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# MODELLING THE COUPLED SURFACE WATER AND GROUND WATER SYSTEM OF THE UPPER RHINE GRABEN

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## 1 INTRODUCTION

The Upper Rhine Graben hydrosystem holds one of the most important groundwater resources in Europe. The alluvia material deposited by the Rhine River during Holocene contains approximately 80 billions cubic meters of fresh water.

The upper limit of the groundwater is very close to the ground surface over an important part of the aquifer extent. Due to the absence of an impermeable cover above the alluvia, this water resource is vulnerable to surface pollutions[1, 2].

The Vulnar project[*] aims at better understanding the functioning of the hydrosystem by the mean of hydrometeorological and hydrogeological modeling. The study area is the hydrological catchment of the Rhine River between Basel (Switzerland) in the South and Lauterbourg (France) in the North. It is made of two contrasting parts, the alluvial plain and the mountainous areas West and East of it.

The catchment area is approximately 13,900 km² large, of which the plain represents 4,655 km². The Rhine River flows over approximately 200 km from South to North on the

[*] http://www.geosciences.mines-paristech.fr/equipes-de-recherche/systemes-hydrologiques-et-reservoirs/vulnar

alluvial material deposited by the river, on a width of 30 to 40 km. This material is very permeable, and hydrogeologically homogenous.

Several studies conducted on this strategic resource have shown the importance of the interactions between surface waters and groundwater on the functioning of the hydrosystem[3]. Indeed the aquifer is recharged by effective precipitation, but also by the infiltration of rivers entering the plain from the mountainous catchments, and by subsurface flows from these catchments (lateral input process) [4, 5]. Although this aquifer seems well known on various aspects, the research project MONIT underlined the uncertainty on the water budget, especially on the surface – groundwater interactions[4]. However simulation in the MONIT project was bound to the aquifer, with imposed fluxes on its East and West boundaries.

To try to better assess the functioning of the aquifer, and the uncertainty on the interactions, the Vulnar project developed several models covering the whole basin in order to better constrain the boundary conditions of the aquifer, or limited to the aquifer extension. Three different modeling tools are used: i) HPP-INV, a hydrogeological model using a finite elements scheme, and which adjusts the model parameters (mainly transmissivity) with an inversion method[6]. The extent of the area simulated with HPP-INV corresponds to the alluvial aquifer; ii) MODCOU, a more classic hydrogeological model, using a finite difference scheme, and without an included automatic adjustment of the parameters[7]. It is applied on the whole basin from Basel to Lautebourg, including the mountains; iii) the third model is the coupling between the atmospheric surface scheme SURFEX[8] that computes energy and water budget at varying resolution over the whole basin, and the hydrogeological model MODCOU

This study focuses on the estimation of the surface/groundwater exchanges as estimated by the MODCOU models and its sensitivity to the hydrogeological parameters and the estimation of the water budget.

## 2 PRESENTATION OF THE HYDROGEOLOGICAL MODEL MODCOU

MODCOU computes a distributed hydrological budget with a simplified reservoirs scheme and flow in a multilayer aquifer**,** using the finite difference discretization scheme. It also routes the surface flow in the rivers with a simplified Muskingum scheme[9, 10].

Exchanges between the rivers and the aquifer are simulated according to the following equation: $Q_e = \min\left(T_p\left(H - H_0\right), Q_{\lim}, Q_{dis}\right)$, with $Q_e$ the exchange flow (negative for infiltration and positive for drainage), $T_p$ the transfer coefficient which represents the river bed transmissivity, H the aquifer level, $H_0$ the river level, $Q_{lim}$ the maximum infiltrating flow on each river cell and $Q_{dis}$ the infiltration flow corresponding to the available water quantity in each grid cell.

The drainage of the aquifer can also occur outside the river cells. Indeed if the piezometric level reaches the ground level, water is drained, and transferred to the closest river. The flow calculation also uses a coefficient $T_p$ representing an upper layer transmissivity.

Another process represented is the reinfiltration of water previously flowing on the surface of the catchment, and which reaches a zone of more permeable material with an underlying water table. This process is allowed only on the cells bordering the alluvial plain, at the mountains foot, and corresponds to lateral input to the aquifer.

MODCOU has already been applied on several French basins[7, 9, 10] and also on some other European basins[11].

