COMBINED WATERSHED AND GROUNDWATER MODELLING TO INVESTIGATE LOWLAND RUNOFF PROCESSES - ILLUSTRATED FOR THE LIETZENGRABEN BASIN (GERMANY)

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ABSTRACT

Since the last decades in several lowland watersheds of north-east Germany a decreasing runoff combined with temporal hydrological droughts are observed. This paper makes the case for an intermediate complexity, quasi-distributed, comprehensive, large-watershed model, which falls between the fully distributed, physically based hydrological modelling system of the type of the MIKE SHE model and the lumped, conceptual rainfall-runoff modelling system. This is achieved by integrating the quasi-distributed watershed model ArcEGMO©/PSCN with the fully distributed groundwater model ASM. The advantage of this approach is the use of readily available data, the handling of watershed heterogeneities (multiple land uses, soil layers, vegetation structures) and the significantly increased flexibility in handling stream-aquifer interactions. The mechanics of integrating the components are outlined, and model calibration, validation and simulation of real-world scenarios are briefly presented. Because of the fact, that main part of this basin was influenced by additional water supply more then 80 years, the aim of these scenarios was to derive management strategies to support the water balance of the catchment area, especially taken into account the interaction between surface and ground water.

These applications demonstrate the practicability and versatility of this relatively simple and conceptual clear approach, making public acceptance of the integrated watershed modelling system much easier.

1. INTRODUCTION

The concept of catchment modelling has been changed since the last decades because the complete water circle including soil-vegetation-atmosphere relations becomes more and more important by describing the processes of runoff generation [6, 15]. For estimation the occurrence of floods or high runoff events a classical precipitation-runoff model like SIMHYD [1] may be still the right instrument. But for low and lowest runoff modelling not only the meteorological situation within the different evaporation parts (like transpiration, interception, real evaporation from different surfaces) is important to understand runoff composition but also the subsurface flow processes. That is because precipitation affects not directly to the river, but through soil and groundwater passage. Especially in lowland catchments interflow and base flow components become very important, and the runoff process is dependent on subsurface/surface water transfers and ground water flow

[17].

Distributed numerical physically-based models account for the spatial variability of land, soil and geological parameters, and one of the most well-known, complete representations of the physical hydrological cycle is the distributed model MIKE-SHE [14]. These capabilities make the models very powerful, but also data-demanding, and these data are often not available. Therefore the development and application of more flexible coupled surface and subsurface watershed models is a challenge for watershed hydrology [19]. In this approach we want to show how to improve runoff simulation in a small lowland watershed achieved by coupling the distributed watershed model ArcEGMO©/PSCN [13, 8] with the groundwater model ASM [7].

The study area is located in the north-east of Berlin at the border to Brandenburg. This area had been used for land-water-treatment of municipal sewage since the beginning of the last century. The sewage was stopped 1985, but was extended especially in the 1970s and 1980s. So the runoff of in the natural receiving stream, called Lietzengraben, was mostly generated by sewage farming and amounts 1 or 1.5 m^3/s, but today it is only about 10% of the former value [12]. Downstream wetlands and fishponds did profit by the anthropogenic influence, so they were nominated as nature protection areas. Because they cannot be fed from the natural water supply under recent climatic conditions, measures like irrigation and dams can be installed to raise the available water in this region. To support the decision-making for an optimal composition of this water management strategies, an integrated surface-subsurface watershed study was carried out.

2. MATERIAL AND METHODS

2.1. **Modelling tools.** To describe the complex movement of water interactions between groundwater and surface water, a physical based model was set up by using the hydrological modelling system ArcEGMO© (Pfützner 2002). ArcEGMO© consists of a modelling frame within conceptual submodels describing hydrological processes taking place in complex landscapes and river basins (Fig. 1). The hydrological processes are separated into six model "layers": meteorology (MET), runoff composition depending on soil and vegetation (ABI), river runoff (Q), overland runoff (RD), management (MAN) and groundwater (GW). In each layer different modules are available for calculation the runoff components, so that depending on the problem to be solved a suitable combination of different hydrological approaches can be composed (for example, the accumulation process of river runoff can be described by convolution operation or unit hydrograph). A detailed approach for modelling soil water movement (in the layer ABI) and effects of vegetations is the PSCN module (Plant-Soil-Carbon-Nitrogen-Modul) [8]. PSCN describes the temperature-dependent processes of evapotranspiration, interception, surface water storage, infiltration and both lateral and vertical soil water movement following the multiple layer capacity approach of Koitzsch [10] and Glugla [4].

