The potential to influence runoff processes by changes in land use

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Abstract. Different runoff processes like Hortonian overland flow (HOF), saturation overland flow (SOF), or fast subsurface flow (SSF) generate storm runoff in catchments. HOF reacts rapidly to precipitation, SOF producing areas first have to be saturated and show therefore a delayed reaction. More delayed but faster than usually assumed due to preferential flow is SSF. Areas with high infiltration rates and storage capacities or percolation into the bedrock contribute little to storm runoff. Based on geo-information of soils, geology, topography, and land use, as well as rainfall and infiltration experiments combined with tracer techniques, areas in catchments were identified where different types of runoff processes occur during precipitation events. With these evaluations, maps of dominant runoff processes in the catchment were set-up. In order to study effects of land use changes on storm runoff, this methodology was applied to three meso-scale catchments in the Nahe basin with different land use composition. In areas with delayed runoff contribution, a change in land use has little effect. A reduction of storm runoff by a change of land use or land use management practices is only possible on areas where fast reacting runoff processes can be transformed into a slower one. Based on the knowledge of the spatial distribution of the dominant runoff processes and land use, the potential for influencing storm runoff characteristics (e.g. runoff peak, total runoff) for different rainfall events in the catchment was assessed.

1 Introduction

The influence of land use changes on storm runoff generation has been frequently studied in the last decade. Most workers used either conceptual rainfall-runoff models (e.g. Bultot et al., 1990, Caspary, 1990, Koehler, 1992) or distributed physically-based rainfall-runoff models (e.g. Parkin et al., 1996) for their investigations. Both modelling approaches have their limitations though. Distributed physically-based rainfall-runoff models use a high number of parameters, which are difficult to determine and the modelling concepts often do not describe the occurring runoff generation processes adequately. Conceptual rainfall-runoff models use less parameter but describe the transformation of rainfall to runoff with simple concepts. This simplification prevents to transfer measured physiographic properties and state variables directly into modelling parameters.

To avoid these problems, this study investigates the influence of land use change on storm runoff by identifying the dominant runoff processes (DRPs) in a catchment (Naef et al., 1998, Naef et al., 1999, Scherrer, 1997). The dominant runoff process on a site is the process that contributes most to runoff for a given rainfall event. The identification of the dominant runoff processes allows detailed insights in the runoff generation of a catchment. It is a suitable tool to determine the contributing areas under different initial conditions and different rainfall characteristics (Gutknecht, 1996, Bonell, 1998). Four different DRPs are distinguished: Hortonian overland flow (HOF) due to infiltration excess, saturation overland flow (SOF) due to saturation excess, lateral subsurface flow (SSF) in the soil and deep percolation or groundwater recharge (DP).

Based on the spatial pattern and the runoff response of each DRP, it is possible to calculate their contribution to storm runoff. After merging this information with the current land use, areas can be evaluated, where a land use change can potentially influence the storm runoff and the runoff processes can be influenced by land use change. Only a combination of both factors will lead to a significant change of storm runoff.

The approach was tested in three meso-scale catchments (about 10 km^2) in the federal state of Rheinland Pfalz, Germany, and will be exemplified at the 'Sulzbach' catchment.

2 Identification of dominant runoff processes (DRP)

The identification of DRPs requires a good understanding of the structure and variability of the hydrological processes in the catchment (Scherrer et. al., 2000). The DRP processes on the plot and hillslope scale are investigated by assessing of the storage capacity, the permeability and the layering of the soil. Besides, field experiments like infiltration and sprinkling experiments combined with tracer techniques are performed. These investigations allow together with topographical maps, land use maps, soil maps, geological maps, soil fertility maps ('Bodenschätzung'), and forestry maps ('Forstliche Standortkartierung'), the mapping of the different DRPs in a catchment. An analysis of past floods based on recorded hydrographs, historical floods and other sources helps to verify the results.

In the following the methodology to determine the DRPs will be illustrated for three sites in the 'Sulzbach' catchment

The soil at site A (Fig. 1) has a low permeability due to a high bulk density, a clayey soil texture and few macropores (cracks and earthworm channels). The storage capacity of the soil is moderate because the soil only developed to a depth of 50 cm and shows no signs of frequent saturation. Due to the low permeability of the topsoil, the precipitation intensity often exceeds the maximum infiltration rate of the soil, leading to Hortonian overland flow (HOF) as dominant runoff processes at this site.

