

# Identification of flood-generating forest areas and forestry measures for water retention

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## Abstract

In addition to flood disasters along major rivers, damage caused by the flooding of smaller tributaries is also of considerable significance. Within the European WaReLa-project, water retention measures are being investigated that have positive effects within small watersheds. Geographic information system-based assessment keys were developed on the basis of digital forest site classifications to evaluate the water retention functions that depend on landscape features and land-use. The keys lead to digital maps identifying sensitive forest sites and linear structures. The maps provide a spatial distribution of runoff types and intensities. Forest inventory data are the basis for forestry measures to support water retention. The assessment keys and a tool box of forestry water retention measures are part of a Decision Support System (DSS) that is under development within the WaReLa-project. The DSS includes an evaluation tool for the economic consequences and the eco-efficiency of flood-precaution measures.

Keywords: runoff, forest site, decision tree, flood-generating forest areas, forestry water retention measures, retention basin, flood plain

## 1 Introduction

Flood damage caused by smaller rivers can be mitigated by reducing and temporally delaying runoff peaks. The purpose of this paper is to introduce a part of the European project – Water Retention by Land-Use or WaReLa ([www.warela.de](http://www.warela.de) / [www.warela.eu](http://www.warela.eu)) – to a wider public. This project is intended to identify effective water-retention and runoff-delaying measures in forest, agricultural, and residential areas. The efficiency of forestry measures related to flood damage prevention depends on landscape features, including geological and soil factors. Forest soil and near-surface bedrock may store water. Within this context, measures that are found to be efficient will be incorporated into a spatial planning expert system, within which a geographic information system (GIS) will enable the simultaneous visualization of both the potential retention capacity of forest sites and of the recommended site-dependent, precautionary forestry measures. The aim is that these measures, developed within the WaReLa-project, will form the basis for co-operative, trans-national, river basin management in regions with low mountain ranges to assist in flood mitigation efforts. A key point of this paper is to identify flood-generating forest areas as a basis for recommending appropriate forestry practices aimed at reducing the occurrence of damaging floods within small watersheds. In addition, this paper discusses such forestry measures in the light of their support within the scientific community and discusses suitable efficiency assessment methods.

## 2 Flood relevant forest areas and forest features

### 2.1 Runoff in Forests

A knowledge of site-dependent runoff processes is a basic prerequisite for the planning and management of decentralized flood-protection measures. Theoretically, runoff can be reduced and delayed as long as the water storage capacity of forest sites is not exceeded. Runoff greatly depends on precipitation conditions, vegetation cover, the physical characteristics of the humus layers, soil horizons, and the bedrock of a particular site (SCHÜLER *et al.* 2002). Tree roots encourage the development of a system of macropores that may be used as preferential seepage pathways delivering water to deeper soil (WHIPKEY 1965; MOSLEY 1979). The processes of interception, evaporation, and transpiration within tree crowns and other forest vegetation types are a key hydrological function and impact of forests (BENNECKE 1992; HOFFMANN 1982; PECK and MAYER 1996). The positive influence of forests on the decrease and delay of runoff has been discussed for decades in the literature (MOLTSCHANOV 1966; HIBBERT 1967; VORONKOV *et al.* 1976; ROSEMANN 1988; MOESCHKE 1998; MENDEL 2000).

In forests soils with high infiltration capacity, no impermeable layers and permeable bedrock, water percolates to a great depth (DP = Deep Percolation; Fig. 1). Deep, permeable soils have a good retention capacity and peakflow-delaying potential. In winter, when evapotranspiration is decreased and soils are saturated, these void and crack systems discharge water through springs. If voids dominate in the soil, the main discharge is controlled by hydraulic pressure, whereas, if cracks dominate then it is based on direct runoff (SCHÜLER *et al.* 2002).