## 3 REFERENCE SIMULATION

For the reference simulation, we used hydrodynamical parameters from the inverse modeling conducted with the HPP-INV model[6]. The maximum flow for infiltration of water on a grid cell of 250 m from the rivers to the water table was set equal to 50 L/s and the transfer coefficient between surface and groundwater to 0.05 $m^2/s$. Lateral input to the aquifer is taken into account. This simulation was conducted for the period from August 2000 to July 2005.

Figure 1 (a) shows simulation results in terms of the quality of the simulation at several hydrometric stations and piezometric measure points. River flows are better simulated in the Vosges than in the Plain and in the Schwarzwald. This is due to the fact that the meteorological analysis we used (SAFRAN[12]) had less data in Germany than in France, and for the plain stations to the complex interactions between rivers and the aquifer. The piezometric level seems underestimated in the North and overestimated in the South. This pattern could be due to the transmissivity repartition or to excessive river infiltration related to the constant river heads used in the model.

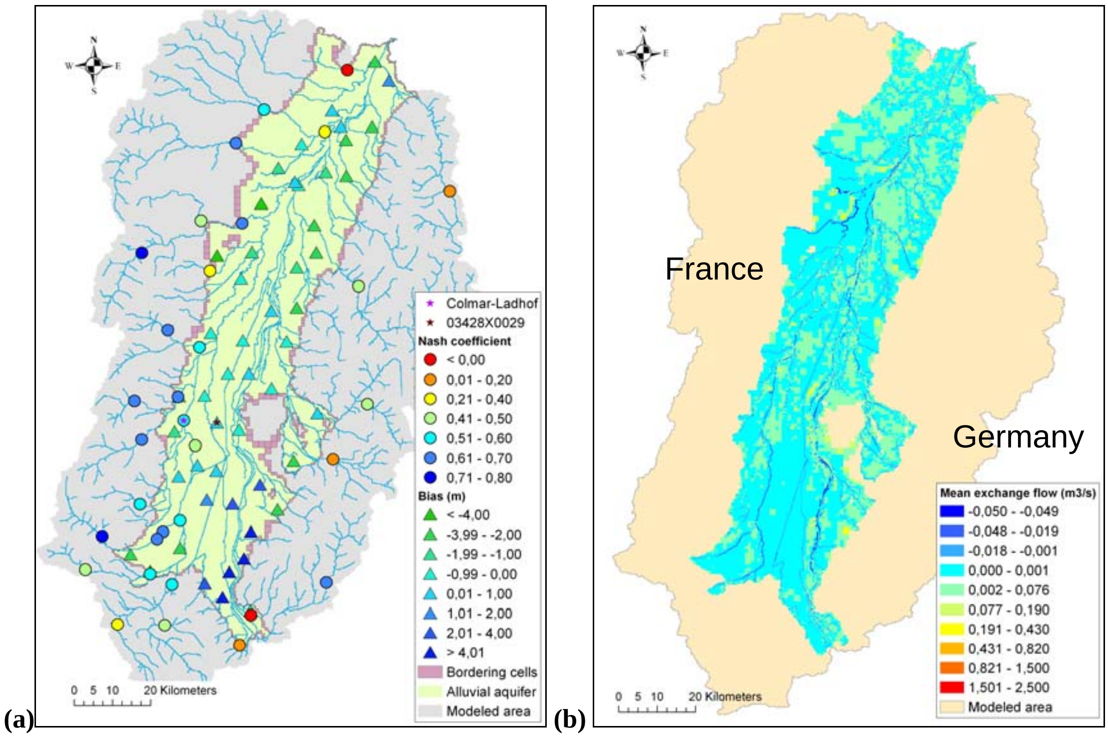



Figure 1 : Simulated domain with : (a) Average bias between observed and simulated piezometric levels on each piezometer (triangles) and daily Nash efficiency at each hydrometric station (circles) for 2000-2005 ; (b) Mean exchange flows between surface and groundwater on each aquifer cell.

The right hand map (Figure 1 (b)) shows the mean exchange flow between the surface layer, including the rivers, and the aquifer, on each model cell and for the 5 simulated years. Negative values correspond to an infiltration toward the aquifer, and positive values to the drainage of the aquifer. As expected infiltration occurs in the rivers beds only, and drainage can occur on the whole aquifer surface.

## 4 SENSIVITY TESTS

Simulations were conducted with different parameters sets, in order to assess the sensitivity of the model to several parameters, with a special focus on those concerning the surface water – groundwater interactions.

We tested several values for the maximum infiltration rate on river cells. First we used 50 L/s, then 25 L/s and finally 0 L/s which corresponds to the case where the surface-groundwater interactions can exist only in the form of drainage of the water table.