The groundwater module EGMO-GW, implemented into ArcEGMO©, is a simplified storage approach, which does not represent the fully temporal and spatial distributed groundwater flow. Because all runoff generation processes described by ArcEGMO© are spatial distributed, the description of groundwater movement must be distributed in time and space also. To take this into account, the well known two dimensional ASM-modell [7] was coupled with ArcEGMO© instead of EGMO-GW.

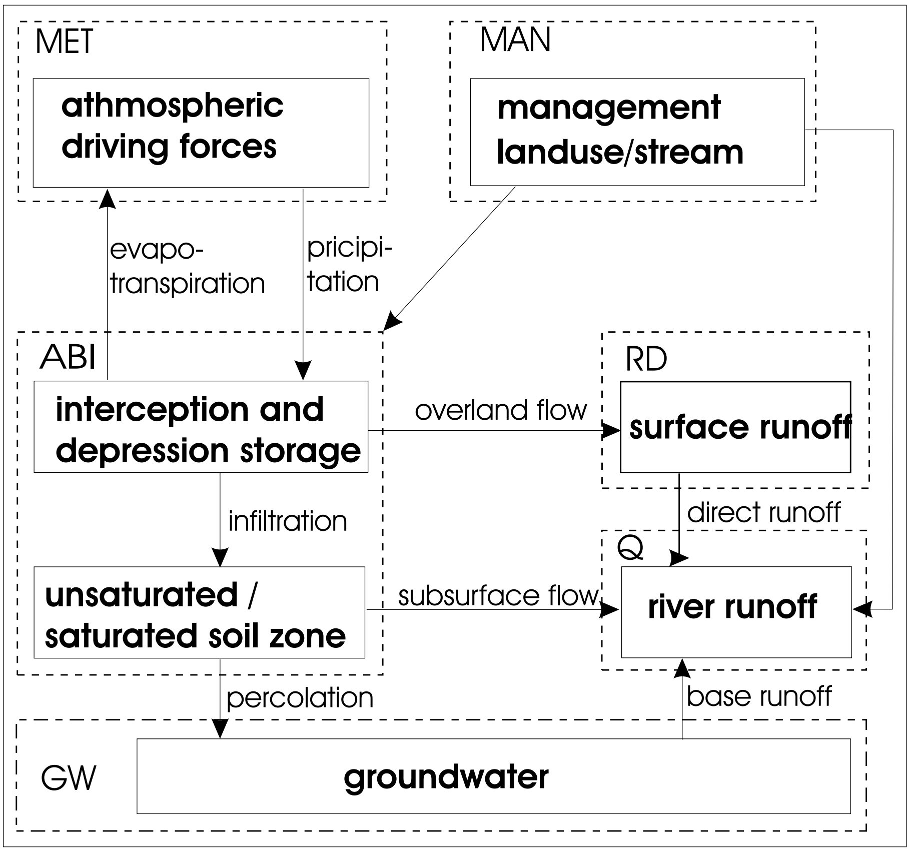

FIGURE 1. Structure in ArcEGMO©

In the following the modelling concepts for the main runoff components and their coupling are described more in detail

2.2. **Infiltration.** With the help of PCSN module the soil water dynamics was simulated considering evaporation, evapotranspiration, interception, summed up to the effective evaporation. The remaining water amount in the soil profile was divided into an infiltration and overland runoff component. For calculating the infiltration rate $Pb(t)$, the degree of sealing, the effective precipitation and the infiltration capacity are used as shown in equation 1.

$$Pb(t) = (1 - \Psi) \quad min \quad (P01(t) \quad , \quad F_{pot}(t)) \tag{1}$$

with Ψ as the degree of sealing (while the sealed part of surface causes overlandflow, the unsealed part causes infiltration), P01 as the precipitation reaching the soil surface, and $F_{pot}(t)$ as the infiltration capacity of the upper soil layer, in dependence of the saturated conductivity and relative soil moisture (based on Horten's empirical formula). If infiltration is not possible because of high sealing or soil saturation, surface runoff will be generated.