Overland flow can be found on forested, steep slopes with poor drainage, generally combined with extremely high rainfall (BOTT 2002). Even forest soils with minimal infiltration rates of  $50 \text{ mm}\cdot\text{h}^{-1}$  have sufficient drainage capacity (DVWK 1985; WEILER *et al.* 2000). The infiltration rate of the upper soil horizons depends on the soil texture and on the bulk density (e.g. dense clay soils have a low infiltration capacity). However, it is normal for forest soils formed under the weathering conditions of a humid climate to have relatively low bulk densities (up to  $1.2 \text{ g}\cdot\text{cm}^{-3}$ ). Drainage is generally only reduced by compaction from heavy forest machinery. This is why the location and density of logging trails requires close consideration by forest planners.

Hortonian overland flow (HOF; Fig. 1) (BEVEN 2004; HORTON 1933) requires a low infiltration capacity and/or steep slopes in combination with high rainfall intensities. Low infiltration rates can be found on

- impermeable soils,
- compacted soils without structure,
- soils with clay substrates in the upper soil horizons,
- forest roads and log trails.

On sites with low field capacity, with impermeable clay or loamy layers and without preferential seepage pathways, saturated overland flow (SOF; Fig. 1) occurs once water saturation is reached. The lower the void capacity of a soil, the faster and more intensive the runoff that develops after rainfall (BOTT 2002).

On perched sites with higher field capacity but impermeable soil horizons or bedrock, water is transmitted laterally in the soil as long as the soils are not saturated with water. The

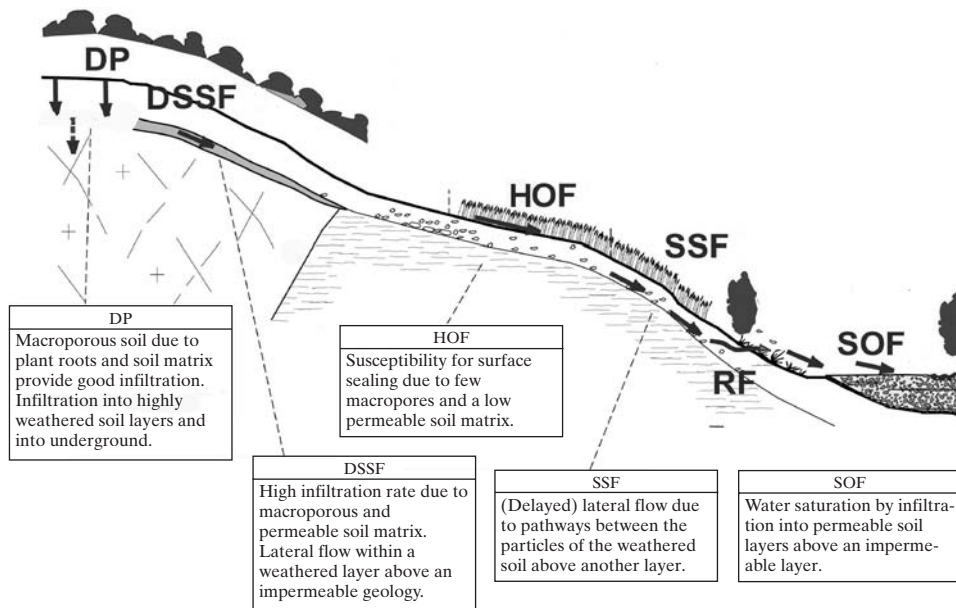


Fig. 1. Runoff processes in forest ecosystems. Origin: Federal Institute of Technology, 2001 modified.

water flows preferentially in pipes or in permeable layers, with runoff velocities of up to  $2 \text{ cm}\cdot\text{s}^{-1}$  (WHIPKEY 1965; BEASLEY 1976; MOSLEY 1979; FEYEN 1998).

In this paper, water flow in soil above an impenetrable layer is termed subsurface flow (SSF; Fig. 1), and interflow above bedrock is termed deep subsurface flow (DSSF; Fig. 1).

