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Land-use effects on flood generation – considering soil hydraulic measurements in modelling

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Abstract. The investigation in the catchment of the Mulde (51°0′55″ N, 13°15′54″ E Saxony, Germany) researches the effect of afforestation measures on the soil hydraulic properties. The concept of a "false chronosequence" was used to quantify the time-dependent dynamical character of the forest impact. Four adjacent plots were identified at a test location with comparable pedological start conditions and a set of tree stands of different age: (1) arable field (initial state); (2) 6-year-old afforestation; (3) 50-year-old afforestation; (4) ancient natural forest ("target" stocking). Water retention curves and unsaturated conductivities were analysed in the lab. In the field, the undisturbed infiltration capacities were measured quantitatively (hood infiltrometer) and qualitatively (brilliant blue tracer). Pronounced differences between all 4 plots were detected. The afforestation causes an increased infiltration and soil water retention potential. Especially the topsoil layers showed a distinct increase in conductivity and portion of coarse/middle pores. The influence of these changes on rainfall-runoff calculations at the test location was analysed in this study.

1 Introduction

The European Flood-Directive (EC 2007) points out the need of flood risk maps. Based on these maps flood risk management plans will be prepared focusing on prevention, protection, and preparedness. The assessment of the catchments' potential to retain water in the landscape is part of the management plans. This effort has to be done river-basin-oriented and directly linked to the EU-Water-Framework-Directive (EC 2000). Thus, emphasis has to be put on the detection of synergy effects between the good ecological status (e.g. minimize technical impacts) of the water bodies and flood protection. As a partner in the Integrated Project "FLOODsite" (6th EU-FP) we investigate the impact of land-use on runoff formation and runoff concentration. Additionally, the novel Water Law of Saxony (SächsWG 2004) contains regulations concerning "flood formation areas" (*"Hochwasserentstehungsgebiete"*). For such "flood formation areas" the novel law addresses the conservation and improvement of the natural water retention.

It is generally accepted that changes in land-use patterns (e.g. expansion of settlements including road-construction, deforestation, distinct practices in arable and grassland management) contribute to an increased frequency and severity of flood generation. For forest land-use, it has been stated that afforestation and the promotion of sustainable forest management will considerably increase the water retention in landscapes (FAO 2003). However, there is a controversial debate on the quantitative impact of such non-structural flood risk management measures with respect to event size and scale-based physical conditions (e.g. Calder et al., 2007; Laurance 2007). Modelling approaches very often neglect important aspects when rainfall-runoff-models are parameterised. Hence, many models just consider vegetation parameters (root depth, leaf area index (LAI), canopy height or parameters generalized in the curve number (CN) approach). Some more advanced models (e.g. AKWA-M: Münch 2004; WaSiM-ETH: Schulla and Jasper 2001) also include pre-event soil water storage by calculating land-use specific evapotranspiration and related soil water dynamics. In addition, one should also be aware that changes in the vegetation cover (e.g. conversion from arable land into grassland or forest) in the mid- to long-term will also result in distinct changes in soil hydraulic properties (infiltration, percolation, retention).

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2 Methods and material

2.1 False chronosequence

Afforestation appears to be a potential measure to increase the water retention in the landscape (FAO, 2003; Münch et al., 2007; Wahren et al., 2008). However, the influence of such long-term measures is not easy to observe at experimental sites. RR-models help to estimate the effect of measures but they describe only the processes as they are implemented in the applied model. In such RR-model based analyses, the change in land-use often is accomplished just by changing the above-mentioned vegetation parameters whereas most of the soil hydraulic properties remain unchanged. Furthermore, the typical practice is to parameterise the soil hydraulic characteristics by fitting the RR-model to a given runoff hydrograph. Due to that, the physical background of the soil parameters gets lost and a reliable prediction of the impact of a changed land-use is impossible.

The ongoing debate (e.g. Calder, 2006; Schüler, 2006; Wahren et al., 2007a) on decentral flood protection by adapted land-use still presents a lot of uncertainty associated with the model-based assessment of the efficiency of such measures.

