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Modelling groundwater recharge from intermittently flooded areas by calibration of time dependent leakage parameters

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Abstract Groundwater dynamics in river valleys are mainly determined by the floodwater dynamics of the river. Besides riverbank infiltration, groundwater recharge from intermittently flooded areas is the most important process. To implement this transient recharge rate into a regional groundwater model the leakage concept is proposed. This approach requires a time dependent leakage coefficient. The determination of that kind of leakage coefficient by analysing the hydraulic properties of representative soil profiles in the study area in the Elbe valley north of Magdeburg, Eastern Germany, is presented in this paper. It was calibrated by means of the numerically calculated outflux of the individual soil profiles with floodwater level as the above, and groundwater table as the below boundary condition.

INTRODUCTION

To achieve sustainable development of river valley ecosystems future human activities in such areas have to be evaluated carefully. These ecosystems are mainly related to hydrological processes with an emphasis on floodwater and groundwater dynamics. For the effect of the floodwater dynamics on the groundwater, two important processes can be distinguished: riverbank infiltration and groundwater recharge from intermittently flooded areas. These processes have to be implemented in forecasting tools for decision-makers, for instance, to evaluate the change in groundwater dynamics caused by proposed hydraulic engineering activities.

In the Elbe River valley north of Magdeburg, eastern Germany, a study area was considered where a back transfer of the dikes is planned. In this area of several square kilometres extent, abandoned river channels and other typical flood plain landforms are found. To calculate the groundwater dynamics for the actual, as well as for the proposed situation, a regional scale (tens of kilometres) groundwater flow model was developed (Mohrlok & Jirka, 1999a,b). Both effects of floodwater dynamics on the groundwater are implemented using the leakage concept. For the riverbank infiltration processes the ordinary steady state concept was applied. The groundwater recharge from intermittent flooded areas such as flood plains or channels is transferred to a leakage infiltration rate with time dependent leakage parameters.

APPROACH

The percolation of floodwater through the unsaturated zone is a transient process. It depends on the properties and thickness of the soils in the flooded areas as well as the duration of the flooding and the corresponding time series of the flood water table. In order to consider the transient recharge rates $q_L(\mathbf{x},t)$ from those areas at certain locations $\mathbf{x}$ a transient leakage concept depending on the potential head difference between the surface water and groundwater $\left(h_{SW}(\mathbf{x},t) - h_{GW}(\mathbf{x},t)\right)$ is implemented in the regional groundwater model:

$$q_L(\mathbf{x},t) = \lambda(\mathbf{x},t)\left(h_{SW}(\mathbf{x},t) - h_{GW}(\mathbf{x},t)\right) \tag{1}$$

The transient leakage parameter $\lambda(\mathbf{x},t)$ has to be determined for the whole of the intermittently flooded area. Therefore for each of the soil profiles investigated in the study area, the recharge rates $q_L(\mathbf{x},t)$ for given floodwater and groundwater tables were calculated by the numerical solution of the one-dimensional Richards' equation using the SWMS code (Šimunek *et al.*, 1994). The soil profiles investigated were selected according to the morphology in the study area in order to represent the whole area with a couple of profiles. For the application of the Richards' equation the van Genuchten-Mualem parameters of the different soil layers within each profile were determined by drainage experiments on soil samples of the respective layers (Table 1).

Table 1 Classifications (German classes) and hydraulic parameters of the soil profile layers.

Profile	Depth (cm)	Classification	θ_r	θ_s	K_s (cm s^{-1})	n	α (cm^{-1})	Location
No. 1	0–20	Ah (Lu)	0.14	0.44	4.7×10^{-4}	1.147	0.053	lower Ohre terrace
	20–62	M (Lu)	0.29	0.44	2.4×10^{-3}	1.349	0.163	
	62–135	GoM (Tl)	0.08	0.43	6.2×10^{-4}	1.043	0.045	
No. 2	0–34	Ah (Ls4)	0.08	0.47	2.5×10^{-3}	1.086	0.069	lower Elbe terrace
	34–60	GoM (Su4)	0.06	0.39	6.5×10^{-5}	1.296	0.013	
	60–160	Go (Slu)	0.08	0.42	8.6×10^{-5}	1.512	0.013	
No. 3	0–30	Mah (Lu)	0.06	0.48	3.9×10^{-3}	1.083	0.097	lower abandoned Elbe channel
	30–125	GoM (Tl)	0.07	0.44	2.7×10^{-5}	1.078	0.017	
	125–140	Go (Sl4)	0.08	0.41	3.0×10^{-4}	1.135	0.029	
No. 4	0–20	Ah (Lu)	0.14	0.44	4.7×10^{-4}	1.147	0.053	upper Elbe terrace
	20–103	M (Slu)	0.08	0.37	4.9×10^{-4}	1.785	0.022	
	103–180	Go (Ls4)	0.08	0.32	1.2×10^{-4}	1.227	0.027	
No. 5	0–37	Go (Lu4)	0.08	0.45	1.1×10^{-3}	1.081	0.043	upper abandoned Elbe channel
	37–60	Gor (Sl3)	0.08	0.27	1.2×10^{-3}	2.080	0.130	
No. 6	0–30	Go (Lu)	0.08	0.45	4.6×10^{-4}	1.107	0.050	upper abandoned Ohre channel
	30–70	Gor (Sl2)	0.08	0.27	9.1×10^{-5}	1.660	0.026	
No. 7	0–30	Ah (Lu)	0.14	0.44	4.7×10^{-4}	1.147	0.053	upper Ohre terrace
	30–70	M (Lu)	0.08	0.44	3.9×10^{-4}	1.075	0.031	

