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Modelling of surface water – groundwater interaction on the Alzette river basin in Luxembourg

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Abstract

Detailed field measurements of water table levels and river stages operated on the Alzette river basin in Luxembourg have pointed out that the runoff response of the catchment due to rainfall is strongly dependent on the groundwater level behaviour and consequently on the water storage of the catchment. This is due to the soil structure and geology of the area, which allow the formation of fast preferential flow that quickly reaches the aquifer and rapidly increases the near-stream saturated area.

In order to simulate such situation an integrated approach that allows the simulation of coupled groundwater and surface water flows is necessary; for this purpose the 'Representative Elementary Watershed' (REW) model is selected.

The model considers the total watershed area as subdivided in a number of sub-watersheds according to the Strahler stream order system. Each sub-watershed is considered as a spatial unit, and is divided in various zones according to the different physical processes observed. Only averaged quantities are considered within each zone, and mass exchange processes are evaluated between the various zones and the various sub-watersheds.

In particular the mass exchange between the saturated zone and the channel reaches is simulated, allowing an interaction between groundwater and surface water.

Calibration of the model is performed by means of piezographic measures as well as channel flow data available from the Centre de Recherche Public Gabriel Lippmann (CRP-GL) of Luxembourg.

Introduction

Since 1995 a dense hydro-climatological observation network comprising rain gauges, stream gauges and piezographs operates on the Alzette catchment. By analysis of the data some insights on the flood-generating processes in the Alzette catchment has been gained. In particular, channel flow data and piezographic measures show that the catchment runoff response to a rainfall event is strongly dependent on the observed water table level.

The objective of this study is to simulate water table variations and the interaction between dominant hydrological processes that affect the hydrograph generation.

The REW approach is particularly suitable for simulating hydrological processes interactions, and for this reason it is selected for this study.

Study area

The Alzette River basin is located almost entirely in Luxemburg, and has an area of 1,176 km^2. For this study the Hesperange sub-catchment in the south Alzette is selected.

The Hesperange sub-catchment covers an area of 268 km^2, its elevation ranges between 260 and 450 m a.s.l. and average slope is 3.8°. Watershed geometrical properties are extracted from a digital elevation model with a grid size of 50 m.

Soil cover is mainly represented by pastures and forests, while the geology of the study area is characterized by Mesozoic rocks, dominated by marls and schists.

Model description

The REW model is a physically based, semi-distributed, deterministic model, based on the application of balance equations directly at the sub-catchment scale.

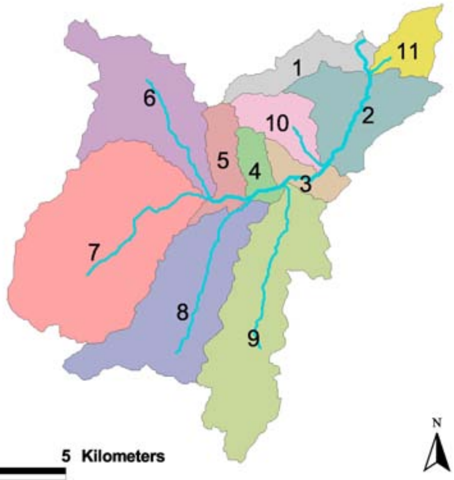

Figure 1. Hesperange sub-catchment sub-divided in REW's.

The river network is generated directly from the DEM of the area, and the watershed is discredited into a number of sub-watersheds or REW's depending on the Strahler order that is selected (Fig. 1).

In the approach balance laws of mass and momentum are spatially averaged over a REW, and constitutive relations (such as Darcy's law, Chézy formula, and the Saint Venant equation) are derived directly at the REW scale.
Each REW therefore is a spatially lumped unit that is represented by spatially averaged parameters and variables.
The REW model, compared to other hydrological models, presents the advantages to posses a low number of parameters, and to require small computational efforts.

Processes interaction

Each REW is subdivided in five zones based on the major hydrological processes that take place within an REW, their different geometries and time scales. The five zones are: saturated zone (below the water table), unsaturated zone (above the water table), channel reach, concentrated overland flow (soil surface corresponding to the unsaturated zone), saturated overland flow (soil surface corresponding to the saturated zone).