## 2.2 Identification of runoff-generating plots and discharge-contributing areas by forest site survey

In assessing the hydrological sensitivities of catchments in low mountain ranges, a distinction can be made between runoff-generating plots and discharge-contributing areas: runoff-generating plots need not necessarily also be contributing areas. The runoff-generating plots are those locations where a process occurs, under given site and precipitation conditions, while the contributing areas are responsible for the discharge depending on water saturation as shown by NAEF and SCHERRER (2003), WALDENMEYER (2003), and SCHMOCKER-FACKEL (2004). Water from runoff-generating sites on hilltops may either infiltrate or merge with several other runoff-generating sites further down-slope in areas with runoff accumulation. If selective precautionary forestry management mitigates runoff from runoff-generating areas to contributing areas, the discharge will indirectly be delayed and decreased. Therefore an expert system was developed to indicate the dominant flow process and the potential runoff velocity for runoff-generating plots as a basis for the planning of retention and delaying measures in forests. The process determination at the plot scale does not consider influences from neighbouring process areas nor whether the area is connected by linear structures (e.g. roads and ditches). Even if the influences between neighbouring plots are known, it is difficult to infer the discharge process at catchment scale from the processes at the plot scale.

The discharge process with the interaction between neighbouring process areas can be captured by a rainfall runoff model (CASPER 2004). Although this approach is part of the WaReLa-project, it is not the subject of this paper.

The expert system begins with the identification of the flood plains of rivers and brooks as sensitive water-accumulation and discharge-contributing areas using an automated GIS algorithm (SCHÜLER 2004). This GIS tool adopts the ecological identification of flood plains from the forest site survey. In situations where the forest site survey does not have information about flood plains, the tool automatically derives the floodable river environs from a digital elevation model by evaluating the elevation of the flood plains and banks above the normal water level. The consequence of this designation is that flood plains will be managed with a view to their function as retention areas for peak-flow water – not as production forests.

The core of the expert system is a decision scheme that is based on special investigations to map the dominant runoff processes at the plot scale according to the methods used by SCHERRER (1997) and SCHMOCKER-FACKEL (2004). This method assesses runoff as a complex process dependent on soil surface sealing, topsoil-compaction, matrix-permeability, bulk-density, water-storage capacity in the soil, macroporosity, lateral flow-paths, barriers to vertical flow, and the underlying geology. This information can be collected during a standard forest site survey. Spatial runoff sensitivities are generated and visualized with GIS using the digital information from the forest site survey.

As part of the expert system, the spatially relevant runoff sensitivities are derived with a decision tree (Fig. 2). Normally, several flow processes are observed in a plot. The decision tree summarizes all the necessary steps and decisions for a systematic determination of the dominant runoff processes in a plot using “yes/no” decisions. Long-term or seasonal fluctuation criteria, such as vegetation cover, which do not change the potential sensitivity of the sites, are not taken into account by the decision tree. The scheme captures in detail the very complex nature of runoff formation. Key site parameters are matrix permeability, hydraulic conductivity, stagnant moisture, and water storage capacity. The decision tree expresses the water storage capacity as productive field capacity. This capacity includes all soil pores with a size of 0.2–50  $\mu\text{m}$ . These pores are filled with slowly moving capillary or adsorbed water. The large macropores (>50  $\mu\text{m}$ ) also have a significant storage capacity, but typically these pores drain very quickly, so that they do not represent an effective flow-delaying storage capacity. The productive field capacity can be derived from forest site maps with this information. One aim of the expert system is to automate the process determination using existing digital forest site maps.

To derive hydrological interpretations, the decision tree uses key questions such as, “drainage/hydraulic conductivity in the upper soil – moderate to rapid (> 5  $\text{cm}\cdot\text{d}^{-1}$ ) – yes/no?” Possible answers to these key questions are summarized in a simple Excel sheet with soil substratum characterizing properties edited by the forest site survey.

The first key question that has to be answered for the process determination is: “Soils with impermeable layers without coarse cracks and voids – yes/no?” If the answer is affirmative, the decision tree leads to either overland flow (SOF, HOF) or subsurface flow (SSF) above impermeable layers. If the infiltration of water is inhibited by stagnant moisture, groundwater or low hydraulic conductivity in the upper soil, overland flow will be the resulting answer. If the answer to the next key question “drainage/hydraulic conductivity moderate to rapid” is yes, then infiltration is possible and subsurface flow is the dominant runoff process. The decision tree leads to saturated overland flow (SOF) only for shallow soils in flat areas that have a low water storage capacity and that are quickly saturated. On very steep slopes the possibility increases that water will not infiltrate, indicating Hortonian overland flow (HOF).