θ_r = residual water content
θ_s = saturated water content
K_s (cm s^{-1}) = saturated hydraulic conductivity
n, α (cm^{-1}) = van Genuchten parameters

Different transient recharge rates $q_L(\mathbf{x},t)$ could be obtained from the numerical modelling with different boundary and initial conditions. By fitting these recharge rates $q_L(\mathbf{x},t)$ transient leakage parameters $\lambda(\mathbf{x},t)$ were calibrated, which mainly represent the hydraulic properties of the profiles. This procedure enables the consideration of the groundwater recharge from intermittently flooded areas within the regional scale groundwater flow model.

RESULTS

Infiltration simulations

The results of the numerical simulations, which were carried out to calculate the transient recharge rates, are illustrated for profile no. 1. This profile was investigated to a depth of 135 cm below ground level, and three soil layers were distinguished (Fig. 1). Table 2 summarizes the simulations carried out using varying depths for the lowest layer, 73 and 200 cm, and different floodwater levels, 1, 10 and 30 cm. The groundwater table was set at the base of the profile.

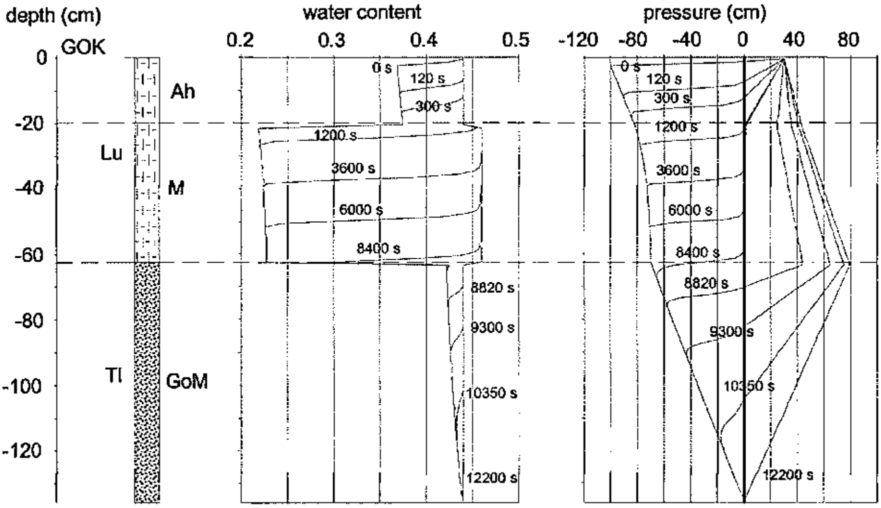

Fig. 1 Soil profile no. 1: stratification, development of water and pressure profiles.

Table 2 Parameters for the simulations presented for soil profile no 1.

Simulation	Depth layer 1 (cm)	Depth layer 2 (cm)	Depth layer 3 (cm)	Floodwater table (cm above ground level)
No. 1	0–20	20–62	62–135	1
No. 2	0–20	20–62	62–135	10
No. 3	0–20	20–62	62–135	30
No. 4	0–20	20–62	62–262	10

The development of the percolation wetting front is illustrated for simulation no. 3 by means of the transient water content and pressure profiles in Fig. 1. These profiles illustrate well the hydraulic properties of the different layers. The most permeable second layer is underlain by the less permeable third layer with low drainable porosity. This causes an intermediate constant pressure profile in the second layer during the saturation process and an increasing pressure profile when the third layer becomes saturated. For the same reason the sharpest saturation front is found in the second layer.

The transient recharge rates $q_L(\mathbf{x},t)$ for the different simulations are similar (Fig. 2). After remaining at a low level during the saturation of the soil profile, in all cases a steep increase to approximately the same level at the breakthrough to saturated conditions, was observed. The recharge rates of the different simulations were mainly distinguished by the respective time scale of their breakthrough. For the deepest profile the initial flux is lower due the slightly different initial conditions. Furthermore, the breakthrough comes more than three times later than for the short profile with the same floodwater table. In the short profile a strong decrease in the breakthrough time with increasing floodwater table was observed.

