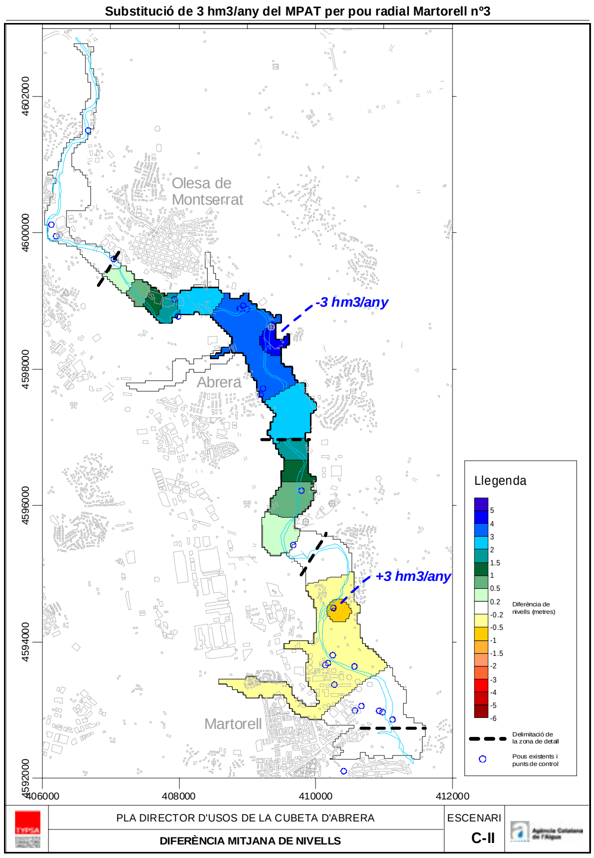

Figure 5. Drawdown map obtained with the improved aquifer-river interaction. The effects are consistent with some pumping tests and data available up to date.

A close look on the groundwater levels shows a highly variable storage capacity of the aquifer. A total increment of about 1.2 Mm^3 occurred during the 4-years modelling period. However, there are periods when total groundwater storage is drastically reduced leading to extremely low groundwater heads in some areas. The model is capable of simulating the flexible interactions and the compensating role of the river on the groundwater system. Increasing groundwater extraction in the southern part would cause a relative small and more realistic (compared to the results of the first model) maximum drawdown of 1 m nearby the well location. Water balance shows higher groundwater extraction gets compensated by an increment of the net recharge in the southern part of the study area. On the other hand, reducing withdrawal by 3 Mm^3/yr results in a recuperation of groundwater level of up to 5 m in the central part. Net river recharge increases since the connection between river and aquifer is partially restored.

In general, reasonable results were obtained when comparing calculated groundwater levels with the monthly measured heads. Only during extreme stress conditions with very high drawdown rates, computed heads can not match well the measured levels. This is partly due to the poor-quality of measurement networks in the area.

5 CONCLUSIONS

For the local water authorities, it is crucial to have a tool to support decision making by simulating different possible future scenarios. The objective of this study was to improve an existing groundwater management model for an intensively used alluvial aquifer. The main change consisted of implementing a new river-aquifer interaction. Although the net mass balances of both models were similar, their conceptual behaviours are significantly different.

The approach to estimate the river coefficient that defines the aquifer-river interaction was based on the streambed slope, assuming that this is strongly related to the infiltration capacity, as confirmed by other studies. This approach has proved to be very useful and applicable to regional studies when no information on streambed deposits is available. The comparison of simulated and observed groundwater levels led to satisfying results, giving sufficient confidence in the model for use in decision making.

Results of the improved model give insight into river-aquifer dynamics. It was confirmed that the extension of the infiltrating and draining river zones can be seasonally-dependent and the river discharge regime must be taken into account. This makes the model a useful tool to define warning groundwater thresholds and to indentify areas for managed artificial recharge. This novel methodology of using streambed slope to pre-estimate the river coefficients is promising and might be applied to other aquifers where the interaction with the river is dominant. Therefore, it is recommended to further study and improve this methodology in other similar alluvial aquifers, provided that reliable groundwater level measurements exist.

6 ACKNOWLEDGEMENTS

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