If the answers to the first key questions identify that the soils have no impermeable layers, and that the infiltration of water is not inhibited, deep percolation (DP) is indicated. If water movement may be stopped or delayed above impermeable bedrock, then deep subsurface flow (DSSF) is indicated. If the infiltration of surface water is inhibited, then the danger of overland flow (SOF, HOF) increases, particularly on shallow soils with a small water storage capacity. On sites that are not excessively steep, and on soils with a greater storage capacity, water can move downslope, within the runoff-generating plot. Here, the decision tree leads to either deep percolation (DP) or to deep subsurface flow (DSSF) if water movement is above impermeable bedrock.

To grade the runoff processes, the velocity of runoff development is estimated with respect to the slope of the particular runoff-generating plot. For slopes up to  $2^\circ$ , erosion is limited (GRYSCHKO 2000). Runoff will be greatly delayed. This is marked as degree 3 for runoff processes: SOF3 and SSF3. On gently ( $>2^\circ$ ) to steeper slopes ( $<20^\circ$ ), runoff has a slight delay. This is expressed as degree 2: HOF2, SOF2, and SSF2. For sites  $>20^\circ$ , or highly sensitive areas with slopes as low as  $5^\circ$ , runoff starts immediately (degree 1: HOF1, SOF1, and SSF1). On very steep slopes there is the potential for rapid overland flow with a strong likelihood of erosion. Here, the decision tree follows the Universal Soil Loss Equation (USLE) (WISCHMEIER and SMITH 1978). Compared with a "standard slope" of  $4^\circ$ , the USLE shows a 20-fold increase in erosion danger on slopes of  $20^\circ$  and a 90-fold increase on slopes of  $40^\circ$ . In addition to slope gradient, soil surface roughness and the infiltration rate influence runoff velocity. In addition to slope and soil physical properties, which are responsible for runoff, the starting velocity of subsurface flow (SSF) depends on water tension and gravity, as well as horizontal and vertical hydraulic conductivity, which is influenced by the size, distribution, and continuity of the voids (NOGUCHI *et al.* 1999).

It is not possible to derive the starting velocity of deep subsurface flow (DSSF) from surface geomorphology – this requires hydrogeomorphic mapping. However, this is not considered necessary in retention measure planning, because deep subsurface flow is not influenced by surficial land-use measures.

The spatial information pertaining to runoff processes and runoff velocities can be linked and evaluated, within GIS using the decision tree. The GIS presents the spatially related plot runoff sensitivities. These digital maps are the basis for planning runoff retention and attenuation measures in forests (Fig. 3).

### 2.3 Discharge accelerating linear structures

The planning of water retention precautionary measures requires an inventory of discharge-accelerating linear structures – drainage and road ditches, pipes, runoff lines and erosion channels, forest roads, and logging trails (BOTT 2002). A decision tree with "yes/no"- key questions was developed to evaluate runoff from forest roads (BACKES 2005; Fig. 4). The underlying premise is that forest roads promote rapid runoff. This negative effect can be diminished with special construction methods and precautionary measures. The first question of the decision tree asks if a road seals the forest soil surface. If it does, then a forest road causes Hortonian overland flow (HOF). If the road and accompanying ditches enable the surface water to be widely diffused back into the forest, the runoff is estimated to be comparable to that of the surrounding forest sites. For dirt forest roads, the next question asks if the road has a humus layer, branch-wood reinforcement, or vegetation cover. Our investigations showed that these can improve the runoff reaction (BACKES 2005). Surface water on bare dirt roads becomes overland flow (SOF, HOF), and the steeper the road the faster the runoff.



