Contribution de la modélisation hydraulique en rivière pour la quantification des échanges entre la nappe et la rivière dans un modèle hydrologique régional

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L'objectif de cette étude est de contribuer à une meilleure simulation des niveaux d'eau dans le réseau hydrographique à l'échelle régionale afin d'améliorer la simulation des interactions nappe-rivière et de mieux quantifier les niveaux piézométriques dans les aquifères. La méthodologie s'appuie sur la plateforme de modélisation intégrée des hydrosystèmes EAU-Dyssée. La plateforme repose sur le couplage de modèles experts simulant: bilan hydrique, écoulements de surface et souterrain, transfert en zone non saturée, la croissance des plantes et le transport. Nous proposons ici une méthode de changement d'échelle dans laquelle la modélisation fine des processus hydrauliques à haute résolution permet d'améliorer la représentation des profils d'eau en rivière et les interactions nappe-rivière à l'échelle régionale.

La méthodologie a été testée dans le bassin versant de l'Oise (sous bassin de le Seine) d'une superficie de 17000 Km^2, pour la période 1989-1995. Nous avons utilisé HEC-RAS pour la modélisation hydraulique (équations de Saint-Venant 1D) sur un tronçon de l'Oise de 188 km. Le calage de ce modèle a été effectué en faisant varier le coefficient de Manning n (1/K) avec pour objectif de reproduire les courbes de tarage observées. L'efficacité du modèle hydraulique est évaluée par les critères statistiques classiques de Nash, RMSE, biais à 5 stations hydrométriques. Une courbe de tarage est définie à partir de la simulation hydraulique à la résolution du modèle HEC, tous les 200m en moyenne.

Ces courbes de tarage sont ensuite projetées comme conditions aux limites sur les mailles rivière du modèle régional EAU-Dyssée (résolution de 1 km) afin de simuler la fluctuation du niveau d'eau en fonction du débit routé par le module de routage (RAPID). Les échanges entre les mailles rivière et les nappes (modèle SAM) sont ensuite estimés à partir d'une relation de type loi de Darcy se basant sur les gradients de charge verticaux entre la rivière et la nappe.

L'impact de la fluctuation des niveaux en rivière sur les isopièzes a été analysé par rapport à un état de référence pour lequel les niveaux en rivière sont fixes. L'analyse des résultats sur la période de simulation montre un écart moyen des niveaux piézométriques pouvant atteindre 1.9 m pour les mailles souterraines situées sous les mailles rivière. Cet écart est plus important pour l'Eocène que pour la Craie sous-jacente, et il se réduit si l'on considère des mailles souterraines plus éloignées de la rivière.

Ce travail montre l'intérêt de l'approche pour mieux évaluer les interactions nappes-rivières à l'échelle régionale avec un faible coût de calcul. Il offre des perspectives intéressantes pour simuler des processus jusque là négligés par le modèle EAU-Dyssée, comme l'élimination de nitrate dans les zones humides qui sont souvent situées à la zone de contact entre les nappes souterraines et la rivière.

1 Introduction

The interaction between surface and groundwater is complex and depends on many physical factors that are directly related to topography, geology, and climate (Sophocleous, 2002; Winter, 1999, 2002). Due to the level of complexity, modelers consider limited or no interactions between surface and subsurface flows. Therefore, even though specific models provide good results for simulating the water flows, deviations occur when the interactions between these domains become important (Gunduz et al., 2005)**.**

The recognition of those interactions motivated researchers to focus on coupled models. Pinder and Sauer (1971), Smith and Woolhiser (1971), Freeze (1972), Cunningham and Sinclair (1979), Akan and Yen (1981), Gerard (1981), Ledoux (1984), Abbott (1986), Swain and Wexler (1991), VanderKwaak and Loague (2001) and Morita and Yen (2002) have formulated coupled models which simulate surface and subsurface interactions. Ideally, coupling the surface and subsurface flow would involve a 3D surface flow component based on the complete Navier–Stokes equations and a 3D variably saturated subsurface flow component. However, such models suffer from several drawbacks: (i) absence or inadequacy of measured data to calibrate/control model outputs (Beven, 1992; Polus, 2010), (ii) the inadequacy of those equations at large spatial scale and (iii) the insufficient computational power. Because of these limitations, the use of simpler models is widespread in the hydrological community and is particularly adapted to large-scale applications.

