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A process based assessment of the potential to reduce flood runoff by land use change

Felix Naef*, Simon Scherrer, Markus Weiler

Institute of Hydromechanics and Water Resources Management, Swiss Federal Institute of Technology, HIF C 44, CH-8093 Zürich, Switzerland

Abstract

Various runoff processes with widely varying infiltration and retention capacities, such as Hortonian overland flow, saturation overland flow and fast subsurface flow, form storm runoff in catchments. Areas can be classified according to these different runoff processes on the basis of information on soil characteristics, geology, topography, and land use. The results of such classifications can be verified with infiltration experiments combined with tracer techniques.

A reduction of storm runoff by a change of land use or land use management practices is only feasible on sites, where infiltration and matrix wetting can be enhanced. In order to estimate the effects of possible land use changes on storm runoff, the spatial distribution of the dominant runoff processes and the actual land use was assessed in a meso-scale catchment in the state of Rheinland Pfalz, Germany. Based on assumptions on how changes in land use might influence the runoff processes, the potential for flood runoff reduction could be estimated.

Keywords: Land use change; Runoff generation; Storm runoff; Flood reduction; Runoff; Processes

1. Introduction

The impact of land use changes on storm runoff generation is a current topic in hydrologic research and is often assessed by rainfall-runoff model simulations (e.g. Bultot et al., 1990; Parkin et al., 1996). However, converting measured or assumed physiographic properties and state variables into model parameters is difficult. In this study, the assessment of the impact of land use change on storm runoff is based on the distribution of the dominant runoff processes (DRP) in a catchment. These DRP can be identified through detailed field work (Naef et al., 1998, 1999; Scherrer and Naef, 2002). The DRP on a site is the process that contributes most to runoff for a given rainfall event. Four different DRPs were used: 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 (DP) or groundwater recharge. The knowledge of the spatial distribution of the DRPs in a catchment allows detailed understanding of the runoff generation and provides a tool to determine the contributing areas under different initial catchment conditions and rainfall characteristics (Gutknecht, 1996; Bonell, 1998).

The runoff response of each DRP is inferred from field experiments. Combining this information with knowledge of the current land use and assumptions how land use changes influence the DRPs, locations can be identified, where runoff processes can be altered by changing land use. To lead to significant reductions in storm runoff, land use changes have to affect the DRP in a sizable part of the catchments. The

* Corresponding author. Tel.: +41-1-632-4136; fax: +41-1-633-1224.

E-mail address: naef@ihw.baug.ethz.ch (F. Naef).

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consequences of these ideas are demonstrated for the Sulzbach catchment, a meso-scale catchment of 8.4 km^2 in the Federal State of Rheinland Pfalz, Germany.

2. Identification of dominant runoff processes

The identification of DRPs requires a good understanding of the structure and variability of the hydrological processes. Scherrer and Naef (2002) describe a decision scheme to identify the DRP occurring on grassland hillslopes. This scheme was developed from results of sprinkling experiments on 60 m^2 plots at 18 sites in Switzerland. The detailed evaluation of these experiments allowed the quantification of macropore flow and soil matrix flux based on the hydrological properties of the soil (Naef et al., 1998).

Weiler and Naef (2002) used a dye tracer in rainfall artificially applied to 1 m^2 plots at grassland sites. After sprinkling, the plots were excavated to a depth of about 1 m and cut into vertical slices of 5 and 10 cm thickness. The observed dye patterns made it possible to identify macropores and soil matrix flow paths. Though the plots were small, the detailed observation could be used to validate the scheme proposed by Scherrer and Naef (2002) for identifying the governing runoff formation on any grassland sub-catchment.

The following runoff processes are contained in this decision scheme. Immediate Hortonian overland flow (HOF1) occurs on soils with very restricted infiltration, on soils with few macropores and extremely high clay content, on soils compacted by machinery or animals or on low permeability bedrock. HOF2, a slightly delayed version of overland flow, occurs on soils affected by compaction and low macroporosity or surface sealing, on hydrophobic soils or on soils with medium macroporosity and low water exchange between macropores and the surrounding matrix.

On moist or wet soils, which can be saturated during a short burst of rainfall, immediate saturation overland flow (SOF1) is expected. A much delayed saturation overland flow (SOF3) occurs on thick macroporous soils with a permeable matrix. Rapid subsurface flow (SSF1) results if an impermeable horizon of soils with higher bulk density or impermeable bedrock on a steep slope is overlaid by shallow soil and an effective system of lateral flow paths. On less shallow soils SSF2, on deeper soils SSF3 occurs. Deep percolation (DP) results in thick permeable soils or on permeable shallow soils with very permeable substratum and bedrock.