2.3. **Surface runoff.** Overland runoff is calculated in dependence on several classes of landcover and vegetation, like agriculture, greenlands, woods, industries, settlements etc..

Each of these classes is defined by the following parameters: root depth, capacity of interception, leaf area index (lai), albedo, roughness, sealing degree and degree of coverage. Some of these parameters can vary seasonally, like root depth and leaf area index on agriculture, so that the description of the landcover is already dynamically approximated. The description of surface runoff is realized by the theory of kinematic waves, where the dynamic equation by Saint-Venant is reduced to the term of gravitation and friction [5, 18].

2.4. **Soil water movement.** Infiltrating water $Pb(t)$ percolates through soil layers and could be retarded by storage. Water storage is determined by soil specific values like field capacity (FC) and permanent wilting point (PWP). If the volumetric soil water content exceeds the field capacity a vertical flow (percolation $P[mm/d]$) or horizontal flow (hypodermic runoff $P^h[mm/d]$) is generated in every layer. The alteration of water content $\theta(z_j, t)$ in a layer z_j per timestep t results from equation 2:

$$\frac{\Delta\theta(z_j,t)}{\Delta t} = \frac{\Delta\theta_w(z_j,t)}{\Delta t} = Pb(z_j,t) - E(z_j,t) - P(z_j,t) - P^h(z_j,t) \tag{2}$$

The soil moisture gets reduced by withdrawal of soil evaporation and evapotranspiration $E[mm/d]$. The percolation $P(z_j)$ from soil layer z_j to its lower soil layer results from equation 3 in dependence of soil temperature B(zj), water content at field capacity θ_{FC} and soil dependent conductivity parameter λ:

$$P(z_j) = \begin{cases} 0 & \Leftrightarrow \theta(z_j) \geq \theta_{FC}(z_j) \vee B(z_j) < 0°C \\ \lambda(\theta(z_j) - \theta_{FC}(z_j))^2 & \Leftrightarrow \theta(z_j) > \theta_{FC}(z_j) \vee B(z_j) \geq 0°C \end{cases} \tag{3}$$

Percolating water from the lowest soil layer $P(z_e)$, could be considered as groundwater recharge, which leads to the elevation of the groundwater table in dependence of the local storage capacity and the groundwater flow. $P(z_e)$ is the linking parameter from PSCN to ASM describing the resulting percolation rate as a groundwater recharge or source term.

2.5. **Riverstream runoff.** The river stream runoff at every timestep $Q(t)$ can basically described by the Kalinin-Miljukov approach [16] by the runoff of the last timstep $(Q(t-1)$, and the actual water supply $Qzu(t)$ and last timestep $Qzu(t-1)$ as shown in equation 4

$$Q(t) = Q(t-1) + (Qzu(t-1) - Q(t-1)) * C1 + (Qzu(t) - Qzu(t-1)) * C2 \tag{4}$$

with $C1 = 1 - exp(-dtK\tau)$ and $C2 = 1 - C1 * K\tau/dt$ and $K\tau = f(Q)$. To investigate retention parameter $K\tau$, various quantities of river cross-sections are basically provided. This approach is extended by a description of tailback effects in the river stream. The tailback is activated if the elevation of water in the upstream river segment is lower than in the downstream segment. The dam up area due to weirs is preferred for groundwater enrichment, caused of raised water levels.

2.6. **Coupling ArcEGMO©/PSCN with ASM.** The coupling of both models described above was realized by an exchange of spatial distributed flow rates per time step. The time steps of both models can be chosen optionally, with smaller ones in the surface flow model compared to the groundwater model, because of different mean flow velocities. However, the spatial distribution needs to be the same in both models.