To assess land-use effects on soil hydraulic properties we implemented experimental work on afforested sites. The concept of a "false chronosequence" was used to keep the effort reasonable. For our purpose it was necessary to find a location where afforested arable land next to an arable plot, which was still in use, could be investigated. It was quite important that the pedogenetic background settings (geology, elevation, slope, aspect etc.) of the plots were similar. In the best case, there might be several adjacent plots representing different ages of afforestation and an ancient close-to-nature forest stand.

A cropland plot represented the initial state, the plots with different old trees stood for succession stages after tree planting, whereas the ancient forest represented the "target" stocking. For each of these plots the soil hydraulic properties were identified.

2.2 Investigation site

An adequate investigation site was searched in the upper Mulde catchment (Saxony, Germany). This catchment is part of the transnational Elbe river basin.

A suitable site was found at the eastern border of the "Zellwald" forest in the Saxon loess hill zone (51°0′55″ N, 13°15′54″ E). In this protected area some spots of arable land had been afforested in the past. An excellent setting was detected with the following land-use sequence on adjacent plots:

(1) arable field (initial state);

(2) 6-year-old afforestation (young afforestation);

(3) 50-year-old afforestation (old afforestation);

(4) ancient natural forest ("0target" stocking).

The pedological background ("start") conditions were comparable. All plots were characterised by a loamy silt substrate derived from the initial loess parent material.

2.3 Measurements

The "forest effect", in comparison to other land-uses on floods, can be split into two general parts: retention by additional provided storage (higher water consumption and higher interception) and decelerating runoff by shifting water into slower pathways (improved infiltration and vertical percolation, cf. Wahren et al., 2007b). The key values to assess the retention capacity are the air-filled pore-space (empty soil storage) before a rainstorm occurs and the infiltration capacity.

A combination of field and lab measurements was applied to examine the soil hydraulic behaviour under the different land-uses. The aim was to detect both the land-use driven change in the soil matrix for water retention and the on-site infiltration conditions, which are highly dependent on the soil structure (macropores etc.).

2.3.1 Field measurements

Infiltration capacities

Hood infiltrometer (Schwärzel and Punzel, 2007) field tests in conjunction with time-domain reflectometry (TDR) measurements were carried out to characterize the effect of afforestration on saturated and near-saturated soil hydraulic conductivity. Hood infiltrometer enables the measurement of hydraulic properties from saturation up to the bubble point of the soil. Detailed information on the method and data analysis is given by Schwärzel and Punzel (2007). For every land-use plot we performed five replicate measurements.

Tracer experiments

To visualise changes in the infiltration pathways, dye tracer experiments were conducted for each of the four plots. "Brilliant Blue FCF" has been frequently used as a dye tracer to stain flow pathways in porous media (Flury and Flühler, 1995) and has a low toxicity (Flury and Flühler, 1994). This colour tracer was used to avoid any ecosystem damage in the protected area "Zellwald".

For the experiments, at each of the testing plots, a 1 m^2 spot was selected where we simulated a 50 mm rainfall event during 15 min (high pre-event soil moisture). A 3 $g\,L^{-1}$ "Brilliant Blue" solution was applied with a watering can (Fig. 1.).

Vertical cross-sections of 1 m (width)×∼2 m (depth – depending on the depth of tracer penetration) were

Fig. 1. Application of the dye-tracer "Brilliant Blue FCF".

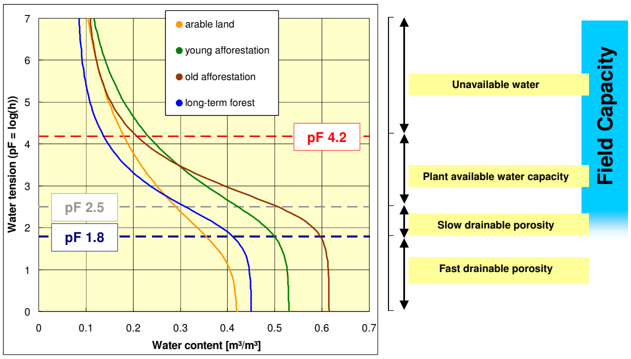

Fig. 2. Water retention – topsoil layer (30 cm).

photographed and drawn on transparent plastic foil at 25 cm intervals. Spatial maps of "Brilliant Blue FCF" distribution were derived from the digital photographs combined with the foils.