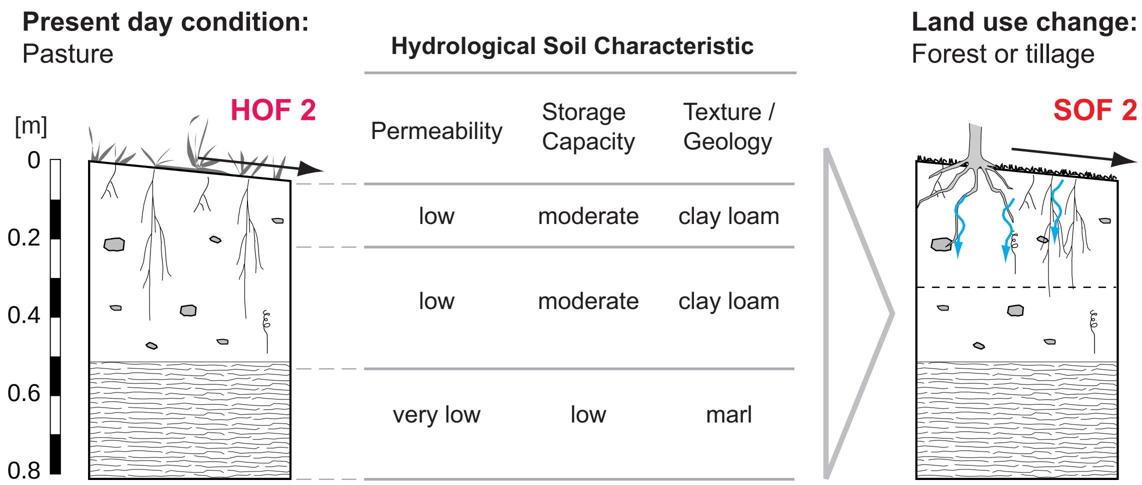

Figure 1: Site A: Cambisol with HOF 2 (left) and change to SOF 2 after land use change (right)

The soil at site B (Fig. 2) lies in a small hollow and shows as a sign for frequent saturation hydromorphic features, a clayey texture, and a groundwater table near the soil surface even after an extended dry period. The storage capacity of this soil will be quite rapidly exceeded and saturated overland flow (SOF) as dominant runoff process will occur. Sprinkling and dye tracer experiments confirmed the limited storage capacity of the soil and the resulting surface flow.

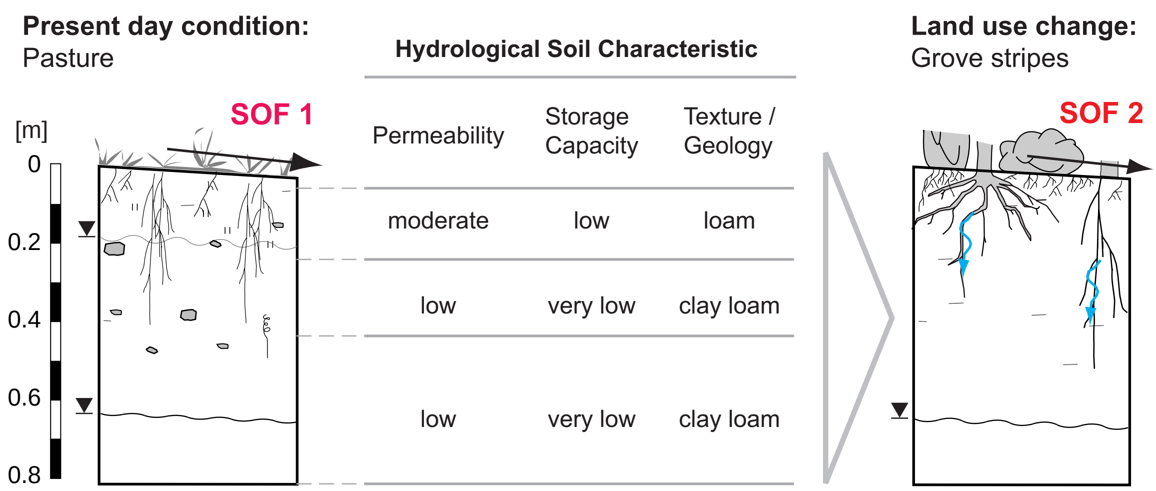

Figure 2: Site B: Gleysol with SOF 1 (left) and change to SOF 2 after land use change (right)