The identification of the DRPs is illustrated for three sites in the Sulzbach catchment (Fig. 1). Fig. 2 shows some characteristics of the soil profile at Site A. The soil has a clayey soil texture, low permeability due to a high bulk density 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 low permeability of the topsoil the precipitation intensity often exceeds the maximum infiltration rate of the soil, leading to slightly delayed Hortonian overland flow (HOF2).

The soil at site B (Fig. 3) is located in a small hollow and shows signs of frequent saturation. It has a clayey texture and the groundwater table is near the soil surface, even after extended dry periods. During rainfall, the storage capacity of this soil is exceeded quite rapidly and saturated overland flow (SOF1) will occur as the dominant runoff process. Sprinkling and dye tracer experiments confirmed and quantified the limited storage capacity of this soil and the resulting overland flow.

At site C (Fig. 4) the soil has 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 referred to as SOF3 in contrast to the rapidly formed SOF1 at site B.

In soil layers on slopes with a high lateral permeability due to macropores, pipes or highly permeable layers, relatively fast subsurface flow (SSF) can be generated (Mosley, 1979; Wilson et al., 1990; Weiler et al., 1998). The contribution of this process to total runoff can be substantial, however, SSF was not directly measured in this study.

In total, 24 soil profiles were analysed in this way in the 8.4 km^2 Sulzbach catchment. In addition, sprinkler and tracer experiments were performed at seven critical sites to observe the actual infiltration behaviour. These investigations were used, in combination with maps of topography, land use, soil types,

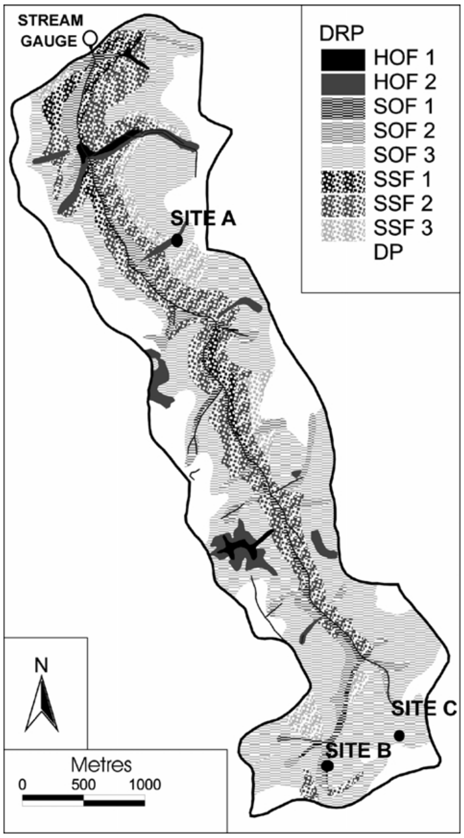

Fig. 1. Spatial distribution of the dominant runoff processes (DRP) in the Sulzbach catchment. Indicated are the sites used to demonstrate effects of land use change on runoff processes.

geology and the decision scheme of Scherrer and Naef (2002) to map the DRPs throughout the catchment.

The resulting spatial distribution of the DRPs in the Sulzbach catchment is shown in Fig. 1, while quantitative information on areal contributions is given in Table 1. Delayed SOF and SSF dominate runoff generation in the catchment, although fast reacting processes such as HOF1, HOF2 and SOF1 are also present. The morphologic characteristics of the catchment influence the spatial distribution of the DRPs. SOF1 and SOF2 are found at the flat and narrow valley bottom. The fairly steep and forested hillslopes are dominated by subsurface flow. Delayed saturated overland flow (SOF3) and deep percolation occur on the agricultural land on the plateaux away from stream valleys. Some smaller areas with pronounced soil compaction were identified as HOF2. The isolated urbanised areas were characterised as Hortonian overland flow (HOF1 or HOF2).

3. Runoff processes govern catchment response

The catchment response to intense precipitation depends both on the proportion of the area where particular runoff processes occur and on the spatial distribution of the different DRPs. For example

- A small catchment, where a large proportion of the area produces HOF, reacts strongest to convective rainfall events, independent of soil moisture conditions.
- A catchment with a high percentage of SOF areas reacts strongly to rainfall events under wet initial soil moisture conditions.
- A catchment with large areas of delayed SOF (SOF3) does not contribute to runoff except in large precipitation events falling on wet soils.

