XVIII International Conference on Water Resources
CMWR 2010
J. Carrera (Ed)
CIMNE, Barcelona 2010

CONTRIBUTION OF 1D RIVER FLOW MODELING TO THE QUANTIFICATION OF STREAM-AQUIFER INTERACTIONS IN A REGIONAL HYDROLOGICAL MODEL

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Key words: Hydraulic modeling, Stream-Aquifer Interactions, regional scale modeling.

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 [1]. 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 [2]. The recognition of these interactions motivated researchers to focus on coupled models [3, 4, 5, 6, 7]. 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 [8, 9]; (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, as in MIKE-SHE [10], HEC-HMS/HEC-RAS [11] and CAWAQS [12, 13] for instance.

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. We first describe the general modeling strategy and our case study in the Oise River basin. The results then illustrate the efficiency of this strategy to simulate realistic river stages at the regional scale, and the impact of the resulting river stage fluctuations on the piezometric head.

2 MODELS DESCRIPTION

2.1 General strategy

The modeling platform Eau-Dyssée couples existing specialized models to address water resources and quality in regional scale river basins. Following the hydrogeological model MODCOU [14, 15], it is composed of four interconnected components to represent the water cycles: the surface component, the unsaturated zone, the saturated zone or aquifers and the river network. Each component is represented by a spatially distributed module, outlined below. Within this general framework, we propose a strategy to benefit from the results of a high resolution 1D channel flow model (HEC-RAS [16]) 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.

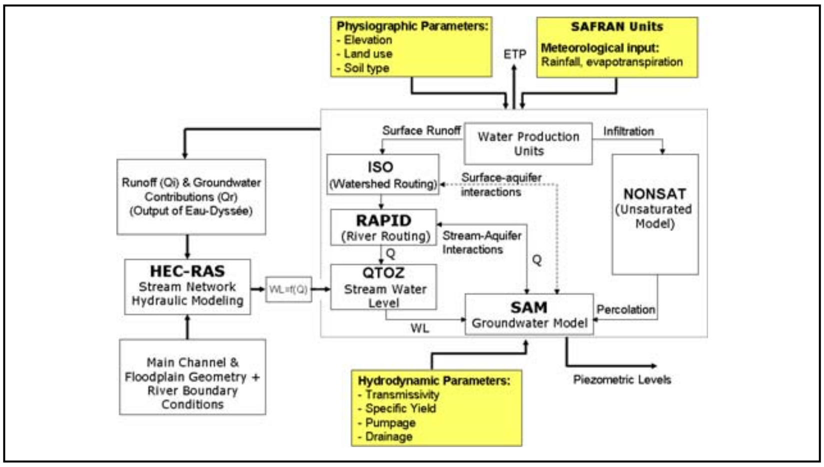

Figure 1: Modeling Framework

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. 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 discharge routed 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.

2.2 The regional scale hydrogeological model Eau-Dyssée

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[17]. The domain is divided into production zones to which an eight parameter model called production function is associated[15]. Each production functions computes 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 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.

Unsaturated zone: The infiltrated water partitioned by the production functions is transferred vertically to the groundwater table by the unsaturated-zone model NONSAT[15, 18]. 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.

Saturated zone: The SAM model (for Simulation des Aquifères Multicouches; formerly MODCOU[14]) is a regional spatially distributed model that computes the temporal distribution of the piezometric heads of multilayer aquifers, using the diffusivity equation. It also computes exchange between aquifer and river. The former version of SAM (MODCOU) has been applied to many basins of varying scales and hydrogeological settings.

Hydrological river routing: The in-stream discharge routing within the platform Eau-Dyssée is performed by RAPID[19], which is based on the Muskingum routing scheme. It simulates discharge and water volume in all cells of a river network (1km * 1km) at a daily time step.

2.3 The QtoZ river stage module

This module was added to Eau-Dyssée to calculate 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.

2.4 Hydraulic model HEC-RAS

To characterize the required rating curves at high longitudinal resolution, we used the hydraulic model HEC-RAS[16], version 4. 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.

3 STUDY AREA: THE CONSTRUCTION OF THE OISE RIVER MODEL

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). It joins the Seine River at Conflans-Sainte-Honorine, 75 km downstream from Paris along the Seine River. In terms of hydrogeology, the Oise network drains two main geological formations, Eocene sands and limestones, and Cretaceous chalk (Figure 2b). The simulated reach of the Oise River (Figure 2a) runs 131 km downstream from Sempigny until the confluence with the Seine River. We also simulate the downstream parts of the tributaries, namely the Aisne downstream from Herant and the Thérain downstream from Beauvais. The total length of the simulated stream network is 188 km, and the directly contributing area defines an interbasin of 4000 km^2 (Figure 2a).