At site C the soil has a high permeability to a depth of 70 cm due to macropores, favourable soil texture, high root density and a low bulk density. The storage capacity is high. However, during wet periods and after prolonged rainfall, soil saturation and runoff will occur. This delayed saturation overland flow is called SOF 3 in contrast to the rapidly formed SOF 1 at site B.

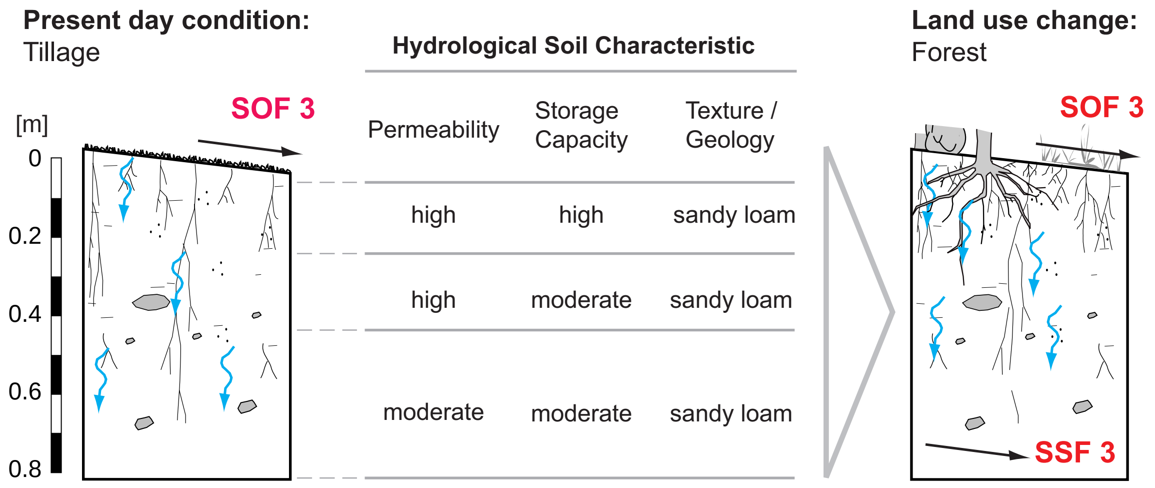

Figure 3: Site C: Cambisol with SOF 3 (left) and change to SOF 3 or SSF 3 after land use change (right)

In soil layers on slopes with a high lateral permeability due to macropores, pipes or high permeable layers (Mosley, 1979, Wilson et al., 1990, Weiler et al., 1998) relatively fast subsurface flow (SSF) can be formed. The contribution of this process to the total runoff can be substantial, however the flow is usually too much delayed to increase the peak flow substantially.

The spatial distribution of the different DRPs in the Sulzbach catchment (8.4 km^2) is shown in Fig. 4, the percentages in Table 1.