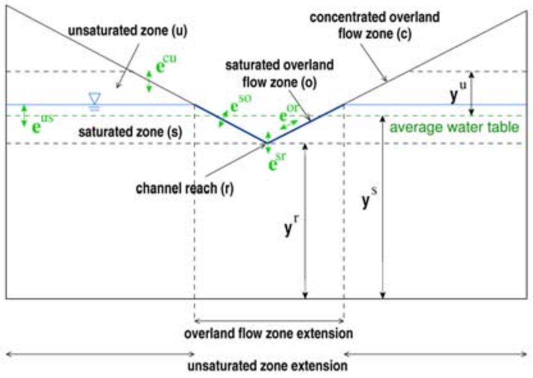

Figure 2. REW cross section.

Fig. 2 shows a cross section of an REW based on the five zones above mentioned, where the mass exchange e^{ij} is allowed for the zones i and j. The position of the water table determines the extension of the various zones.

Model sensitivity and calibration

A model sensitivity analysis is performed in order get some insights in the model behaviour and to help model calibration. A sensitivity analysis varying one parameter at time while keeping the others constant is performed. The change in some hydrograph properties is investigated, and in particular the variation in peak discharge, time to reach the peak and time to reach equilibrium is defined. The same analysis is executed on the simulated water table level. The calibration procedure is carried out by trial and errors, trying to maximize the objective function given by the Coefficient of Determination (R^2).

Results and discussion

Observed water table levels at a piezographic station nearby the catchment outlet and simulated counter parts for REW1 are shown in Fig. 3. The R^2 for the entire simulation period is 0.80, showing that there is a good fit between observed and simulated averaged water table levels.

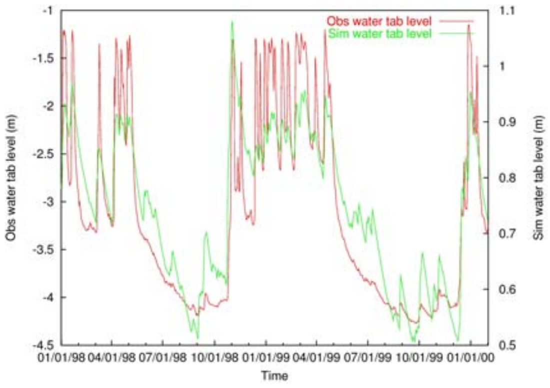

Figure 3. Water table level simulation.

The hydrograph simulation of Fig. 4 shows a R^2 of 0.64. Even though the high peaks as well as the base flow trend is quite well simulated, some hydrograph peaks for low water table values are not observed in reality. This is the main reason why the R^2 is not higher.

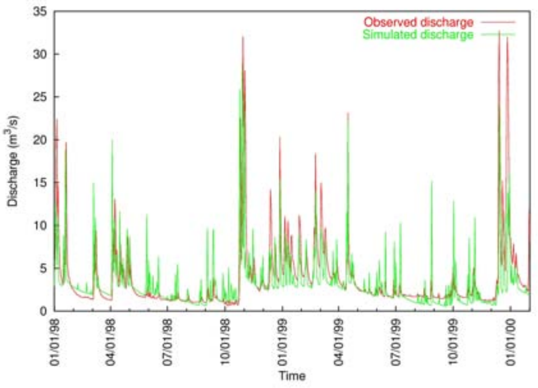

Figure 4. Hydrograph simulation.

The recession limbs of the hydrograph could be simulated more accurately, but this objective was beyond the intentions of this study. The REW model in its current configuration does not consider processes with time scales in between the ‘very fast’ direct runoff coming from the saturated overland flow zone and the ‘very slow’ groundwater flow from the saturated zone.

Future research and conclusions

This application allows us to define the subjects for future research.
The first objective is improving the water table level – saturated overland flow zone relation by improving the manner topography is simulated. When considered that peak discharges are mainly dependent on the extension of this area, the role of topography is evident. Future research will then focus on the derivation of the soil profile for each REW from geometrical properties directly obtainable from the DEM of the study area.
A second subject deals about the simulation of the recession limbs of the hydrograph. This task will probably require the implementation of other components that consider additional hydrological processes, such as rapid groundwater flow, or perched subsurface flow.
We conclude that the REW model for this application has given satisfactory results, and it is a promising tool to simulate interacting hydrological processes.
This work shows that catchment runoff is well simulated after model calibration by means of piezometric observations, indicating that the water table level represented by the selected piezometer graph is a good indicator of the catchment behaviour.

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