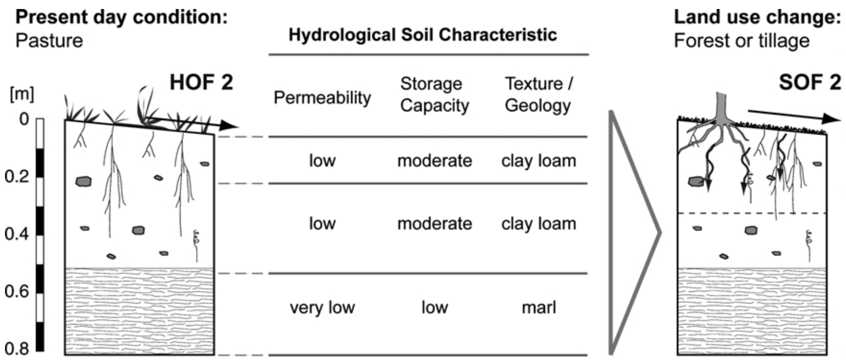

Fig. 2. Site A: profile of a Cambisol with Hortonian overland flow HOF2 (left) with a change to delayed saturated overland flow SOF2 (right) after an assumed land use change (tillage combined with introduction of plants having a high root density and lush surface cover).

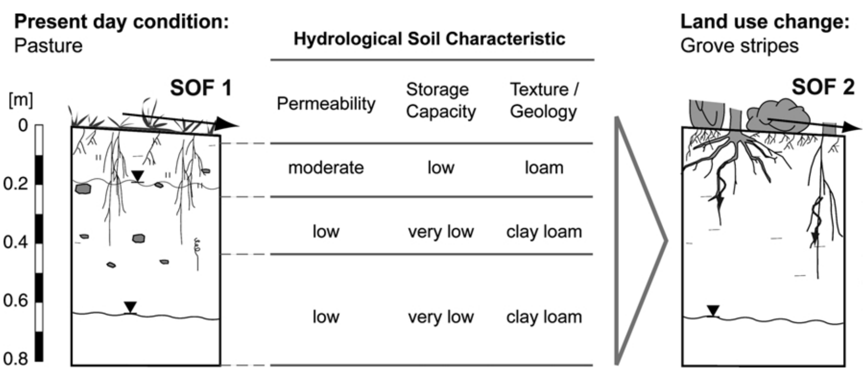

Fig. 3. Site B: profile of a Gleysol with SOF1 (left) with a change to SOF2 (right) after an assumed land use change (introducing grove strips).

- A catchment with predominant SSF areas reacts slower to any type of precipitation than catchments with large HOF or SOF areas and generally produces smaller peak flows, although total runoff can be significant.

To evaluate the impact of the assessed DRP areas on the response of the Sulzbach, a rainfall-runoff model was set up that simulated each DRP separately. The reactions of the HOF and SOF areas in the model were derived from the sprinkler experiments in the catchment. The overall discharge from these areas was proportional to the areas in the DRP map. DRPs at the plot scale describe mainly the vertical movement of the water. Therefore, some qualitative considerations of lateral flow processes were included, when drawing the DRP map for the catchment, like an increased saturation at the foot of a hillslope due to flow from above. Since SSF was not directly observed, the assumed reaction from SSF areas was checked against the difference between total flow measured and the HOF and SOF contributions.

An example of these model simulations is given in Fig. 5. It shows the contribution of the different DRP areas to total runoff during a large storm in December 1993, when 84 mm of precipitation were recorded in the 10 days preceding the storm and 78 mm during the storm.

4. Potential to reduce floods by land use change

Depending on the distribution of the DRPs, catchments react very differently to identical large precipitation events. Catchments with large areas of HOF, SOF1 or SOF2 processes will react rapidly and strongly. Therefore, if flood flows should be reduced by land use changes, substantial areas with rapid runoff processes have to be transformed into areas with slower processes such as SOF3, SSF or DP. In the following, some ideas are presented how DRPs

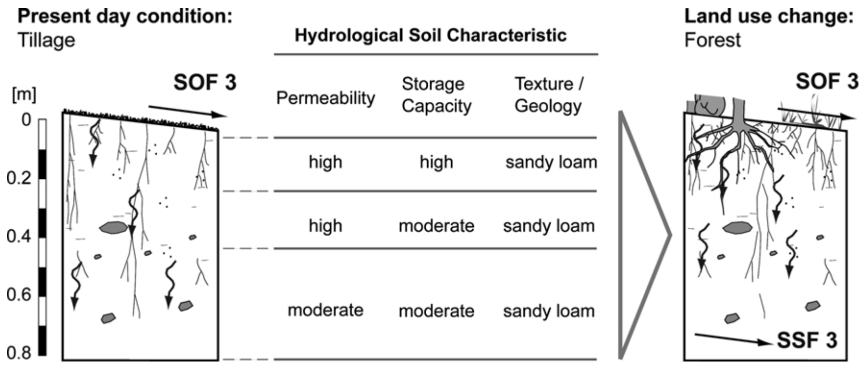

Fig. 4. Site C: profile of a Cambisol with SOF3 (left) and change to SSF3 (right) after an assumed afforestation.