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 2a). Observed lateral inflows representing sub-catchments along the simulated stream are inputs into the hydraulic model if available. 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.

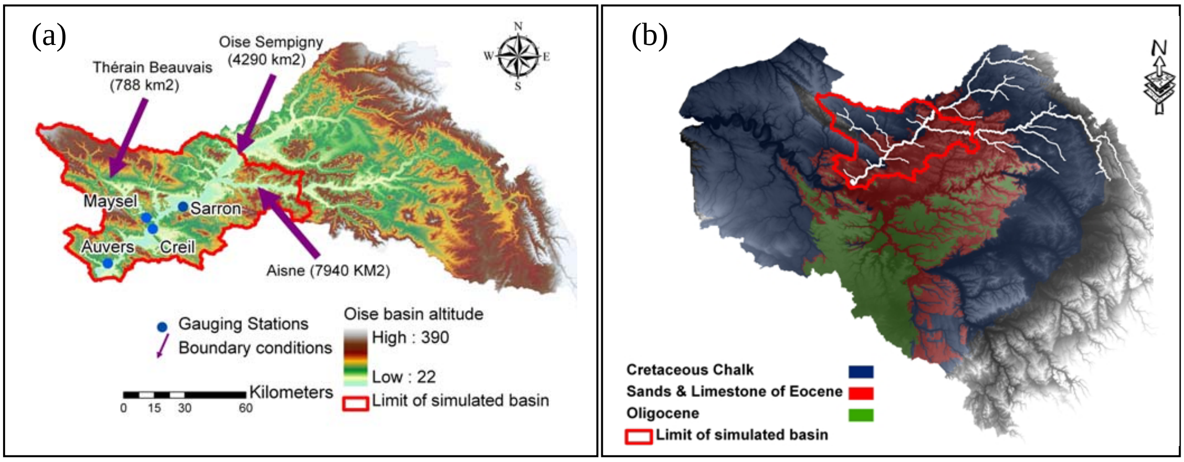

Figure 2: a) Oise River basin boundary conditions and gauging stations; b) Oise basin location within the Seine basin and its main geological formations

4 RESULTS AND DISCUSSION

4.1 Calibration of the high resolution hydraulic model

We calibrated 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 (e.g. at Sarron, Figure 3a, b). The aim was to maximize the efficiency of the hydraulic model, evaluated by several classical 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 0.032 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.

Table 1: Statistical criteria of HEC-RAS simulations computed at the daily time step

		Discharge			Water level		
Station	Period	NS	Bias (%)	RMSE (m3/s)	R^2	Bias (%)	RMSE (m)
Sarron	1990-1995	0.97	-4.0	12	0.96	-0.26	0.17
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

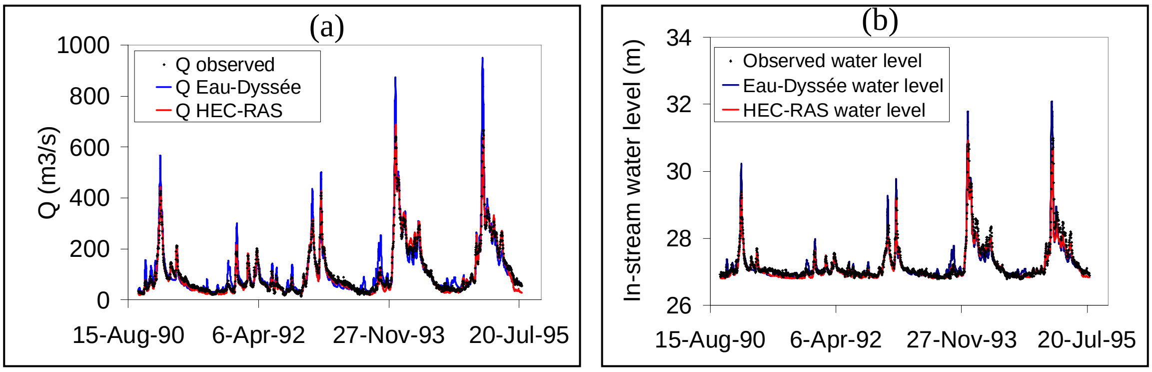

Figure 3: a) HEC-RAS & Eau-Dyssée simulated discharge hydrographs at Sarron; b) HEC-RAS & Eau-Dyssée simulated water levels at Sarron

4.2 Simulated discharge and river stage by the regional-scale model

Discharge hydrographs are simulated by the regional model EAU-Dyssée after implementing the new methodology of in-stream water level fluctuations. The stream network is represented by 202 river cells (1km * 1km). The simulation is forced over the entire Oise basin using the Météo-France SAFRAN meterological database (precipitation and potential evapotranspiration), and the discharge at the upstream boundaries of the test reaches comes from Eau-Dyssée (whereas we used observed hydrographs for the HEC-RAS simulation). The discharge and water levels simulated in the test reaches by the regional model Eau-Dyssée compares satisfactorily with 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. (e.g. at Sarron, Figure 3a, b). The NS and bias criteria at Sarron station are 0.85 and 6%, respectively for discharge and 0.79 and -0.05%, respectively for water levels.