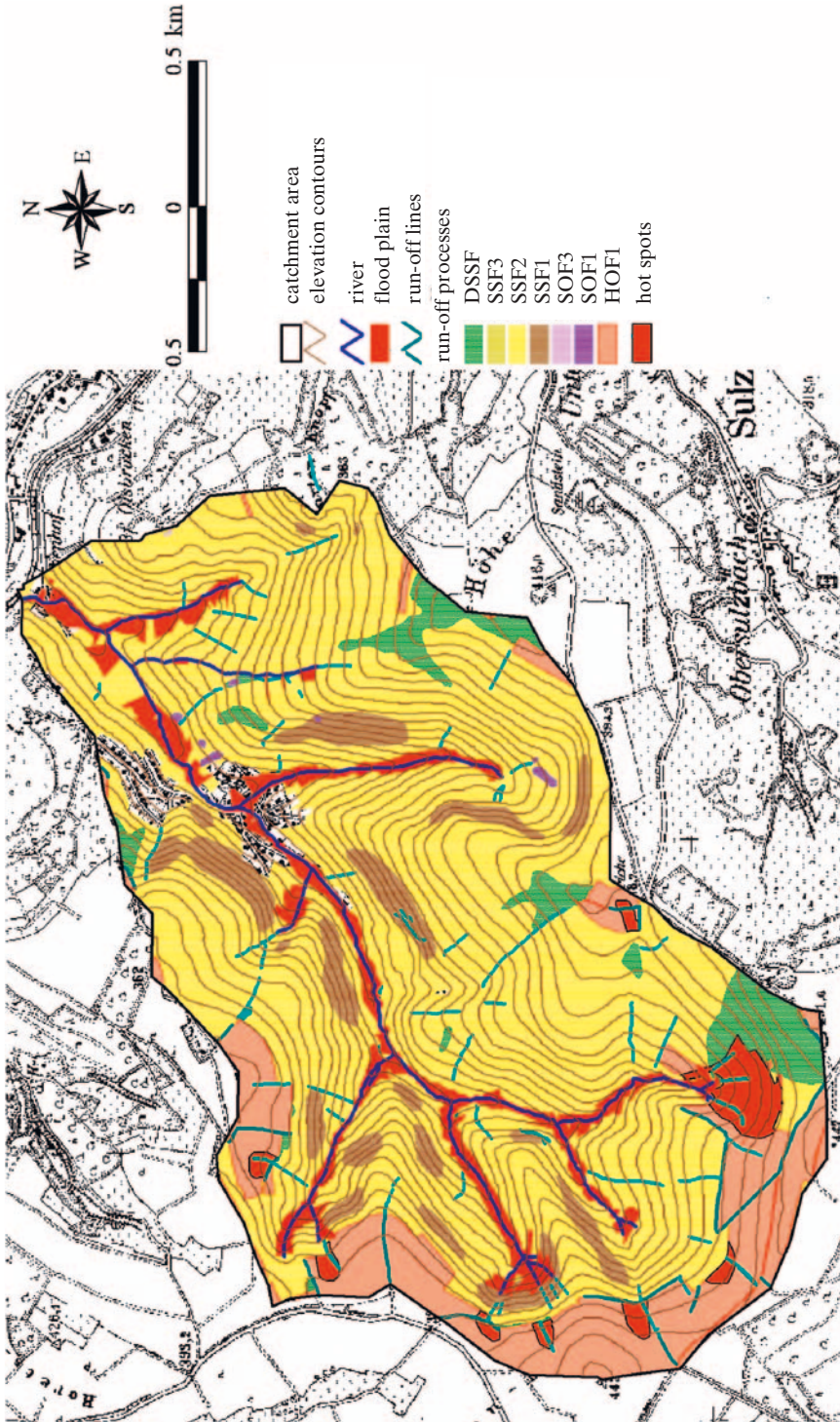


Fig. 3. This map, produced within the WaReLa-project, displays runoff sensitivities in a test site in the south west of Germany. It is the result of linking the spatially explicit information of the forest site survey with the decision tree of runoff sensitivities.

