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COUPLING RIVER AND SUBSURFACE FLOW MODEL FOR AN INTEGRATED ANALYSIS OF RECEIVING WATER QUALITY

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Summary. Sustainable river basin management often requires an integrated understanding of surface-subsurface flow and transport processes. The software framework OpenGeoSys (OGS) and the EPA Storm Water Management Model (SWMM) have been coupled to accomplish this. In this work OGS simulates flow in confined and unconfined aquifers applying the Darcy equation, while surface channel runoff is described with the Saint-Venant approach using EPA-SWMM. Aquifer and river are coupled via exchange fluxes. The sensitivity of the simulation results is examined in reference to a leakance parameter in the calculation of coupling source terms. The application of the coupled model to a real-life case study (Poltva catchment, Western Ukraine) is outlined.

1 INTRODUCTION

The ecological significance of human impacts on groundwater-surface water interactions are emphasized by Sophocleous (2002)[5] while typical interactions between groundwater-surface water are examined in Dahl et al. (2007)[8]. Studies on fully-integrated hydrologic modeling (surface-subsurface systems) include VanderKwaak and Loague (2001)[24], Panday and Huyakorn (2004)[22], Gunduz and Aral (2005)[6], Jones et al. (2006)[19], Kollet and Maxwell (2006, 2008)[20,21], Krause et al. (2007)[9], Qu and Duffy (2007)[23], Andersen and Acworth (2009)[12], Delfs et al. (2009a,b)[15,16] and Bailly-Comte et al. (2009)[13].

SWMM, originally developed for runoff modelling in urban drainage systems, contains a flexible set of modelling capabilities, which also allow the description of non-uniform flow and associated pollutant transport through irregular channels, such as river systems [7,10,17]. Blumensaat et al. (2009)[14] successfully applied an integrated sewer-river model based on SWMM for the analysis of infrastructure optimisation measures for river water quality improvement. In this case, however, interactions between ground- and surface water were disregarded.

One strength of OGS is its overland-soil-groundwater system modelling capabilities with Euler (finite element / volume) and Lagrangian (random walk particle tracking) methods[11].

In this work SWMM and OGS[18] are coupled. The coupling fluxes for water exchange between the Saint-Venant equations for open channel flow and the groundwater flow equations for confined and unconfined aquifers are introduced. A verification example for both a connected and disconnected river-aquifer system are presented and the effects of a leakance parameter in the coupling flux calculation studied. Finally, the the model is utilized to examine the Poltva catchment in the Western Ukraine.

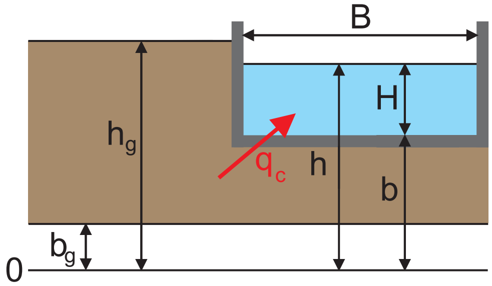

Figure 1: Coupling flux q_c for a gaining river (b_g is the aquifer bottom height and B the river width).

2 RIVER-AQUIFER COUPLING

OpenGeoSys utilizes a compartment approach[11] to allow rapid coupling of individual processes. The governing equations of each flow process (in this case, river and aquifer flow) are separately solved in a coupling loop (partitioned coupling). In the coupling iteration OGS solves the algebraic equation for the aquifer and calls SWMM for river flow. Water exchange at the common compartment interface is included with a coupling flux as a source-sink term in the governing equations. The coupling flux for a connected river-aquifer system is given by

$$q_c = \Lambda \left(h - h_g \right) \tag{1}$$

where $h = H + b$ is the surface water head, H is the river water depth, b the river bottom height, h_g the hydraulic head in the aquifer and Λ is the leakance. For $q_c < 0$ the river is a 'gaining river' (Fig. 1) and for $q_c > 0$ a 'losing river'. If river and aquifer are disconnected ($h_g < b$), the exchange flux reads

$$q_c = \Lambda H. \tag{2}$$

Influence of a wetted perimeter can be included with a relationship of the form[6] $\Lambda = \Lambda(H)$. In the following, OGS solves the Darcy groundwater flow equations[3] for confined and unconfined aquifers, and SWMM the Saint-Venant equations[4] for river flow.