Often, the river network is a set of square cells that is a subset of surface cells. In such studies, 2D routing of surface and subsurface water up to a river cell usually precedes 1D routing through the river network, which is either grid or vector based. Amongst these models are CASC2D (Julien et al., 1995), LISFLOOD (De Roo et al., 2000), MIKE-SHE (Refsgaard and Storm, 1995; Thompson et al., 2004), HEC-HMS/HEC-RAS studies (Knebl et al., 2005) and CAWAQS (Flipo et al. 2007 a, b).

In this study, an original methodology is proposed to couple surface and subsurface flow. This methodology is based on an upscaling approach, which allows for benefiting from high resolution hydraulic modeling outputs to improve the representation of fluctuating river stage in a regional scale hydrogeological model. The hydrogeological model (Eau-Dyssée) computes runoff and groundwater flows that become lateral inflow inputs to the hydraulic model. At the regional scale, the coupling between surface and subsurface flow is ensured by simple pre-established rating curves along the river reach. Then, during the simulation, the difference between water stage in the river and piezometric head is used to calculate and quantify the exchange between aquifer units and rivers.

2 Models description

The modeling platform Eau-Dyssée couples existing specialized models to address water resources and quality in regional scale river basins.

The model is composed of four interconnected phases to represent the water cycles: the surface component, the unsaturated component, the saturated component of the aquifers and the river network component; each component being represented by a spatially distributed module.

Within this general framework, we propose a strategy to benefit from the results of a high resolution 1D channel flow model (HEC-RAS) of the river network within the regional hydrological model Eau-Dyssée (Figure 1). Runoff and groundwater contribution to stream flow are first simulated by Eau-Dyssée at the regional scale considering an imposed water level in each river cell. Then the hydraulic model HEC-RAS is fed by the previous inputs as lateral inflows and computes unsteady flow simulations to derive water profiles and functional relationships between water level and discharge (rating curves) at each cross section of the river network.

The derived rating curves are upscaled and linearly projected along the river grid-cells (1km * 1km) of the regional hydrological model by calculating a length equivalency factor between the river reach and the river grid-cell lengths. This length equivalency factor is used to linearly project the rating curves locations onto the river grid-cells. Then, an equivalent rating curve at the center of each river grid-cell is calculated by averaging the projected rating curves weighted by the distance from the cell center. The river grid-cells rating curves are boundary conditions of the QtoZ module. The QtoZ module is coupled with the regional hydrological routing model RAPID and groundwater model SAM. It provides fluctuating water levels to the groundwater model SAM as function of the routed discharge in the stream by the regional hydrological model RAPID. The SAM groundwater model will use these water levels to simulate and quantify the exchange between the stream grid-cells and aquifer grid-cells. In the following, we give some details of each EAU-Dyssée component and the 1D hydraulic model HEC-RAS.

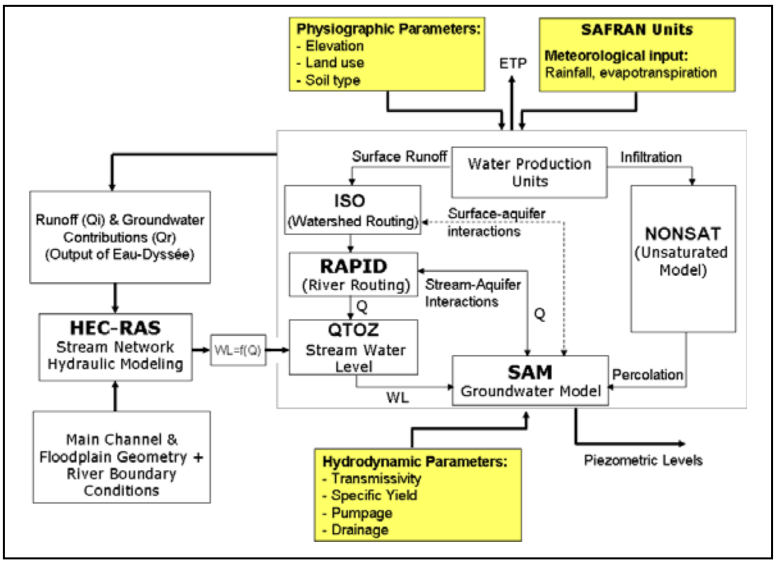

Figure 1: Modeling Framework

2.1 The surface component

The input data consist in a meteorological database (precipitation and potential evapotranspiration) with a daily time step and a spatial resolution of 8 km×8 km. Data has been derived from Météo-France SAFRAN database (Quintana-Segui et al., 2008).