Figure 2 shows the influence of river-aquifer interactions on the Ill River flow (a) and on piezometric heads in the water table (b). The location of the two measure points presented is shown on figure 1(a). It is clear from this that it is necessary to take into account the rivers infiltration to simulate properly the alluvial aquifer levels.

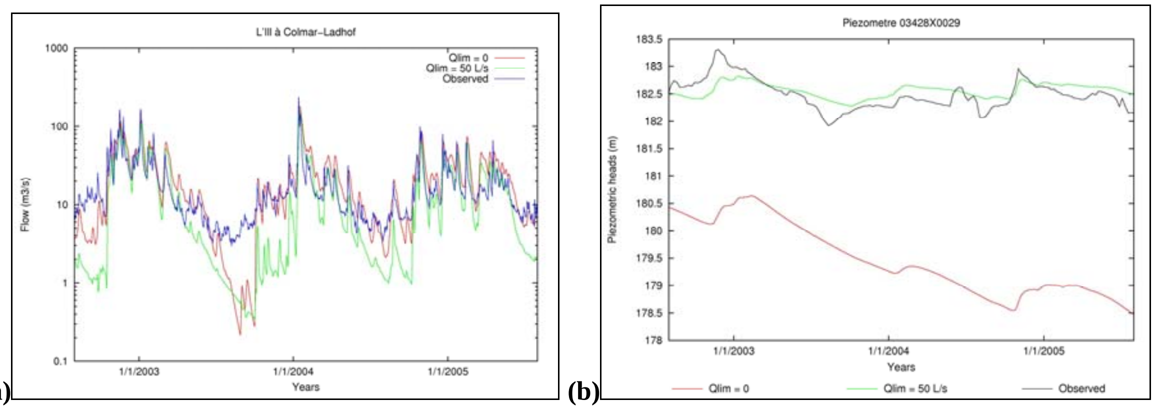
(a)



Figure 2 : Comparison of (a) an observed hydrometric and (b) a piezometric series (black) with simulations with (green) and without (red) infiltration of the rivers to the watertable.

We also tested several values for the riverbed transmissivity (parameter $T_p$). First a value of 0.05 m²/s was used on every grid cell. This value is not very large compared to some transmissivity values used for the aquifer (around 2 m²/s max). Thus we tested values of 0.1 and 0.2 m²/s for the transfer coefficient. Larger values facilitate the exchanges of water between the rivers and the water table. No spatial heterogeneity was introduced for this parameter.

Transmissivity values used are the values obtained by the HPP-INV inverse model used by Majdalani et al.[6]. We tested the sensitivity to this parameter by computing a simulation with all the values doubled, and a simulation with all the values divided by 2.

We also tested a simulation without taking into account the lateral input process, and another simulation using the surface hydrological budget from SURFEX.

The different simulations conducted are summarized in the Table 1, and Table 2 shows the different water budgets obtained with MODCOU and SURFEX-MODCOU.

| **Simulation name** | **Parameters** |
|---|---|
| Reference | Initial values for all the parameters ; $Q_{lim}$ = 50 L/s ; $T_p$ = 0.05 m²/s |
| $Q_{lim}$ = 0 | The maximum infiltration flow in river cells is set to zero. |
| $Q_{lim}$ = 25 L/s | The maximum infiltration flow in river cells is set to 25 L/s |
| $T_p$ = 0.1 m²/s | The transfer coefficient between the aquifer and the hydrographic network is multiplied by two. |
| $T_p$ = 0.2 m²/s | The transfer coefficient between the aquifer and the hydrographic network is multiplied by four. |
| T * 2. | All transmissivities are multiplied by two |
| T / 2. | All transmissivities are divided by two |
| No Lateral Input | No reinfiltration on the bordering cells |
| SURFEX | SURFEX hydrological budget, no lateral input |

Table 1 : Parameters for the 9 simulations conducted.

| **Simulation** | **AET^(A)** | **SR^(A)** | **OF^(A)** | **ERI^(B)** | **AS^(B)** | **IR^(B)** | **DWT^(B)** |
|---|---|---|---|---|---|---|---|
| **Reference** | 628 | 427 | 472 | 227 | -9 | 663 | 825 |
| **$Q_{lim}$ = 0** | - | - | 495 | - | -80 | 0 | 234 |
| **$Q_{lim}$ = 25 L/s** | - | - | 473 | - | -13 | 531 | 696 |
| **$T_p$ = 0.1 m²/s** | - | - | 472 | - | -12 | 798 | 962 |
| **$T_p$ = 0.2 m²/s** | - | - | 473 | - | -14 | 897 | 1064 |
| **T * 2.** | - | - | 475 | - | -21 | 774 | 947 |
| **T / 2.** | - | - | 469 | - | -3 | 544 | 700 |
| **No Lateral Input** | - | 449 | 472 | 160 | -11 | 672 | 770 |
| **SURFEX** | 646 | 399 | 410 | 115 | -17 | 636 | 695 |