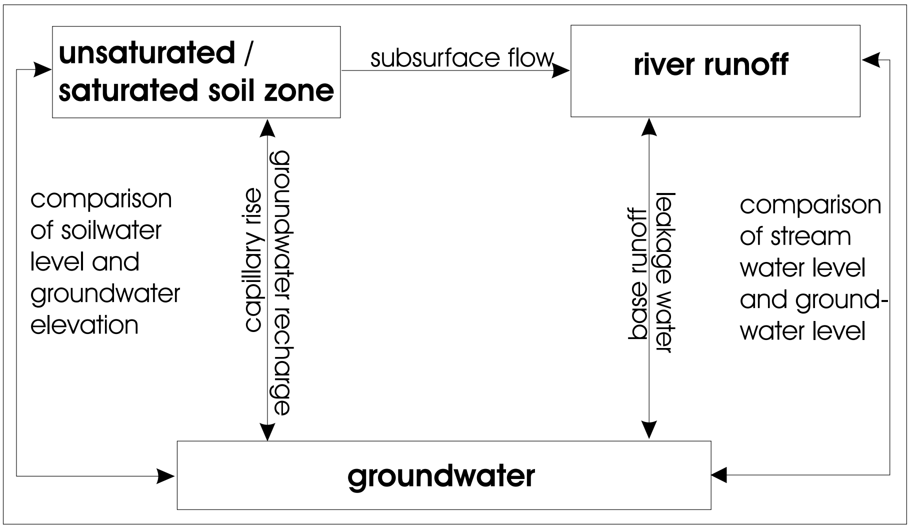

Figure 2. Model coupling

The data transfer takes place between the groundwater model and the soil water module on the one hand, and between the groundwater model and river stream module on the other hand as illustrated in Fig. 2.
The interaction between soil and groundwater consists of vertically dominant flow processes within the transition zone between saturated and unsaturated regions. The groundwater recharge causes an elevation of the phreatic surface followed by a reduction of the unsaturated zone and an increase of the capillary rise. The interaction between stream and groundwater is mainly controlled by the gradient between the surface and the near-surface groundwater levels. The water exchange rate is dependent on these gradients and on the leakage factor which represents the permeability of the river bed, which must be defined for each river section.

2.7. **Inputdata.** The needed data for running the coupled model are meteorological time-series, land surface parameters, soil and groundwater data like porosities and permeabilities, and river stream profiles, roughness and upstream- downstream relations.

3. RESULTS

The model set up was converted in single steps. First, the water balance model was build up and complemented by the river stream modul into the ArgEGMO© tool to simulate runoff time series. As shown in Fig. 3 there are some deviations of the modelled runoff compared to the measured ones, especially during the last year of the time period. Then, the groundwater model was separately created with the help of ASM and applied to the same time period. After calibrating the model on the basis of reference measurements a successful validation could be accomplished which is demonstrated in Fig. 4. Subsequently, the linkage of both models was carried out and comparing the results in Fig. 3, a strongly improved adjustment of modelled and measured runoff amounts for this coupled model can be shown.

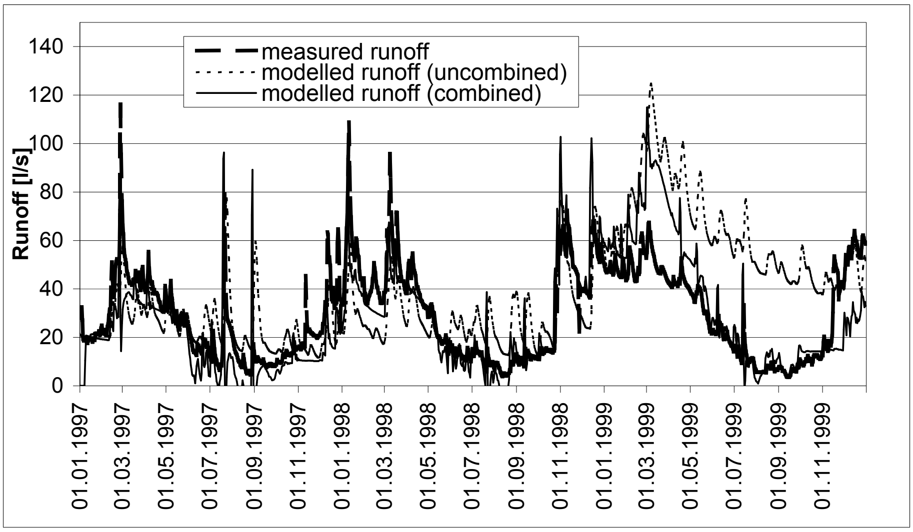

FIGURE 3. Modelled and measured hydrographs at one gauging station, showing the effects of coupling the hydrological model ArcEGMO© with the groundwater model ASM