The domain is divided into production zones to which an eight parameter model called production function is associated (Gomez et al., 2002). The production functions compute the hydrological balance in all the cells of the surface mesh. The outputs from the production function are actual evapotranspiration (AET), soil water stock, volume of water to infiltrate to the aquifer domain and volume of water to join the surface runoff. The surface runoff partitioned by the production function is transported by the model ISO (Figure 1) based on isochronal zones. Each drainage area is divided into a number of isochronal zones equal to the number of time steps necessary for flow to reach the nearest river cell. The transfer times depends on topography and concentration time.

2.2 The unsaturated zone component

The infiltrated water partitioned by the production functions is transferred vertically to the groundwater table by the unsaturated-zone model NONSAT (Gomez et al., 2003; Flipo et al. 2005). This conceptual model consists in a succession of reservoirs. The number of reservoirs is related to the distance between soil horizons and the phreatic surface level. This distance is calculated initially by a steady state simulation with boundary conditions corresponding to the mean annual infiltration.

2.3 The saturated zone component SAM (Simulation des Aquifères Multicouche)

The SAM model (formerly MODCOU; Ledoux et al., 1984, 1989) is a regional spatially distributed model that computes the temporal distribution of the piezometric heads of multilayer aquifers, using the diffusivity equation (De Marsily, 1986). It also computes exchange between aquifer and river. The former version of SAM (MODCOU) has successfully predicted surface and groundwater flow in many basins of varying scales and hydrogeological settings (Ambroise et al., 1995; Etchevers et al., 2002; Gomez et al., 2003; Habets et al., 1999, 2009)

2.4 The river component

2.4.1 The hydrological river routing RAPID

The in-stream discharge routing within the platform Eau-Dyssée is performed by RAPID (David et al, 2009), which is based on the Muskingum routing scheme. It simulates discharge and water volume in all cells of a river network.

2.4.2 The QtoZ water level fluctuation module

The QtoZ module calculates the water level at a given river grid-cell as a function of the discharge routed by RAPID. The module has three options for calculating water level in each river grid-cell: a) fixed water level, b) water level estimated by the mean of a rating curve c) water level estimated by Manning's equation.

Within the platform Eau-Dyssée, the QtoZ module is coupled with the hydrological routing model RAPID and the groundwater model SAM. At each time step of the simulation, QtoZ receives discharge values from RAPID for each river grid-cell and sends a water level to the groundwater model. In this particular study, we only used the second option: rating curves obtained with the hydraulic model HEC-RAS.

2.5 Hydraulic model HEC-RAS

In this study, the hydraulic model, HEC's River Analysis System (HEC-RAS), version 4. (HEC, 2002) was used. It calculates 1D steady and unsteady flow based on the St. Venant equations solved with an implicit finite difference approximations and Preissman's second-order scheme. Basic input data required by the model include the channel network connectivity, cross-section geometry, reach lengths and roughness coefficients (Manning's n). Cross sections are required at representative locations throughout a stream reach and at locations where changes in discharge, slope, shape or roughness occur. Boundary conditions are necessary to define the starting water depth or the discharge at the stream system endpoints, i.e., downstream and upstream.

3 Area of study: the Oise River

The Oise River (France) is the largest tributary of the Seine River (65000 km^2), France. Its total length is 302 km for a catchment area of 17000 km^2 (Figure 2a). Its springs are located in the Belgian province of Hainaut at an altitude of 323 m above sea level. It crosses the border with France approximately 20 km downstream from its source. It joins the Seine River at Conflans-Sainte-Honorine, 75 km downstream from Paris along the Seine River. The population of the basin is 2.15 million inhabitants, mainly located at the downstream part of the basin. The Oise basin is typical of the intensive agricultural practices of the Seine basin (73% of its total area).

The average discharge at the Sarron hydrometric station (14 200 km^2) is 112m^3/s. In terms of hydrogeology, the Oise network drains two main geological formations; Eocene sands and limestones, and Cretaceous chalk (Figure 2b).

The simulated area of the Oise River (Figure 2a) covers 131 km downstream from Sempigny until the confluence with the Seine River at Conflans-Sainte-Honorine. It also includes part of the Oise's major tributaries, namely the Aisne downstream from Herant and the Thérain downstream from Beauvais (Figure 3). The total length of the simulated stream network is 188 km, the simulated area of the basin is 4000 km^2 (Figure 2a).