Table 2 : Water budgets for the different simulations. Water quantities are given in mm/year. (signification of abbreviations : AET=Actual EvapoTranspiration ; SR = Surface Runoff ; OF = Outlet Flow produced on the modeled area ; ERI = Effective Rainfall Infiltration ; AS = Aquifer Storage ; IR = Infiltration of River towards the aquifer ; DWT = Drainage of Water Table to the rivers ; (A) water depths calculated on the whole modeled area 13,900 km²; (B) water depths calculated on the aquifer surface 4,655 km²)

The total precipitations amount to 1097 mm/year, with 70 mm/year of snow. AET is the same for all the simulations except the one using SURFEX hydrological budget where AET is more important, and thus surface runoff and infiltration are less important. We also have the same infiltration and runoff for the simulations using MODCOU hydrological budget, except when the lateral input process is disabled, as this process allows more water to infiltrate towards the aquifer. The exchanges between the rivers and the alluvial aquifer are very sensitive to the parameter set.

Figure 3 shows the results for each simulation in terms of the water quantities involved in the exchanges between the rivers and the aquifer. Qdrain represents the quantity drained by the rivers from the water table, Qinf the quantity of water which infiltrates from the rivers towards the aquifer, and Qtotal is the sum of Qdrain and Qinf.

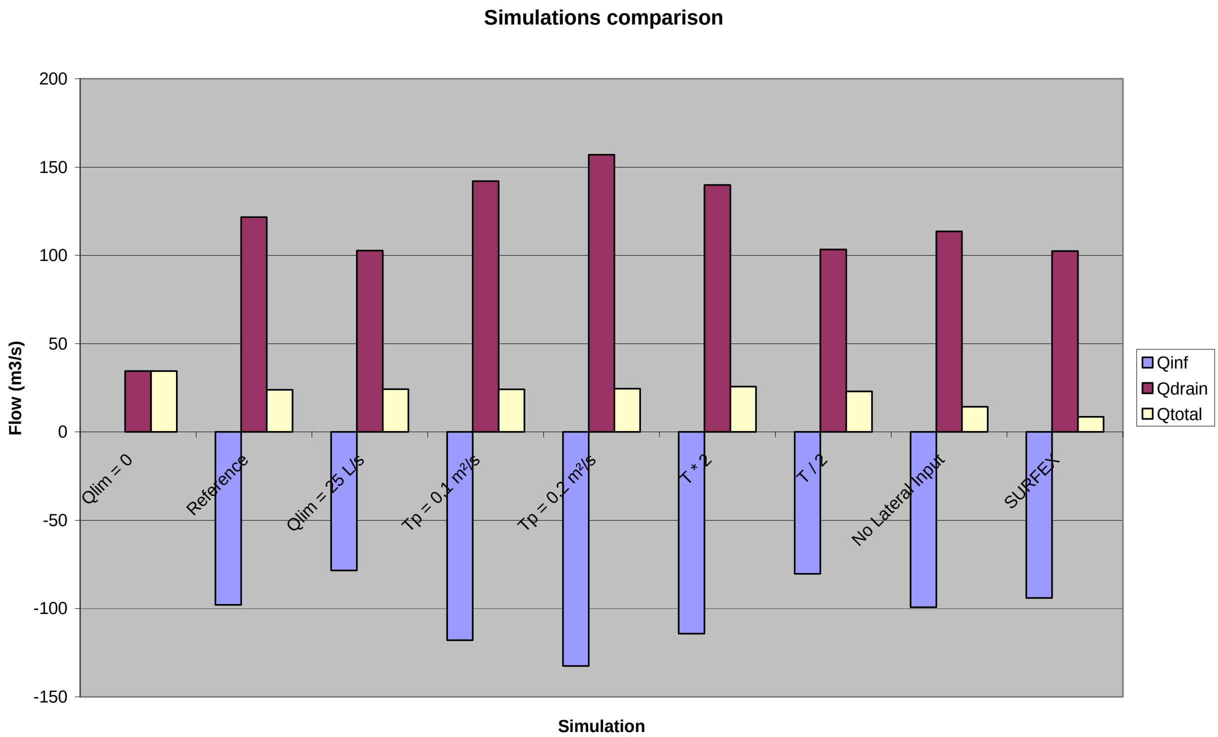



Figure 3 : Water quantities involved in the surface-groundwater interactions for each simulation

Overall, for every simulation the exchanges are rather in the direction of the drainage of the aquifer, which is consistent with a negative storage in the water table. Even though the quantities infiltrated and drained are different from one simulation to another, when we vary the values of $Q_{lim}$, $T_p$ or T, the total is not very different.