2.3.2 Lab measurements

Upon completion of the infiltration experiments, we extracted undisturbed soil cores (three samples per diagnostic horizon), from beneath the positions where the infiltration had been measured. These cores were used to determine (desorption) water retention curves, the unsaturated hydraulic conductivities and bulk densities. The unsaturated soil hydraulic properties were determined in the lab during transient conditions using the evaporation method (Wendroth et al., 1993) and during steady-state conditions using the hanging water column method and a pressure apparatus (Dane and Topp 2002). Hydraulic conductivities were calculated using the approach of Wind (1968).

2.4 Rainfall-runoff-model

To describe the effect of the changed soil hydraulic properties on the output of a rainfall-runoff-model the spatially distributed model AKWA-M was used. The model is based on the water budget model AKWA-M (Golf and Luckner, 1991; Münch, 2004). In recent years it has been advanced by Dr. Dittrich & Partner Hydro-Consult GmbH (Münch et al., 2007; Wahren et al., 2007a). This water balance and rainfall-runoff model simulates the water balance and flood runoff in watersheds and transforms the different processes from a site to a larger area. It contains physically based components (runoff generation) as well as a conceptual background (runoff concentration).

For our study, firstly only the runoff generation was considered. A detailed estimation of the influence that afforestation might have on runoff-concentration (e.g. changed lateral fluxes) was not destined in this study. It would not be possible to simulate it with the chosen experimental setup, although a distinct modification by newly formed roots or changed soil hydraulic properties would be plausible. Our investigation focused on the land-use effects on the site conditions at each plot. Here the plots assume a comparable role to the hydrological response units (HRU) in a spatially distributed model.

AKWA-M calculates the runoff generation processes for HRUs. The 4 different land-uses were represented by 4 HRUs. For each considered plot two rainfall events were calculated with a duration of 2 h and the return periods of 25 (45 mm) and 100 (56 mm) years. First, each plot was parameterised in the "common" way considering land-use change by changing the vegetation parameters (root depth, leaf area index (LAI), canopy height, vegetation density, albedo, macropores, stomatal conductance etc. – cf. Münch, 2004, Münch et al., 2007) without changing the soil hydraulic properties ("unchanged soil"). Thereafter, the newly derived information on changed soil physical conditions was implemented into the model ("changed soil") and the difference between the two model runs was assessed. The calculations were done for three initial pre-event soil moisture situations (high, intermediate, and low). In this article the model results for the initial state (arable plot) were compared with the target state (forest).

3 Results and discussion

3.1 Pore size distribution

Water retention curves (Fig. 2) were analysed in the lab. Distinct differences were detected. For all forest stands an increase of the field capacity was observed (up to the depth of 2 m). In particular the topsoil layers showed a higher portion of coarse/middle pores (Table 1). This effect decreased with the depth.

Table 1. Pore distribution [vol%], related field capacity, and plant available field capacity in the top layers (30 cm).

Land-use	Horizon	Pore Diameter [μm]			Field Capacity	Plant available Field Capacity
		>50	50 – 10	10 – 0.2	[mm]	[mm]
Arable Land	Ap	6	5	3	106±9	55±16
Young Afforestation	Ah	6	9	7	149±3	82±13
Old Afforestation	Ah	5	14	10	179±2	120±21
Ancient Forest	Ah	5	11	8	129±5	77±12

Table 2. Bulk density [g cm^{-3}], total carbon amount [%], organic matter class (AG-Boden 1994; Ad-hoc-AG Boden 2005) in top mineral soils at all investigated plots.