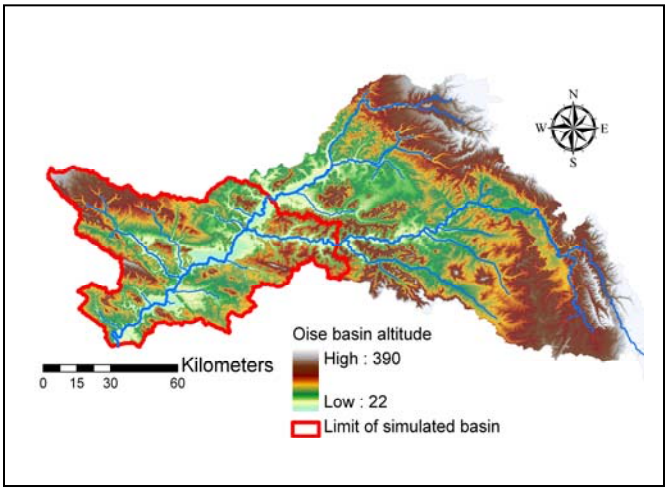

Figure 2a: Oise River basin

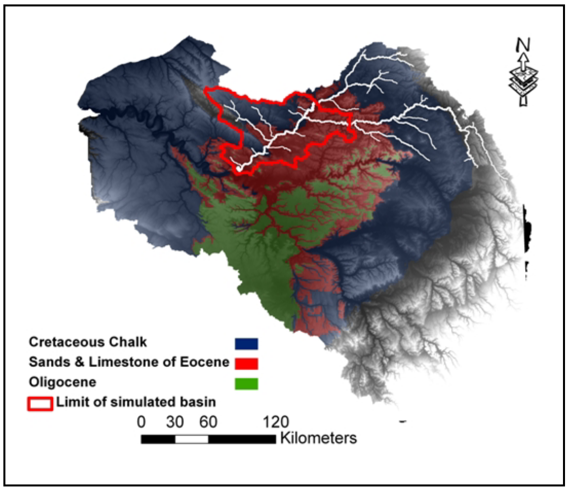

Figure 2b: Oise basin aquifer

4 The construction of the Oise River hydraulic model

The upstream boundary conditions of the Oise River hydraulic model are defined by daily observed discharge hydrographs at Sempigny, Herant (Aisne reach) and Beauvais (Thérain reach) (Figure 3). The downstream boundary condition of the Oise River hydraulic model is a normal depth obtained using the Manning's equation. Observed lateral inflows representing sub-catchments along the simulated stream are inputs into the hydraulic model if available.

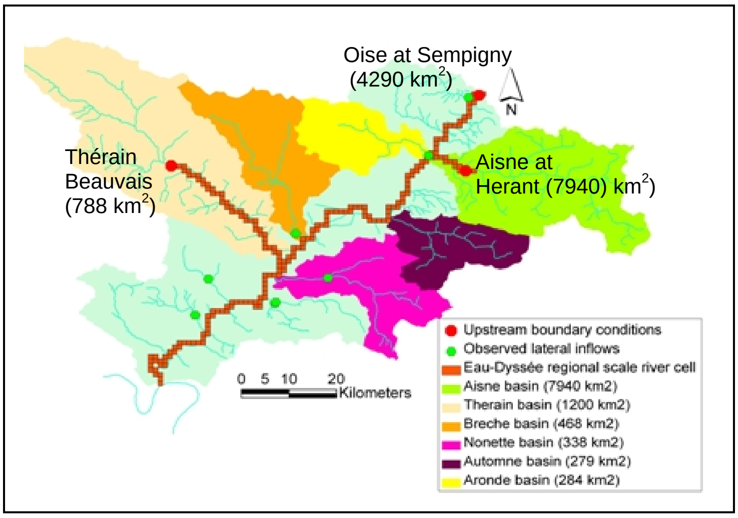

Figure 3: Oise basin boundary condition

The remaining lateral inflows, corresponding to a contributing area of 2180km^2 are simulated by the hydrological platform Eau-Dyssée in form of runoff and groundwater contribution. Note that the latter is simulated assuming a constant in-stream water level. The geometry of the stream network is represented by 414 cross sections containing the main channel and floodplains, which were provided by the French Direction Régionale de l'Environnement (DIREN). The average distance between cross sections is 200m.