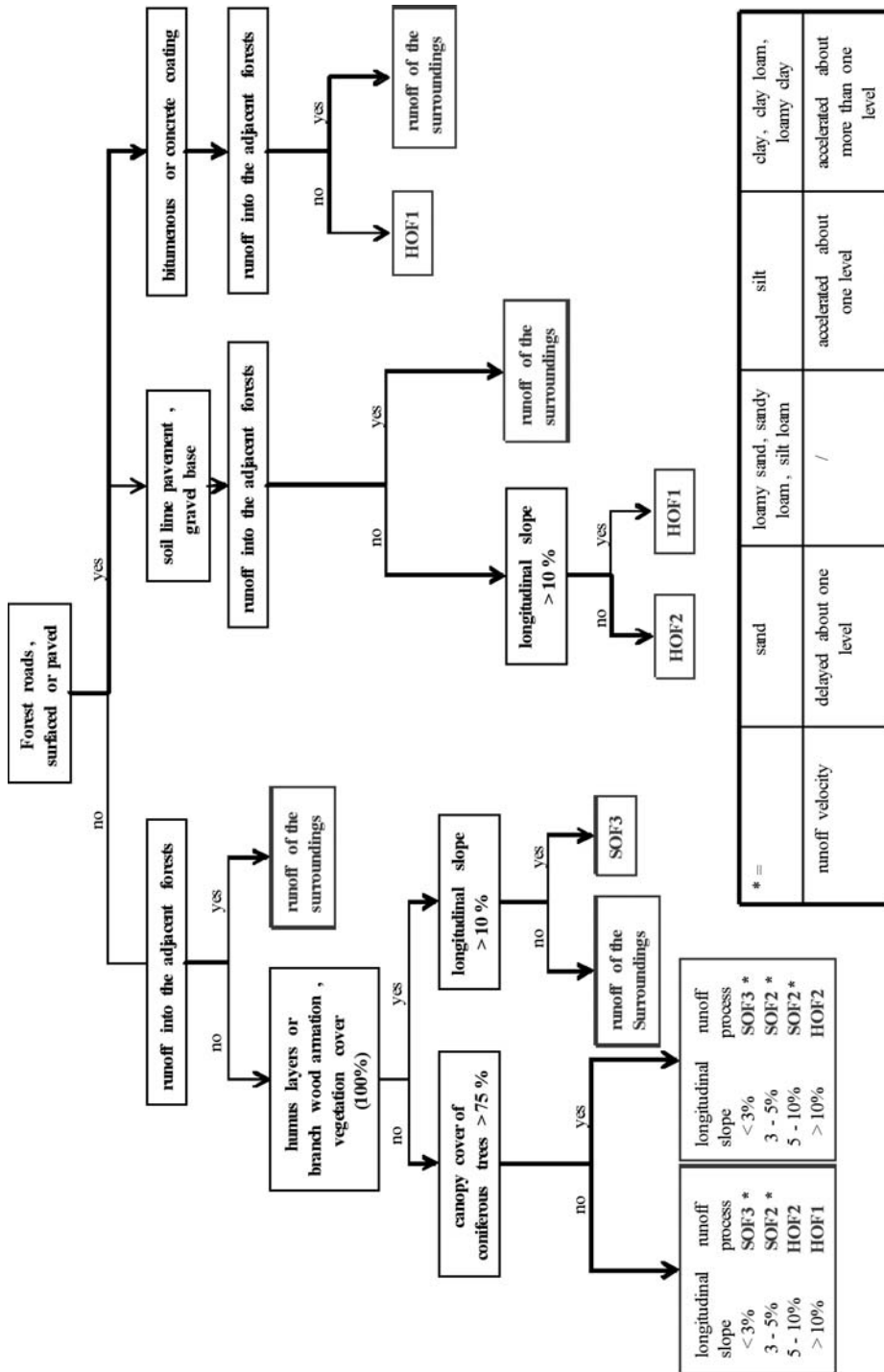


Fig. 4. Decision tree to derive the runoff from forest roads (Backes and Schubert 2005 unpublished).



Forest management is a spatial activity – harvesters, skidders, and forwarders operate in the forest area. The operation of heavy equipment, especially on silty and loamy soils, compacts the soil to deep soil horizons (HILDEBRAND and WIEBEL 1986). The volume of rapidly draining macropores is decreased and the continuity of the soil pore system is disrupted (HILDEBRAND 1983). All extraction trails lose their water retention function, and as they are intensively used linear structures, they increase the velocity and the amount of runoff (BOTT 2002).

The inventory of linear structures and incorporation of the data into digital planning maps are key steps because precautionary measures to deactivate the drainage function of linear structures are likely to be highly efficient in decreasing discharge from catchment areas.