Land-use	Bulk Density	Total carbon amount	Organic matter class
	[g cm^{-3}]	[%]	[-]
Arable Land	1.3±0.10	1.9	h2
Young Afforestation	1.1±0.20	11.1	h5
Old Afforestation	0.8±0.06	12.0	h5
Ancient Forest	1.0±0.09	11.6	h5

Due to the higher amount of stored carbon in forest soils, it was expected that field capacity increased from arable land over growing forest to the ancient forest. However, this was not completely confirmed by our measurements (Table 1). Interestingly, the field capacity of the ancient forests was significant lower than the corresponding values of the afforestration. This might be due to soil compaction by former forestry operations using heavy machinery. The higher bulk density of the ancient forest compared to the afforestrations (Table 2) may support this suggestions. Otherwise, there is no guarantee that there are absolutely any differences in the pedological background settings between the afforested plots and the all-time-forest plot. A reason for long-term forestry land-use at that plot might be that the subsoil of this site was denser leading to water excess (stagnant).

All forest plots showed a distinct higher total carbon amount than the arable plot. No differences in the amount of coarse pores (Ø of pores $\geq$50 μm) between the different plots were found (Table 1). These amount of pores were derived from the fitted water retention curve. The fast drainable porosity is not so importing for water retention but essential for infiltration and percolation (water transport). Thus, not only the amount of the macropores, but also the soil structure is essential to characterize flood retention effects. The macropore conductivity cannot be quantified by lab tests because only small soil core samples (volumes of 100 cm^3) were used.

3.2 Hydraulic conductivity and infiltration

Hydraulic conductivities measured in the lab and in the field are presented in Table 3. Distinct differences between the four land-uses similar to the pore size distribution (cf. Table 1) were observed.

These results confirm the well-known fact, that the topsoil conditions in forests are more favourable for infiltration than under arable use. The hydraulic conductivities at saturation and at field capacity of the forests sites are between two and four times higher than the corresponding conductivities of the cropland site, whereby the absolute variation for replicates on the arable plot (±180 cm d^{-1}) is lower than on the forest plots (±300 cm d^{-1}, ±400 cm d^{-1}, ±450 cm d^{-1}). The higher small-scale heterogeneity under forest is mainly due to the presence of decayed root channels leading to spots with high infiltration rates. It mainly depends on the placement of the hood infiltrometer whether such a high permeable spot is hit or missed. Obviously, the ploughed arable land has a disturbed (destroyed) macropore structure. After infiltration, water cannot further percolate into the subsoil because the macropores are cut at the lower boundary of the plough horizon. Therefore, the infiltration capacity at the arable plot is lower than at the forest plots and less variable.

The infiltration patterns (Fig. 3) clarify, that at high rainfall intensities the water transport through the forest soils is dominated by preferential flow. In contrast to the forest soils, no macropores contributing to the infiltration beyond the plough horizon were detected at the arable plot. Figure 4a shows an isolated macropore, which was not stained by the dye tracer. This pore was cut off by the mechanical impact of the plough. In comparison to that, Figure 4b shows a connected macropore from the young afforestation plot.

Figure 3 also underlines, that the “ancient forest”-plot acts somewhat differently compared to the other test plots. The subsoil layer (deeper than 30 cm) is more compacted. The dye tracer passed the topsoil layer comparatively fast. A big portion of the blue colour remains at the bottom of the loess layer and probably drains laterally. Only some roots were able to penetrate the layer beneath.

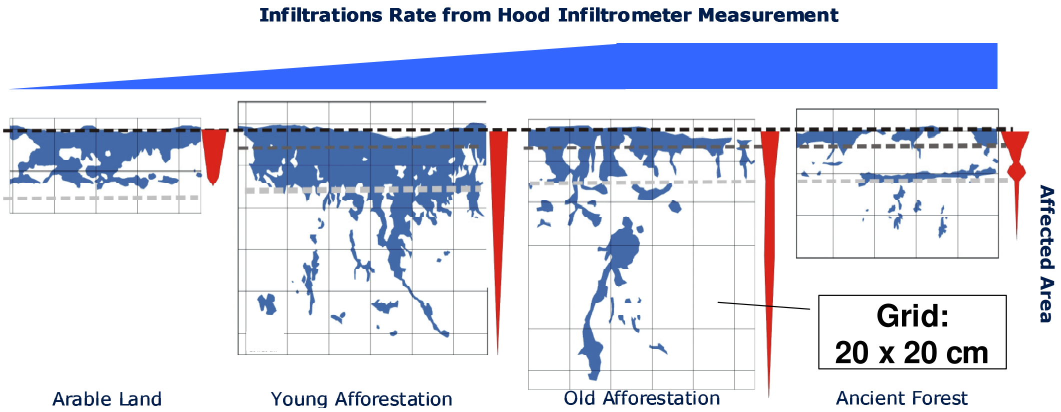

Fig. 3. Infiltration patterns from dye-tracer experiment "Brilliant Blue FCF".