5 Results and discussion

5.1 Hydraulic model performance

The roughness coefficient (Manning's n), which represents surface's resistance to flow and is an integral parameter for calculating water depth in the stream. An increase of Manning's roughness coefficient in the main channel has the following impacts on the hydraulic response: a) local increase in water stage b) decrease of discharge peak as the flood wave moves downstream, c) increase of travel time.

The calibration was performed by fitting simulated discharge and water levels against observations at the gauging stations of Sarron, Maysel, Creil and Auvers sur Oise (Figure 4). The aim was to maximize the efficiency of the hydraulic model, evaluated by Nash-Suttcliffe (NS) (1970), correlation coefficient (R^2), Root Mean Square Error (RMSE) and Bias statistical criteria (Table 1). These criteria were calculated at the daily time step. Different roughness coefficients for different river segments were used to calibrate the hydraulic model. Optimal values of Manning's roughness coefficients varied from 0.026 to 0.32 depending on the reach segment which is in the standard range for such rivers. The roughness coefficient for the floodplain was fixed at 0.04 and had minor influence on the model's performance. Figure 4 shows satisfactory simulated discharges at the available gauging stations. The biases between simulated and observed discharges are largely improved when groundwater contributions from Eau-Dyssée are taken into consideration (Figure 4).

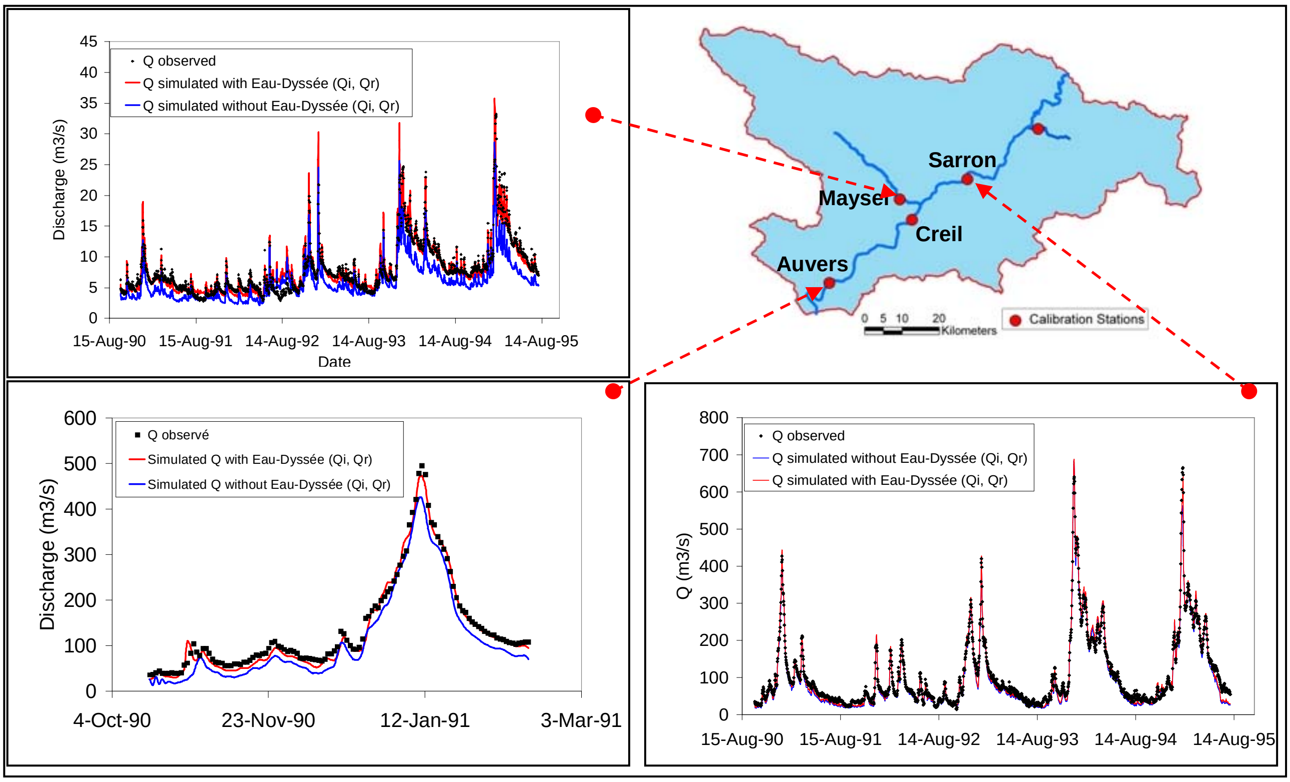

Figure 4: HEC-RAS Simulated discharge hydrographs (with and without Eau-Dyssée contributions) compared to observations at certain hydrometric stations