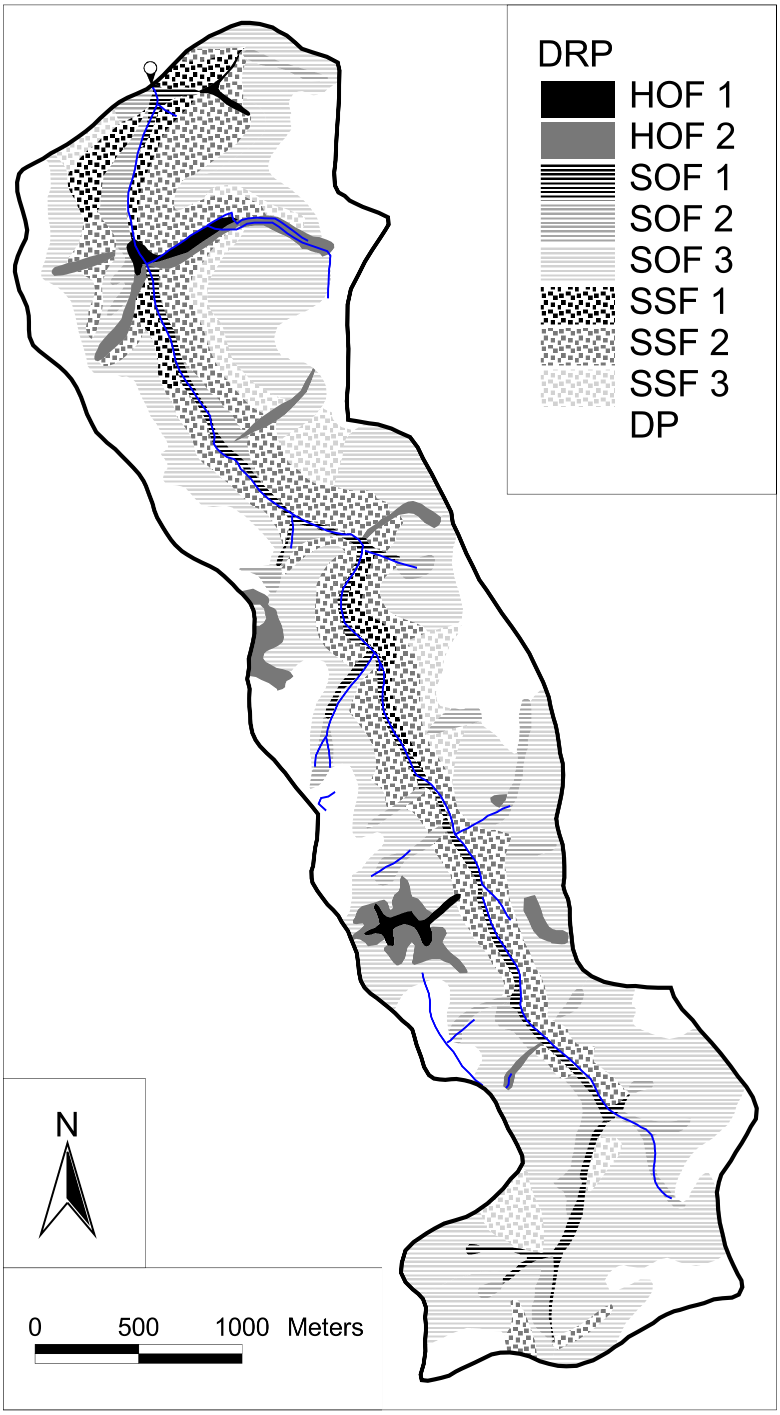

Figure 4: Spatial distribution of the dominant runoff processes in the Sulzbach catchment.

Table 1: Percentages of DRP s for the Sulzbach catchment

Dominant Runoff Process (DRP)	Percentage (%)
HOF 1	4.8
HOF 2	2.3
SOF 1	3.2
SOF 2	5.9
SOF 3	41.5
SSF 1	3.3
SSF 2	15.8
SSF 3	4.8
Deep percolation (DP)	21.3

3 Runoff processes compose catchment response

The catchment response to intense precipitation depends on the spatial distribution of the different DRPs. For example:

- A catchment, where larger areas produce HOF reacts strongly to convective rainfall events, independent of soil moisture conditions.
- A catchment with a high percentage of fast contributing SOF areas reacts stronger to rainfall events under wetter soil moisture conditions.
- A catchment with large areas of delayed SOF (SOF 3) responds mainly to large rainfall events falling on wet soils.
- A catchment with predominant SSF areas reacts delayed with small peak flows. However, the total runoff can be significant.

Fig. 5 shows the contribution of the different runoff processes to storm runoff during the flood in December 1993 in the Sulzbach catchment and the land use on these areas. The values were calculated based on the spatial distribution and the characteristic reaction of the different runoff processes and initial soil moisture conditions.