Table 3. Unsaturated (pF 2.5) and saturated hydraulic conductivity in the top layers.

Land-use	Conductivity (pF 2.5)	Conductivity (sat.)
	cm d^{-1}	cm d^{-1}
Arable Land	0.011±0.02	360±180
Young Afforestation	0.026±0.05	710±300
Old Afforestation	0.043±0.10	1100±400
Ancient Forest	0.032±0.10	1200±450

3.3 Rainfall-runoff calculation

3.3.1 Parameterisation

For the model parameterisation of afforestation, the initial state (arable plot) was compared with the "old afforestation"-plot (target state). The typical way to parameterise land-use changes in RR-models is to change the vegetation parameters. If afforestation is modelled a higher root depth is considered. It implies, that a larger part of the soil water storage can be utilised by root uptake prior to the storm event. Furthermore, an increased vegetation density leads to a higher LAI and an all-year vegetation cover leads to higher rates of interception. This will result in decreased pre-event soil moisture. Moreover, RR-models describe in general a plant specific transpiration.

It depends on the model, how the macropore flow is included. AKWA-M calculates infiltration with the SMINF model (Peschke 1982) and uses for macropores a "bypass-flow-concept" similar to the COUPMODEL approach (Jansson and Karlberg 2001). More macropores are represented by higher bypass conductivity at saturation. The results of our hood infiltrometer measurements (cf. 3.2) support the assumption of former model calculations (Wahren et al., 2007a, b) whereby the infiltration caused by macropores under forest cover is much higher than under traditional arable use (ploughing).

We compared the two above-mentioned different plots (in AKWA-M: Subareas/HRUs). The parameterisation from the typically available soil map (LfULG 2006) for the arable plot was used and the parameters for the afforestation were assumed in two different ways – *first:* changing the in 2.4 named vegetation parameters and macropores (soil properties unchanged); *second:* changing vegetation parameters, macropores, soil hydraulic properties (soil properties changed) and adding a litter layer (Wahren et al., 2007a). The changed soil parameters for the different realisations are shown in Table 4.

3.3.2 Simulation

A 20-yr water balance calculation was simulated for the three HRUs (arable, old forest unchanged, old forest changed). To display the different pre-event soil moisture situation, the empty soil storage, which is available to retain water for a certain time, was defined as:

Empty soil storage (ES) = field capacity – actual soil water content.

The different soil storage distribution functions (empirical non-exceedance probability) for the 20 yr (1984 – 2005) show that the effect of the land-use increases with decrease of the soil moisture (Fig. 5). It is also obvious, that the changed soil parameters have a distinct impact on the calculated retention potential of the HRU.

Especially in the summer months, when some of the most disastrous floods occured in the considered region in Saxony (e.g. August 1897, July 1954, July 1981, August 2002), the deviation between the different parameterisations is pronounced. Figure 6 shows the ES-distributions for the summer month (June–August) for the topsoil layer (0–30 cm) and the layer beneath (30–95 cm).

The graphs show for the Sw-horizon (30–95 cm depth), e.g. that at 80% of the summer days there were 7 mm more soil storage available only considering the changed vegetation, but 15 mm more if the changed soil properties

Table 4. Soil parameters (Pore distribution [-]) for the model calculations.

	depth	Arable Land (initial)	Old Afforestation (target)		
			unchanged soil	changed soil	
litter layer	porosity	−5–0	x	x	0.60
	field capacity		x	x	0.30
	wilting point		x	x	0.10
Ap/Ah	porosity	0–30	0.43	0.43	0.62
	field capacity		0.34	0.34	0.60
	wilting point		0.18	0.18	0.20
Sw	porosity	30–95	0.40	0.40	0.47
	field capacity		0.34	0.34	0.43
	wilting point		0.19	0.19	0.19
Bt-Sd	porosity	95–150	0.37	0.37	0.41
	field capacity		0.31	0.31	0.35
	wilting point		0.17	0.17	0.19
Bt-Sd	porosity	150–200	0.41	0.41	0.41
	field capacity		0.36	0.36	0.36
	wilting point		0.23	0.23	0.23

Table 5. Runoff peaks from an afforested site for initial state and two model parameterisations ("unchanged soil" and "changed soil") for the "target state" land-use (old forest) rainfall 45 mm 2 h^{-1}.