Table 1
Relative areal contributions to DRP evaluated in the Sulzbach catchment (8.4 km^2)

DRP	Area (%)
HOF1	5
HOF2	2
SOF1	3
SOF2	6
SOF3	40
SSF1	3
SSF2	15
SSF3	5
DP	21

might be influenced by land use changes using as examples the three sites discussed in Section 3 (Figs. 2–4).

To delay runoff at site A, where the low permeability of the topsoil causes HOF2 (Fig. 2), the structure of the soil could be improved by tillage combined with plants having a high root density and lush surface cover. This could change HOF2 to SOF2 (Fig. 2 right).

The gleysol of site B under pasture has a fast runoff reaction due to SOF1 (Fig. 3). Tillage and high root density plants would have little effect, as the main problem is the reduced permeability below 20 cm. Drainage of the soil could increase the potential storage capacity. Drained soils, however, often react quickly to rainfall due to preferential flow paths that bypass the soil matrix. A natural way to decrease the soil water content and lower the ground water table is the increase of evapotranspiration by afforestation. In addition, macropores created by roots would also increase the permeability. Thus, by planting grove strips on this plot, SOF1 could be changed to SOF2 (Fig. 3 right).

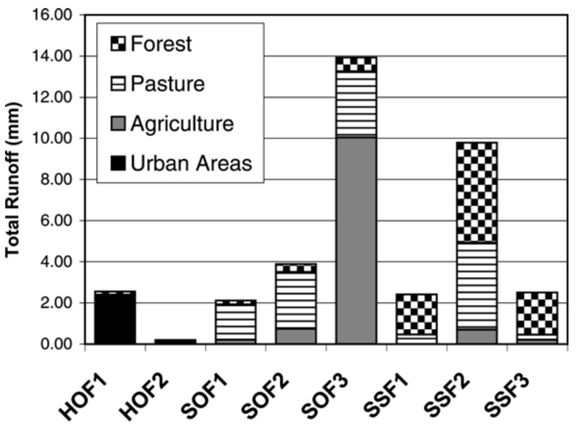

Fig. 5. Contribution of the different runoff processes to storm runoff in the Sulzbach catchment during the December 1993 flood. 84 mm of precipitation was recorded in the 10 days preceding the event, 78 mm during the event. The different land uses on each DRP area is also indicated.

The tilled cambisol at site C (Fig. 4) has already a slow reaction (SOF3) that is difficult to delay further. Afforestation might change the process to SSF3, but total runoff would not change significantly.

The above discussion suggests that an assessment of the effects of land use changes on runoff production has to consider the DRP at the concerned site. Fast reacting DRPs might realistically be changed to slower processes (Site A). However, to delay runoff at site B requires a much larger effort and slowly reacting overland flow processes (Site C) can hardly be further delayed. Subsurface flow processes, occurring mainly in deep soil layers or the geological bedrock, are often outside the sphere of influence of land use changes.

Fig. 5 shows the contributions to total runoff from the assessed DRPs in the Sulzbach catchment, together with the land use on different DRP areas. The major part of the storm runoff is produced by slowly reacting SOF3 and SSF2 areas, which can hardly be influenced. In addition, a large part of the SSF2 areas is already covered by forest or pasture. DRPs like HOF1, SOF1 and SOF2 that offer a realistic potential to reduce runoff, cover only on a small proportion of the Sulzbach catchment (Fig. 5, Table 1) and the SOF1 and SOF2 areas are mainly covered by pasture. For these reasons, storm runoff cannot be significantly reduced by land use changes in the Sulzbach catchment.

5. Conclusion

To evaluate the effects of land use changes on flood characteristics, location and extent of areas of the DRP have to be known. Land use change measures are effective on areas with fast and intensive runoff generation, they are much more costly and less effective in areas with delayed runoff generation. The results given here suggest that land use change can only significantly reduce flood flows in catchments where most of the runoff is generated on areas with rapid runoff production.

Acknowledgments

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