3 VERIFICATION

We consider a rectangular confined aquifer with a size 2000×1000 m^2 and a bottom height $b_g = 0$ coupled at one edge with a river with length 1000m and bottom height $b = 9$ m (Fig. 2a). Groundwater flow in a confined aquifer[3] is spatially discretized with triangular finite elements and river flow with line elements which are located at the triangle edges with corresponding nodes in the xy-plane. Specific validation cases that emphasize coupled surface-subsurface processes can be found for example in Panday and Huyakorn (2004)[22], Kollet and Maxwell (2006)[20], Delfs et al. (2009a)[15].

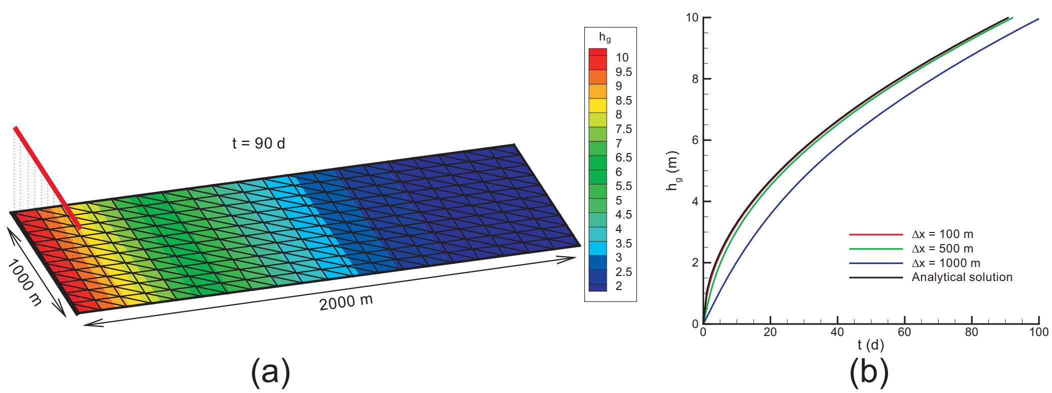

Figure 2: Verification example constant aquifer recharge: (a) Groundwater heads h_g, discretization mesh for edge length $\Delta x = 100m$ and location of river. (b) Comparison of Simulated groundwater depths h_g below the river bed with the analytical solution[2] $h_g = q_g \sqrt{\frac{t}{\pi KLS}}$. Dependence on spatial discretization. Triangular regular mesh with edge length Δx.

3.1 Constant aquifer recharge

The aquifer is initially dry, the river depth fixed at $H = 1$ m and the river bottom height $b = 10$ m such that the aquifer recharge is constant $q_g = q_c = 10^{-6} m/s$ for $t < 90d$. Parameters are given in Tab. 1. A time step size of $\Delta t = 1$ d is chosen. Fig. 2(a) shows groundwater heads and river location for edge lengths $\Delta x = 100$ m. Fig. 2(b) compares simulated groundwater heads h_g below the river for edge lengths between $\Delta x = 100$ m and $\Delta x = 1000$ m in the spatial discretization of groundwater flow with an analytical solution[2].

3.2 Aquifer discharge into river

We set the initial groundwater head at $h_g = 10$ m such that aquifer and river are in equilibrium. Constant recharge of $q_g = 10^{-10}$ m/s is applied on the whole aquifer domain. The river water depth H is again fixed at 1 m which corresponds to an infinite large water body (river width ($B \to \infty$) or Manning parameter $n \to 0$ such that exfiltrating water disappears immediately. Fig. 3(a) shows the influence of the leakance Λ on the coupling flux q_c (river width $B = 1m$). The time step size is chosen $\Delta t = 1$ d, and the aquifer discretization $\Delta x = 100m$. The coupling flux q_c approaches $-q_g l$, where $l = 2000m$ is the aquifer width. The coupling flux shows significant numerical oscillations for $\Lambda > 10^{-2}$ 1/s while for $\Lambda < 10^{-6}$ 1/s water exchange is hindered.