Land-use		Runoff peaks [mm]		
			Pre-event soil moisture	
		high	intermediate	low
Arable Land (initial)		30	27	17
Old Afforestation (target)	soil properties unchanged	17 −43%	16 −41%	13 −24%
	soil properties changed	15 −50%	14 −48%	11 −35%
Difference between both parameterisations [% of peak from initial state]		7	7	11

are taken into account too. For 50% of the summer days it was calculated:

Ah-horizon: (unchanged soil) + 6 mm

(changed soil) + 9 mm

Sw-horizon: (unchanged soil) + 17 mm

(changed soil) + 26 mm

The difference between the two parameterisations is 12 mm at 50% of the empirical non-exceedance probability for the two top layers. To estimate the influence on the runoff generation during flood events two heavy rain events were simulated. For both of these two events three pre-event soil moisture situations were considered (dry, middle, wet).

The first rainfall event has a 25-year return period and an amount of 45 mm within two hours. The compared values are the peaks of the fast runoff components (surface runoff and fast subsurface flow) from the HRU. The deviation between both parameterisations produced by considering or neglecting the changed soil hydraulic properties is shown in Table 5.

The same calculation set was applied for another rainfall event with a 100-yr return period and duration of two hours. The total amount of this event was 56 mm. The difference between the two parameterisations for all three pre-event soil moistures was 4% of the peak from the initial state.

4 Synthesis and conclusion

Our rainfall-runoff calculations produce clear evidence, that implementation of modified soil physical conditions into the model can more realistically describe land-use effects. With

Fig. 4a. Isolated macropore.

Fig. 4b. Connected macropore.

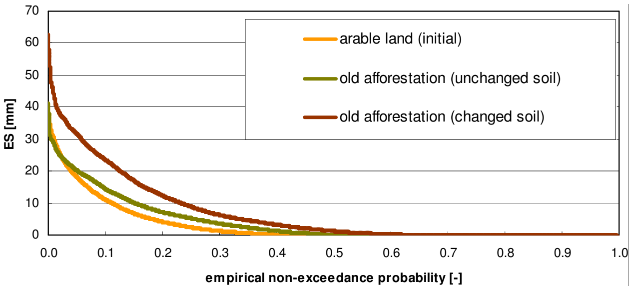

Fig. 5. Empirical non-exceedance probability of empty soil storage (whole year, whole soil profile).

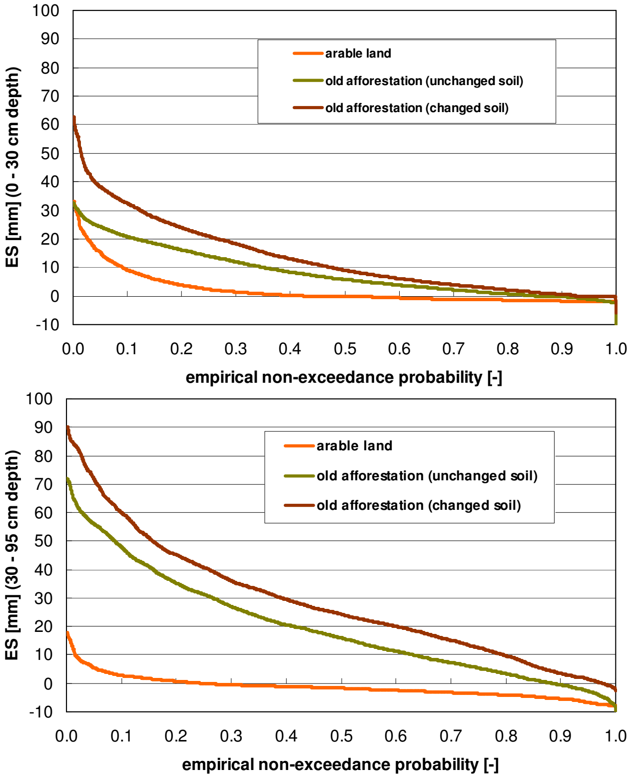

Fig. 6. Empirical non-exceedance probability of empty soil storage (summer month, top soil layer and Sw-horizon).