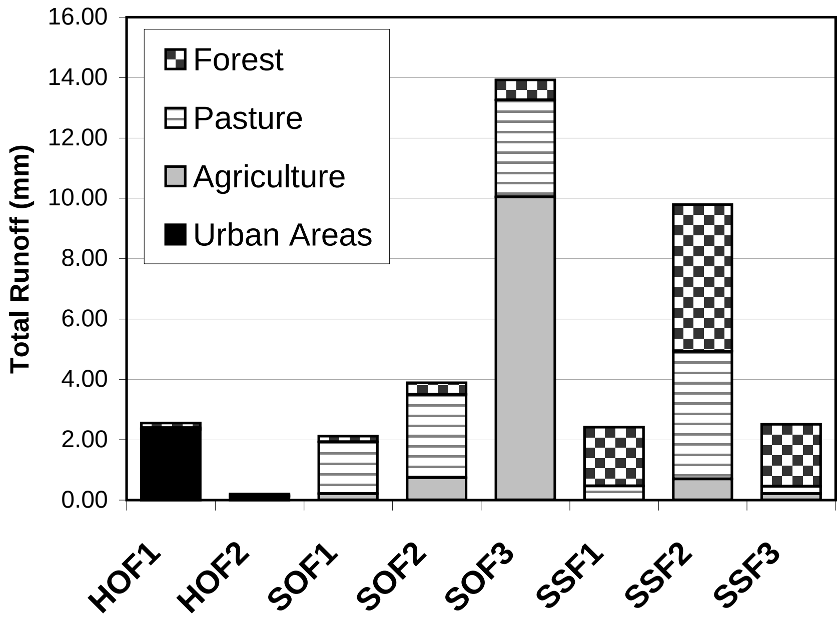

Figure 5: Contribution of the different runoff processes to storm runoff during the flood in December 1993 in the Sulzbach catchment and the land use on these areas

Storm runoff can only be reduced by land use changes, if areas that contribute mainly to runoff can be influenced. In the Sulzbach catchment, the extended areas with slow reacting SOF 3 and SSF 2 are the main contributors to total runoff. Therefore, these areas have to be influenced, if storm runoff should be reduced by land use changes.

4 Potential of land use change

The potential of land use change will be illustrated for the three sites discussed in chapter 2 (Fig. 1 to Fig. 3). To change the runoff process at site A (HOF 2) to a slower one, the permeability of the topsoil has to be increased by enhancing macroporosity with roots or micro-organisms and by improving the structure of the soil. A land use change into forest or tillage combined with plants creating a high root density and a high coverage could change HOF 2 to SOF 2 (Fig. 1 right).

The gleysol of site B under pasture has a fast runoff reaction (SOF 1). To change the runoff processes, the storage capacity of the soil has to be increased. To this purpose, the soil water content and ground water table has to be decreased. Drainage of the soil increases the storage capacity. Drained soils, however, can also react fast due to the preferential flow paths in the drains. A natural way to change the water balance is to increase the evapotranspiration by afforestation. The macropores created by tree roots also increase the permeability. Thus the planting of grove stripes could change SOF 1 to SOF 2 (Fig. 2 right).

The tilled cambisol at site C with SOF 3 (Fig. 3) has a slow runoff reaction. A further delay of the runoff reaction is difficult, due to the already good infiltration and storage potential. Afforestation might change the process from SOF 3 to SSF 3, but total runoff will not change significantly.

Usually only fast reacting flow processes can be changed with realistic measures into slower flow processes. Increasing the permeability of the soil can change the infiltration characteristic on HOF areas. On areas with SOF, the water balance and therefore the soil water content or ground water table can be changed by increasing the evapotranspiration, by changing the pore structure of the soil or by decreasing the groundwater table. However, slow reacting overland flow processes or even subsurface flow processes are difficult to influence because they already have a retarding effect.

Slow reacting overland flow and subsurface flow produce the majority of the storm runoff in the Sulzbach catchment (Fig. 5). Thus, the storm runoff can not be significantly influenced by land use changes.

5 Conclusion

The spatial extension of the different dominant runoff processes (DRP) in a catchment has to be known if effects of land use change on flood characteristic should be evaluated. Mainly those areas in a catchment must be identified, where a significant proportion of storm runoff is generated. Measures to reduce storm runoff are most effective on areas with fast and intensive runoff generation; they are less effective on areas with delayed runoff generation. The results also provide evidence, that land use change has little effects in catchments, where the major floods are generated on areas with delayed runoff generation.

6 Acknowledgments

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