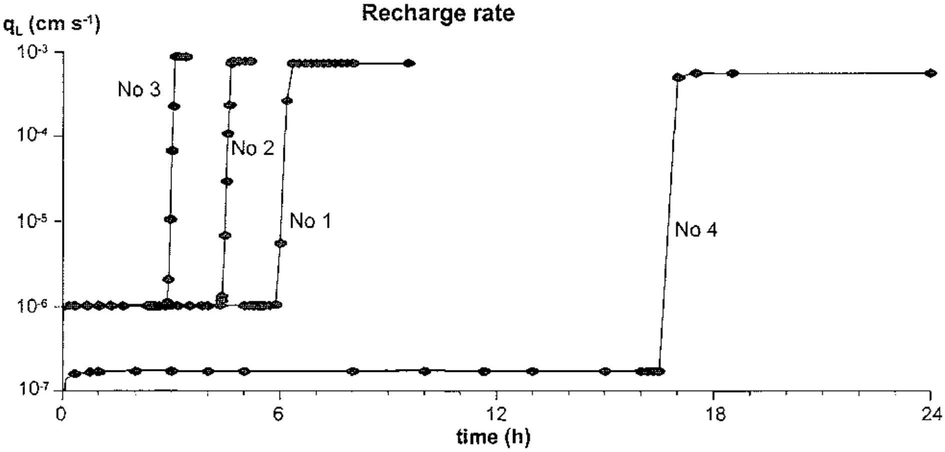

Fig. 2 Transient recharge rates $q_L(\mathbf{x},t)$ for each simulation.

Leakage parameter

The time dependent leakage parameters $\lambda(\mathbf{x},t)$ has been calibrated from these results. The pressure head difference is determined mainly by the floodwater table, so that equation (1) could easily be rearranged and to obtain the leakage parameter $\lambda(\mathbf{x},t)$ (Table 3). Only recharge rates for saturated conditions are important because of the steep increase over several orders of magnitude at the breakthrough. Comparison of the calibrated leakage parameters, especially at saturation, shows a good agreement with those obtained by calculating an effective saturated hydraulic conductivity for the whole profile (Table 3):

$$\lambda'(\mathbf{x}) = \frac{K_{s,eff}(\mathbf{x})}{L(\mathbf{x})} \tag{2}$$

Table 3 Leakage parameters for soil profile no. 1, calibrated λ and calculated λ′.

Simulation	q_L (cm s^{-1})	$h_{SW} - h_{GW}$ (cm)	λ (s^{-1})	$K_{s,eff}$ (cm s^{-1})	L (cm)	λ′ (s^{-1})
No. 1	7.2×10^{-4}	136	5.3×10^{-6}	7.7×10^{-4}	135	5.7×10^{-6}
No. 2	7.7×10^{-4}	145	5.3×10^{-6}	7.7×10^{-4}	135	5.7×10^{-6}
No. 3	8.8×10^{-4}	165	5.3×10^{-6}	7.7×10^{-4}	135	5.7×10^{-6}
No. 4	5.5×10^{-4}	272	2.0×10^{-7}	6.9×10^{-4}	262	2.6×10^{-7}

q_L (cm s^{-1}) = saturated outflux
$h_{SW} - h_{GW}$ (cm) = pressure head difference
λ (s^{-1}) = calibrated leakage parameter
$K_{s,eff}$ (cm s^{-1}) = effective saturated hydraulic conductivity
L (cm) = profile length
λ′ (s^{-1}) = calculated leakage parameter

The values of the leakage parameters depend only on the profile depth and not on the floodwater table. The time delay of less than one day even for the deep soil profile, between rising floodwater table and breakthrough, does not really effect the groundwater dynamics. Therefore the time dependency of the leakage parameters could be neglected with respect to groundwater modelling at a regional scale.

CONCLUSIONS

Groundwater recharge rates in intermittently flooded areas were implemented in a regional groundwater model using the leakage concept. The time dependent leakage parameters could be obtained from numerical simulations of infiltration into a soil profile. Because of the sharp breakthrough (within a time period of less than one day), for the purpose considered here the time dependency can be neglected and the values of the leakage parameters can be estimated directly from the effective saturated hydraulic conductivity of the soil profile.

Additionally, the procedure presented here can be interpreted as an upscaling from the local process of water percolation through an unsaturated soil profile, to the regional process of groundwater recharge. This is essential to model the groundwater dynamics in the river valley and to predict its changes due to proposed activities towards a sustainable development of river valley ecosystems.

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