### **3 Forestry Measures for water retention**

#### **3.1 Maintaining and improving water retention by forestry management practices**

Flood development should be minimized through the precautionary forestry management approach. Precautionary measures for water retention in forests must consider the various site conditions, meteorological events, and the present state of the soil water balance. The efficiency of retention measures varies according to precipitation events and site features (e.g. intensive or continuous rainfall on dry soils with further water storage capacity vs. saturated soils, or, on sites with dominantly deep percolation vs. subsurface flow).

On sites with deep percolation, the avoidance of clear-cutting is less important, because the undisturbed soil and parent substrate is sufficiently porous that deep percolation dominates in contrast to subsurface or overland flow. Other water retention concepts are necessary on sites with compact sub-soils, which tend to hold moisture and produce subsurface flow, and on sites with low infiltration or field capacity. On these sites clear-cutting should be avoided because reduced evapotranspiration will tend to increase runoff (MOLTSCHANOV 1966; HIBBERT 1967; VORONKOV *et al.* 1976; HOFFMANN 1982; ROSEMAN 1988; BENNECKE 1992; PECK and MAYER 1996; MOESCHKE 1998; MENDEL 2000). A permanent forest cover composed of a structured successional mosaic of trees decreases the risk of runoff (BREDEMEIER and SCHÜLER 2004). It is therefore essential to mimic the permanent cover principle of a mosaic cycle in close-to-nature silviculture management with horizontally and vertically structured forest stands using site-adapted tree species (EDER 1997). Vertically and horizontally structured canopies, with high leaf area indices, of a multi-storied stand improve the hydro-ecological efficiency of forests by maintaining high interception and transpiration rates (MÜLLER 1996). In addition to the canopy effects of mixed forest stands, the roots of different tree species exploit different layers and soil depths in the soil. A rapid turn-over of fine-roots promotes the creation of soil macro and mesopores (NOGUCHI *et al.* 1999). Thus, these processes enhance the storage and retention capacity of multi-structured forest ecosystems, while bearing in mind that in close-to-nature silviculture, the harvesting and regeneration phases are occurring simultaneously within a forest stand. Investigations of different regeneration types demonstrated that runoff can be reduced in the hydro-ecologically sensitive phases of forest development (SCHÜLER 2003). Advanced regeneration in multi-storied stands and rapid establishment of regeneration after harvesting maintain the forest influence. Thus the soil will be protected, even if a catastrophic storm damage removes old trees.

Understory vegetation, with abundant litter production and rapid litter decomposition (LEDER 1996), and the liming of acidic or acidified soils, support the biological activity of the soils, and particularly the soil structuring macro-fauna. In addition, the medium-term increase of root density after liming increases the field capacity, even in deeper soil horizons (SCHÜLER 2002). Soils with a distinct pore-system have an increased field capacity – a significant factor in water retention (NOGUCHI *et al.* 1999). Organic matter from timber, branch-wood and litter, left on the soil after tending and felling also supports soil biological activity and protects the void structure of the mineral soil (EISENBARTH 1989).

If high runoff generation sites in extensive agricultural land are identified, it may be necessary to interrupt runoff paths by reforestation before the runoff paths coalesce and form watercourses and erosion channels (Babtie Group 1999).

Wetlands are characterized by high groundwater tables and episodic flooding. Wetlands can have a high water retention capacity, but in the past some wetlands were drained by ditches to enable intensive forestry management (HOFFMANN 1957). The special characteristics and functions of wetlands for water retention can only develop if all man-made drainage systems are de-activated. Man-made forests dependent on drainage will decline in vigour with the removal of drainage ditches, so forestry management must support the re-establishment of natural wetland forest vegetation, which in the low mountain ranges of middle Europe is pubescent birch and red alder (SCHÜLER 2003).

### **3.2 Protection of soil structure and soil scarification**

Runoff will be reduced and delayed if the field storage capacity of soil can be increased. Intensive mechanical scarification to improve soil structure, to break up compacted soil horizons, or to enrich highly acidified soils with basic fertilizers, involves certain risks, particularly on silty and loamy soils with unstable soil structure or high moisture. If the soil pore-system is destroyed, runoff will be increased and flow rates accelerated. Hence scarification should be limited to soils with a predominantly micropore structure, resulting from pedogenic processes or compaction from heavy forest equipment. Only dry soils should be cultivated (SCHNEIDER *et al.* 1997) to avoid long-term impairment of soil water drainage and storage capacities (HORN and LEBERT 1992).