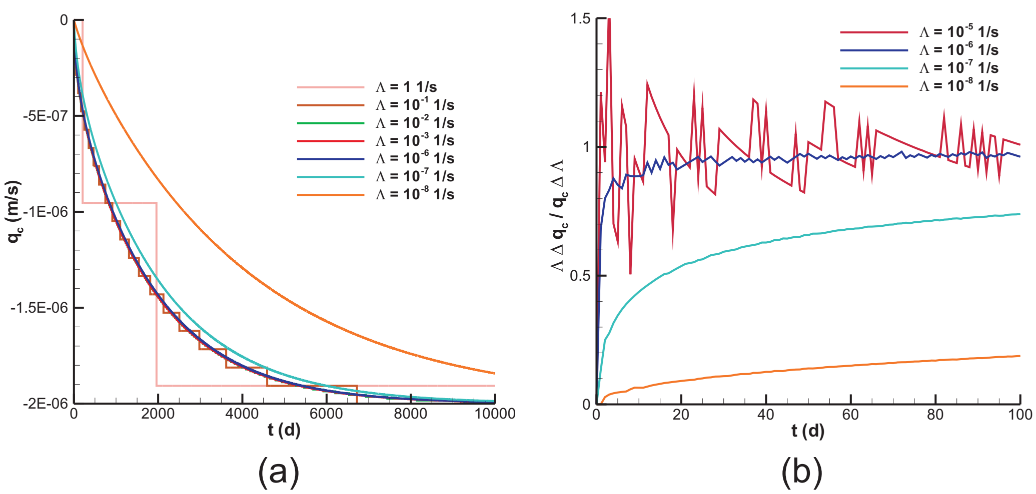

Figure 3: Verification example aquifer discharge into river: (a) Dependence of coupling flux q_c on leakance Λ for. (b) Logarithmic sensitivity of the coupling flux on leakance[16] $\frac{\Lambda \Delta q_c}{q_c \Delta \Lambda} = \frac{q_c(\Lambda[1+\epsilon]) - q_c(\Lambda[1-\epsilon])}{2\epsilon q_c(\Lambda)}$, $\epsilon = 10^{-4}$ for verification example: aquifer discharge into river.

Fig. 3(b) shows the corresponding logarithmic sensitivities of the coupling flux on leakance $\frac{\Lambda \Delta q_c}{q_c \Delta \Lambda}$. The sensitivity is approximately unity for $\Lambda = 10^{-6}$ 1/s. Numerical oscillations increase with Λ. The logarithmic sensitivity decreases for smaller Λ. We found that the oscillations of the sensitivities shown in Fig. 3(b) decrease with higher aquifer recharge q_g. More specifically, a decrease in river recharge by one order of magnitude leads to oscillations in Fig. 3 which correspond to a one order of magnitude higher leakance. If aquifer thickness L and correspondingly river bottom height b are increased, the oscillations are exacerbated. In this case, the oscillations in Fig. 3 for a one order of magnitude thicker aquifer correspond to a one order of magnitude higher leakance. We found that an increase in aquifer conductivity K by two orders of magnitude requires a one order of magnitude higher leakance Λ to avoid hindering of water exchange. The oscillations for a two orders of magnitude higher aquifer conductivity correspond to a one order of magnitude higher leakance. Coupling flux q_c and its sensitivity on leakance $\frac{\Lambda \Delta q_c}{q_c \Delta \Lambda}$ are not significantly affected by aquifer width l and groundwater mesh, but depend on the ratio of storage and time step size $S/\Delta t$ for common time step sizes (e.g. $t = 1$ d). Therefore, we state that there is a C_1 such that $\frac{\Lambda \Delta q_c}{q_c \Delta \Lambda} \approx 1$ for $\Lambda > C_1 \sqrt{K}$ and a C_2 such that no significant oscillations occur for $\Lambda < C_2 q_g \sqrt{K}/L$ where $C2 = C2(S/\Delta t)$. We expect the model to be applicable - i.e. the leakance can be scaled with aquifer conductivity K - for sufficiently high aquifer recharge q_g, low aquifer thickness L and storage to time step ratio $S/\Delta t$.