Table 1: Statistical criteria of HEC-RAS simulations

		Discharge			Water level		
Station	Period	NS	Bias (%)	RMSE (m3/s)	R^2	Bias (%)	RMSE (m)
Sarron	1990-1995	0.97	-4.0	12	0.98	-0.12	0.11
Maysel	1990-1995	0.91	0.15	1.35	NA	NA	NA
Auvers	1990-1991	0.98	-4.0	13.4	NA	NA	NA
Creil	1990-1991	NA	NA	NA	0.94	0.07	0.09

5.2 Simulated discharge at regional scale

Discharge hydrographs are simulated by the regional model EAU-Dyssée after implementing the new methodology of in-stream water level fluctuations. The simulated discharge hydrographs are obtained using the Météo-France SAFRAN database (precipitation and potential evapotranspiration), without forcing any observed discharge hydrographs into the model. The simulated discharge by the regional model EAU-Dyssée is compared with stream flow observations at Sarron station (Figure 5). The results show satisfactory fitting between the regional model and observations in terms of hydrograph shape and timing of peaks, although the model tends to overestimate discharge peaks due to overestimation in the volume of runoff produced during high flow periods (Table 2).

Table 2: Statistical criteria of Eau-Dyssée simulated discharge at Sarron

Station	period	NS	Bias (%)	RMSE (m3/s)
Sarron	1-Oct-1990 – 31-Jul-1995	0.85	6.0	38

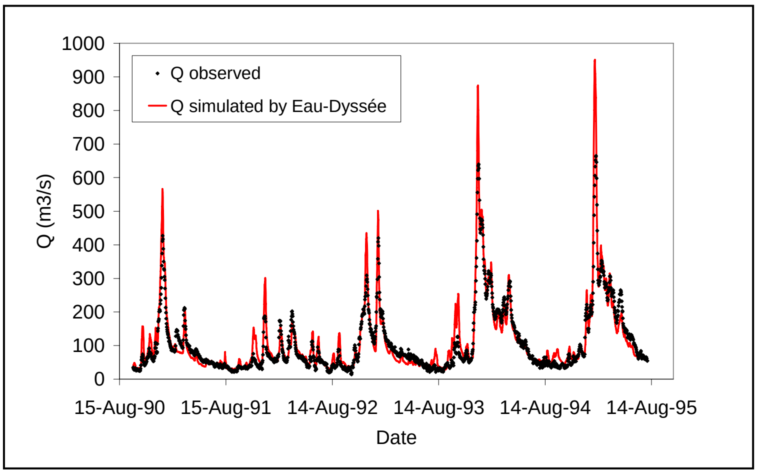

Figure 5: Eau-Dyssée simulated discharge hydrograph compared to observations at Sarron

5.3 Local effect of river water level fluctuations on piezometric head

To assess the impact of stream water level fluctuations on simulated piezometric heads, two regional Eaudyssee simulations were compared. The first one is based on the initial version of Eau-Dyssée where river stages are constant and the second one is based on varying water levels based on the upscaling method. To locally characterize the influence of this process, Figure 6 illustrates the impact of water level fluctuations on piezometric heads. One river grid-cell in connection with two underlying aquifer grid-cells is considered herein. The first aquifer grid-cell is located in the Eocene layer and exchanges directly with the river grid-cell. The second aquifer cell is confined and located in the Chalk layer, which is directly connected with the Eocene grid-cell. In the river grid-cell fluctuation of water level rises up to 7 meters during flood periods. These water level fluctuations lead to a rise of 2 meters in the simulated piezometric heads, whereas the piezometric head varies only of a few centimeters for the simulation with a constant water level.