Figure 4 presents the biases between observed and simulated piezometric heads calculated for 50 piezometers, and for 6 simulations. The values are classified in ascending order for each simulation, independently from the piezometer it represents.

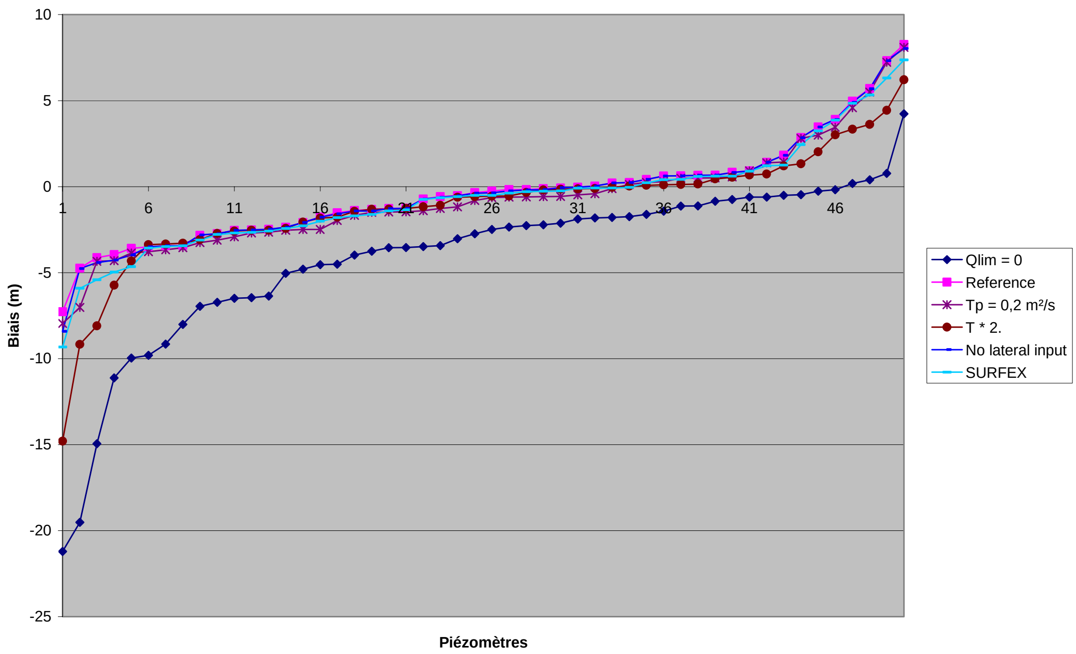



Figure 4 : Sorted biases between observed and simulated piezometric levels averaged over the 5 years period for 50 piezometers and 6 simulations

The outlier simulation is the one where the river is not allowed to infiltrate in the aquifer ($Q_{lim} = 0$). The sorted biases curve is shifted towards negative biases, which underlines an overall underestimation of the piezometric levels.

Although the effective infiltration rate simulated by SURFEX is quite different from the one estimated by MODCOU (lower by 30%), the quality of the simulation is not significantly reduced for the piezometers compared to the MODCOU surface water budget. This can be explained by the fact that the quantities of water exchanged between the water table and the rivers are also different between the two simulations. Thus the surface/groundwater interactions compensate for the deficit of effective rainfall recharge.

## 4 CONCLUSIONS

We presented some results obtained with a coupled hydrogeological model on the Upper Rhine hydrosystem. From these results it is clear that taking into account the interactions between surface water and groundwater is necessary to have a good simulation of the hydrosystem. It is shown that a variation of the input fluxes or the hydrodynamical parameters leads to different water budgets with limited impact on the statistical comparison between observed and simulated piezometric heads and river flows. Some studies have tried to quantify the river-aquifer exchanges with differential gauging[3, 13] on some parts of the basin. Such values will be used in future work to try to assess the simulations.

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