4 APPLICATION TO THE POLTVA CATCHMENT

The river Poltva is a tributary to the river Bug and located in Western Ukraine. The considered river system is heavily affected by wastewater discharges (point sources) and agricultural emissions (diffusive sources), which causes severe water quality problems of transboundary relevance. The boundaries of the Poltva catchment (Fig. 4) were obtained by a GIS-based catchment analysis. Groundwater flow is simulated for an unconfined aquifer[3] which is at the beginning subject to a constant recharge of $q_g = 10^{-9} m/s$ on the whole domain. The aquifer grid size was $\Delta x = 100m$ at the river and $\Delta x = 1000m$ at the catchment boundary where a no-flow boundary condition was assigned. The river course is the result of an analyis of two digital elevation models with resolutions of 30 (not verified) and 90 (verified) meters. The river height declines by 30 m between its spring, the outlets of two wastewater treatment plants, and the confluent with the river Bug. The river source flow (effluent of the wastewater treatment plant) is given by a constant source term of $Q = 3m^3/s$ at the upstream boundary which leads to water depths H between 0.4 and 2.5 meters. The parameters used are given in Tab. 1. A globel time step of $\Delta t = 0.1d$ was chosen. A recharge event for two days with a peak of $q_g = 10^{-6} m/s$ increases the surface water depth by about 10 cm. The logarithmic sensitivities of the coupling flux on leakance $\frac{\Lambda \Delta q_c}{q_c \Delta \Lambda}$ stay at zero for free moving water in the river. We found that the oscillations in the logaritmic sensitivities increase for higher leakances Λ (cmp. with Fig. 3 for coupling flux q_c and its logarithmic sensitivity on leakance Λ). A decrease in leakance reduces the response in river flow.

5 CONCLUSIONS

OGS has been coupled with SWMM to describe the hydraulic interactions between surface and subsurface compartments. The ultimate purpose of the new model is the evaluation of anthropogenic impacts on river water quality.

We presented two benchmark examples: A problem proposed by Gunduz and Aral (2005)[6] and a new example for transient aquifer discharge into a river with constant water depth. A sensitiviy study of the coupling flux on a leakance parameter indicated that the leakance has to be sufficiently high such that water exchange is not hindered ($\Lambda > C_1 \sqrt{K}$) and sufficiently low to avoid numerical oscillations ($\Lambda < C_2 q_g \sqrt{K}/L$ where