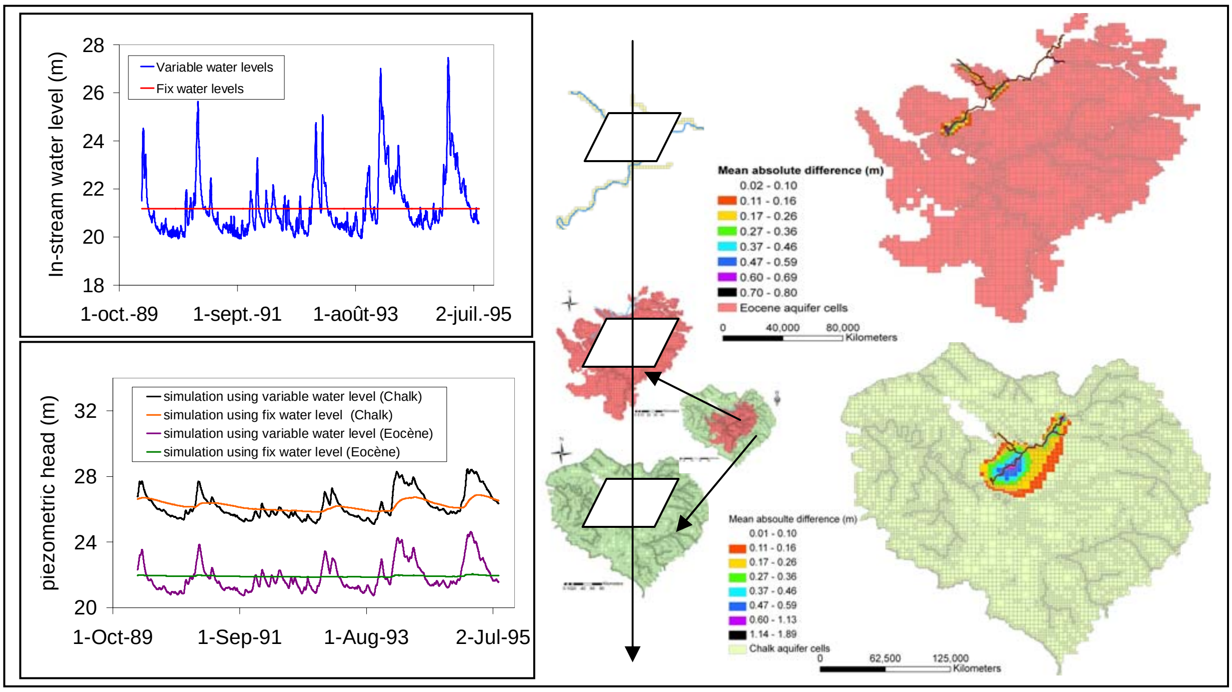

Figure 6: Local and spatial Impact of stream water level fluctuations on piezometric head

5.4 Regional impact of water level fluctuations on piezometric head distribution

In this section, the spatial impact of stream water level fluctuations on piezometric head distributions in adjacent aquifers is investigated. The spatial influence was characterized by calculating the mean absolute difference between the piezometric head of the two simulations in each aquifer cell (Figure 6).

The influenced area of in-stream water level fluctuating compared to fix water level extends over 10km in the Eocene aquifer and 25km in the chalk. The latter is larger because the storage coefficient in the confined aquifer unit is higher than in the unconfined one. The mean absolute difference between the two simulations in each given aquifer cell varies from a few centimeters to more than 1.9m in aquifer grid-cells close to the main stream. As expected the influence of fluctuating water levels on piezometric head decreases with the distance to stream. It then might be that the hydrological model has to be recalibrated in the neighbourhood of the stream networks.

6 Conclusions and perspectives

In this study, a coupling framework for regional hydrological modeling is developed. The methodology is based on upscaling method from local scale to regional scale.

The efficiency of this method is proven in the Oise River (France) and some of its tributaries from Sempigny to the confluence with the Seine River. In-stream water level fluctuations influence piezometric head fields over a range of tens of kilometers. The approach not only implements an additional physical process at the regional scale leading to more realistic water level profiles along streams, but also leads to a considerable computational time saving in the burdensome task of specifying water depths along a large and complex stream network system within a regional model. This work outlines the efficiency of the approach to better simulate water pathways and stream-aquifer interactions at regional scale with low computation cost. Apart from hydrology, it offers interesting perspectives to simulate nitrate elimination in wetlands which are often located at the contact zone between groundwater and in-stream waters. The methodology is also promising when modeling rivers with no observed hydrometric stations, as the output of Eau-Dyssée could be used as forced discharge for the hydraulic model.

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