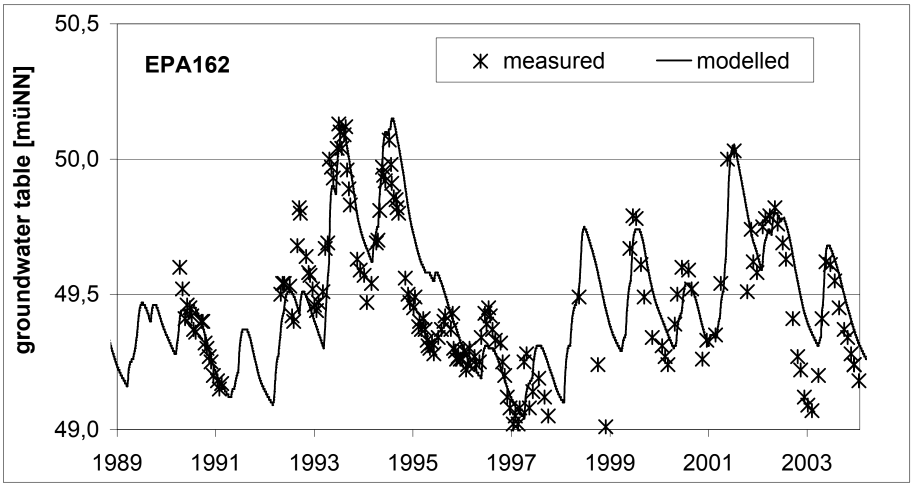

FIGURE 4. Measured and simulated groundwater levels at gauge EPA161

Exemplarily, simulated hydrographs are close to the measured values for the time after shutting down the wastewater application to the Lietzengraben catchment.

As shown by single measurements the runoff during wastewater application (in the 1970s and 1980s) was one order of magnitude higher than today. Investigations in eastern German Lowlands produces evidence of decreased runoff and groundwater level by climate influence since the 1980s [3, 11]. To find out the impact of changed climate conditions to the water balance in the study area , the model was run with today's landuse conditions. Following this scenario, the climate impact leads to an approximate double runoff in the 1970s and 1980s compared to the actual one.

These findings make clear, that it will be difficult to protect the existing surface waters and wetlands because they have been generated under totally different water balance conditions. Now, thes are ecological important reservates and considerable efforts are worth preserving them.

Several scenarios of water management strategies were calculated using the coupled modell, to point out different effects and impacts to the bains ruoff and water balance development.

A scenario of the present state had shown, that the stream water supply to the ponds is about 30 to 35 l/s to maintain the water bodies. This water is not available in summertimes, so they will be reduced by evaporation and withdrawal by drainage to the groundwater. Following the model results, the lakes can dry out during five to eight weeks while hot and dry summer months. Therefore additional water supply is indispensable.

Using additional water supply, management instruments can distribute the available water to sensitive areas like wetlands and ponds. Different scenarios were calculated to find the optimal arrangement of weirs and passes. The investigations are still in effort, but it is allready obvious that a water supply of 65 l/s can rise the mean groundwater level up to 15 cm along the ditches and few 100 meters adjacent. Like this wetlands and ponds are stabilized in dry seasons by this surplus of groundwater storage.

4. CONCLUSIONS

By coupling ArcEGMO©/PSCN with ASM, a comprehensive, multi-layered complex highly distributed hydrological model of Lietzengraben basin was build up, which can described the interaction between groundwater and surface water more precisely. The coupling of the model ArcEGMO©/PSCN and ASM showed an enormous improved fit of measured and modelled runoff curves. Simulations of groundwater flow, runoff-formation, and basin water management make it possible to examine the consequences of present-day and future interventions, thus giving a basis for their assessment. That means e.g. that the effects of dams and artificial water supply can be reproduced in this model. Therefore the model can support further planning and projects in the Lietzengraben catchment.

The efforts of a coupled surface - groundwater model are especially given for lowland situation, where the groundwater has an huge influence on river runoff. Additional situations of water shortage are also well described in dependence of groundwater influence. The developed modeling methodology seems to be transferable for watershed analysis in other lowland regions because of its specific consideration of subsurface runoff components.

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