4.2 Local effect of river stage fluctuations on piezometric head

To assess the impact of stream water level fluctuations on simulated piezometric heads, two regional Eau-Dyssée simulations were compared. The first one is based on varying river stage based on the upscaling method and the second one assumes constant river stages which are deduced from the average of the varying river stages simulation. To locally characterize the influence of this process, we considered one river grid-cell in connection with two underlying aquifer grid-cells (Figure 4). 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, river stage has an amplitude of 7 meters during flood periods. These water level fluctuations lead to a rise of 2 meters in the simulated piezometric head, whereas the piezometric head varies only of a few centimeters for the simulation with a constant stage.

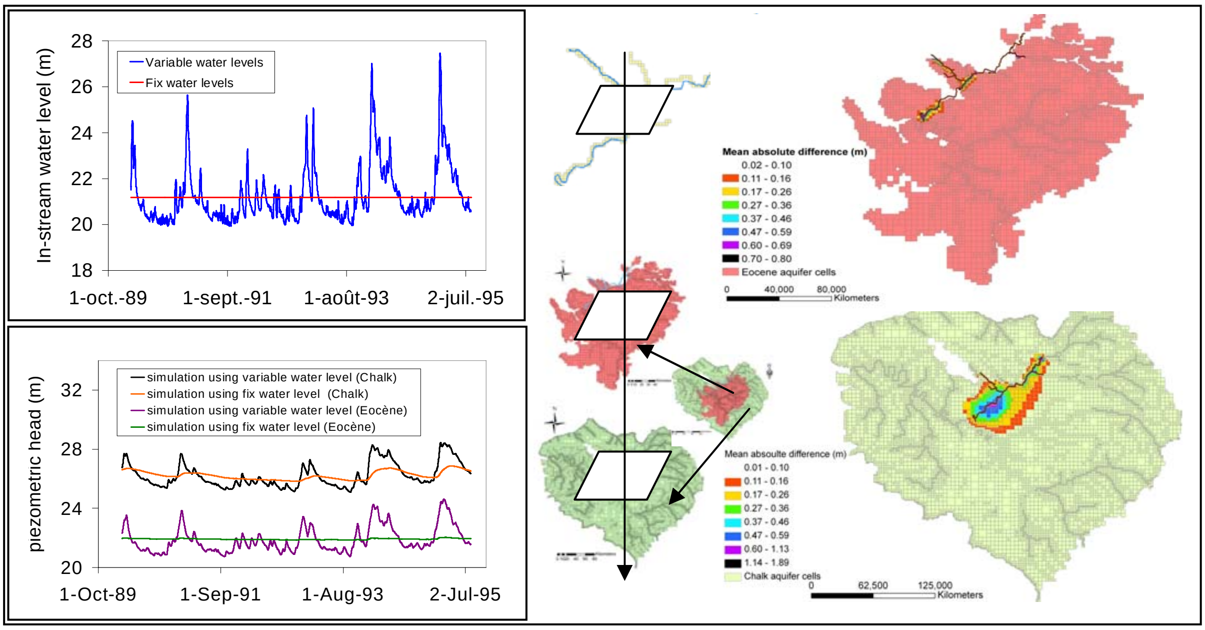

Figure 4: Local and spatial impact of stream water level fluctuations on piezometric head

4.3 Regional impact of river stage 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 4). The influenced area of in-stream fluctuating water level compared to fix water level extends over 10 km around the river in the Eocene aquifer and 25 km 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 1.9 m in aquifer grid-cells close to the main stream. As expected, the influence of fluctuating water levels on piezometric head decreases with distance to the stream.

5 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 this burdensome task, owing to the pre-computation of the rating curves. This work also outlines the importance of this new process to the simulation of stream-aquifer interactions at regional scale. Apart from hydrodynamics, this work offers interesting perspectives, for instance to simulate nitrate elimination in wetlands which are often located at the contact zone between groundwater and in-stream waters.

Acknowledgements

This work was supported by the PIREN-Seine research program on the Seine basin and by the Centre National des Oeuvres Universitaires et Scolaires (CNOUS). We are grateful for the data provided by the Direction Régionale de l'Environnement Ile de France (DIREN) and by Méteo-France.

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