respect to our experimental data soil hydraulics (up to 2 m depth) is clearly related to land-use. Not only the macropores and the pre-event soil moisture are influenced by the land-use but also the water retention characteristics due to a changed pore distribution. Thus, a change in land-use and land cover will have distinct effects on infiltration and water retention. A model-based analysis of retention in catchments should take these changes into account. However, it is logical that it takes time until such changes occur, but from our data it can be concluded that already after 6 year following an afforestation distinct changes in soil physics are detectable.

Especially the topsoil layers showed an increased conductivity and a higher portion of coarse/middle pores causing an increased infiltration and soil water retention potential.

According to former studies (Wahren et al., 2007a), afforestation of arable land was calculated with AKWA-M by:

– an increase of root depth, meaning that a larger part of the soil water storage can be taken up by roots;

– an additional organic (forest floor) layer on top of the mineral soil (increasing the soil water storage capacity);

– a higher amount of organic matter in the top layers of the mineral soil increasing the soil water storage capacity (e.g. changing organic matter class (AG-Boden, 1994) from class “h2” (1–2%) to class “h5” (10–15%));

– a higher amount of macro-pores represented by a higher macro-pore conductivity.

The field observations confirmed the relations for the changed root system with respect to the changed infiltration conditions and the increased soil water storage capacity due to a organic layer (litter layer) on top of the mineral soil. The dependency of field capacity on the amount of organic matter was parameterised according to AG-Boden (1994). The practicability of this procedure is generally supported by our study. However, the suggested range (max. ±15% of field capacity between organic matter classes “h0” and “h5”) does not explain the experimentally observed porosity changes. The measured difference between topsoil layer of the arable plot (class “h2”) and the topsoil layer of the three forest plots (class “h5” – cf. Table 2) would result in a field capacity increase of ∼10% (AG-Boden 1994; Ad-hoc-AG Boden 2005) for the observed site. This value underestimated the measured field capacity changes at the forest plots. It is well-know, that the data in AG-Boden (1994) were mainly collected from arable sites. However, mechanical impact from root growth decreasing the bulk density of the soil could be furthermore assumed. It would be eligible to have more measurements like the data from this study for further pedological background conditions.

The uncertainty in the parameterisation should not lead to a general neglect of the mentioned processes. Our study demonstrates the need of considering changes in both vegetation and soil properties in RR-models. Only such a combined approach ensures to address land-use effects in an appropriate way. The lack of relevant data on changes in soil properties should not lead to the conclusion, that land-use measures are ineffective. It is quite clear that the effectiveness of land-use changes in flood protection is limited. However, the sustainability of such practices and their synergies with respect to nature protection and soil conservation should keep the considerations about that non-structural measures vital.

The soil plays a key role considering decentral flood protection measures. It is the interface splitting precipitation into the characteristic runoff types. The relevant soil properties are affected by nearly all types of land management. Only a part of the land-use caused effects are satisfactorily implemented into models. But the biggest potential of decentral flood retention lies in the sum of effects (infiltration, pre-event soil moisture, soil storage, surface roughness, reduced erosion risk etc. – Markart and Kohl, 1995; Laurance, 2007; Schüler, 2006; Armbruster et al., 2004; Bronstert, 2004).

Targeted measures to improve the natural retention in the watershed are long-term challenges and, thus, the appearance of the benefits may take decades. As a consequence, reliable model calculations are inevitable to estimate the actual potential of land-use strategies and their limitations. Beside the use of state-of-the-art models to predict effects for the present planning and building of flood protection strategies, also tools to predict key parameters (notably relevant soil properties) should be improved continuously in order to minimise the uncertainties.

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