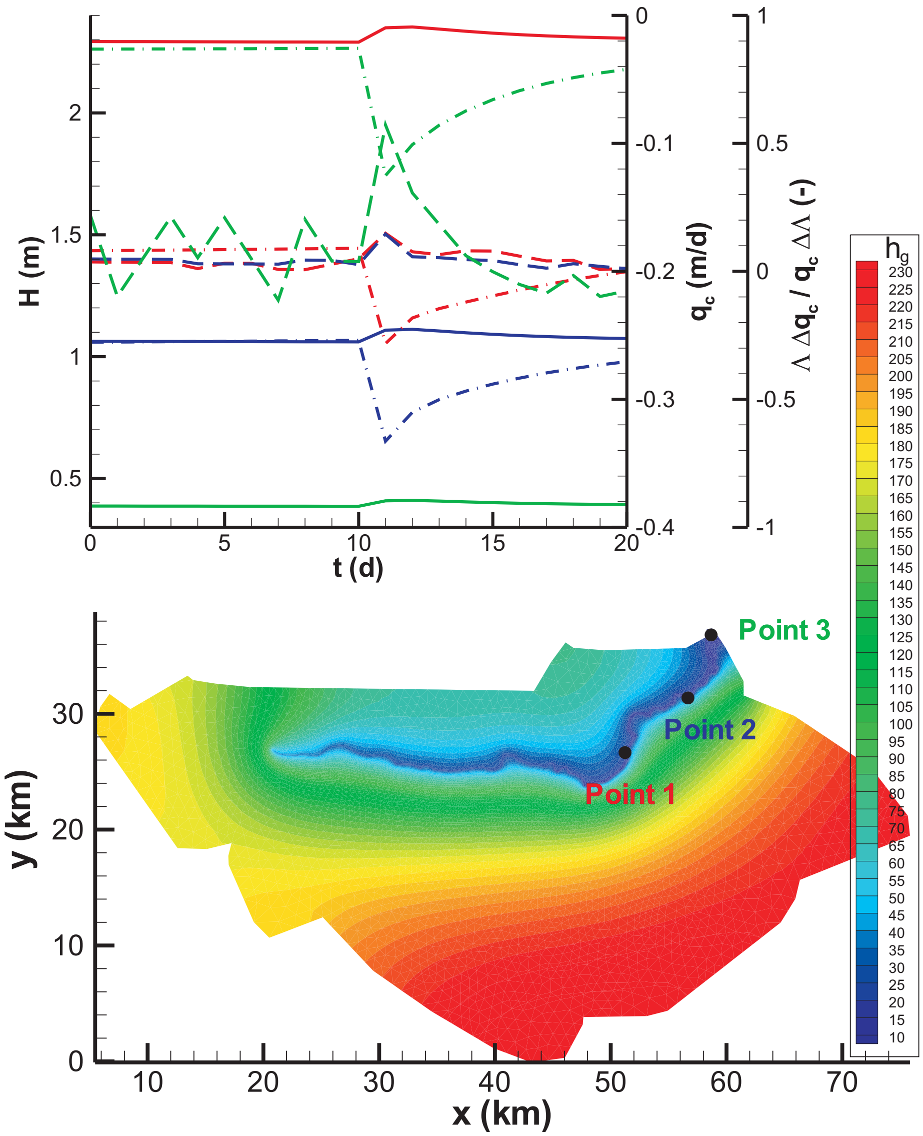

Figure 4: Groundwater heads h_g for constant recharge of $q_g = 10^{-9} m/s$ on Poltva catchment (lower figure part). Response to a linear recharge increase by three orders of magnitude for one day followed by a linear decrease during the following day at three points along the river (upper figure part): Surface water depths H (solid curves), coupling fluxes q_c (dash-dotted curves) and logarithmic sensitivities of the coupling flux on leakance $\frac{\Lambda \Delta q_c}{q_c \Delta \Lambda}$ (dashed curves).

$C_2 = C_2(S/\Delta t)$). The application of the model requires a sufficiently high groundwater recharge q_g and low conductivity K and thickness L.

The coupled model has exemplarily been applied in a case study at the Poltva basin in the Western Ukraine. In a second step, additional state variables (representing relevant pollution substances) will be introduced to model pollution transport within both compartments. Combining the strengths of both models, it is thus possible to perform an integrated analysis of pollution dynamics in receiving waters.

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Parameter	**Symbol**	**Setting**	**Unit**
Verification			
Storage	S	1×10^{-3}	$-$
Conductivity	K	1×10^{-5}	m/s
Aquifer thickness	L	10	m
Application			
Storage	S	0.5	$-$
Conductivity	K	1×10^{-5}	m/s
Leakance	Λ	1×10^{-5}	$1/s$
River width	B	10	m
Manning parameter	n	0.033	$s/m^{1/3}$

Table 1: Parameters of verification and Poltva application examples.