### **3.3 Forest roads – preferential linear structures for discharge**

Forest roads promote rapid runoff, thus any increase in the road network in a watershed can aggravate the runoff situation. For this reason, forest road networks should be reviewed, and road density should be as low as is necessary to meet forest management needs. BOTT (2002) identified a significant increase in runoff with a road density of 50 m·ha<sup>-1</sup> compared with a road density of 20 m·ha<sup>-1</sup>. The Forest Administration Rheinland-Pfalz (2002) recommends, depending on the access within different low mountain range situations, a distance between neighbouring forest roads of 160 to 600 m, which translates to road densities of 16.7 to 62.5 m·ha<sup>-1</sup>.

Accessing steep-slope sites with main and feeder roads is highly questionable from a runoff viewpoint; however, road orientation is hydrologically significant – roads parallel to the slope decrease runoff velocity (BACKES 2005; Forest Administration Rheinland-Pfalz 2002).

Heavy forest vehicles can only drive on forest roads that are stable, and therefore dry. To avoid water saturation of the road grade, forest roads need a rounded transverse profile to drain water from the road (preferably into adjacent forest sites for infiltration, not into ditches). To drain forest roads with an extended longitudinal slope, draining hollows or passages at short intervals, should enable water to flow onto adjacent forest sites (Forest Administration Rheinland-Pfalz 2002, PEICHL 1998).

On forest sites without deep percolation, water from drainage ditches should be collected in small decentralized artificially created hollows adjacent to roads, with a capacity of about 200 to 2000 m<sup>3</sup>, to allow water to evaporate or seep away (OPPERMANN 1993). The greater the road runoff volume becomes, the less likely is the possibility of deep percolation, and the greater the number of hollows required. In cases where many hollows are required, they should be connected in a terraced network (SCHÜLER 2003).

Often, it is not possible to drain surface water from rutted forest roads into the adjacent forest, especially if they are deeply cut into the surrounding area. These roads then channelize water from intensive rainfall out of the forests into nearby ditches, tributaries, or onto sealed roads in residential areas. Rutted roads require re-construction with compacted, non-contaminated soil, and the re-establishment of a rounded transverse profile that drains the surface water into the adjacent forest (SCHÜLER 2003). Road damage should be repaired as soon as possible (Forest Administration Rheinland-Pfalz 2002).

### 3.4 Timber harvesting and log trails

To accommodate economic constraints, including the use of modern forest machines, with a requirement for the best possible soil structure protection, it is necessary for harvesters, skidders and forwarders to operate only on a permanent network of log trails in forests (HILDEBRAND 2002). If the soils are compacted by heavy machinery, the volume of draining macropores is decreased and the continuity of the soil pore system is disrupted. Surface water runoff increases as a result of the additional trail surface drainage. Hence, the logging trail network should be as limited as possible. However, the distance between the logging trails must be short enough that working from the trails is not problematic. Considering the decreased retention function of logging trails, they should be planned so that runoff from these lines can flow back into the adjacent forests (SCHÜLER 2003).

Practical techniques to limit site-level hydrologic impacts include use of low-pressure tyres, weight limits or optimised axle loads (HILDEBRAND *et al.* 2000, MATTHIES *et al.* 1995). In addition, during operations, branch wood can be used to provide reinforcement to extraction roads (EISENBARTH 1989).

To avoid soil compaction by wheeled or tracked forest machines, alternative harvesting and extraction methods have to be applied or new methods developed (e.g. harvesting methods for short timber assortments, the use of promising stepping harvesters or cable-crane systems, and timber extraction using horses). In forestry practice, the use of cable systems for extraction of timber is already established on difficult sites (GAUMITZ 1991). Here the extraction lines are not compacted. Hence the soil maintains its infiltration capacity, hydraulic conductivity, pore-system, and thus increases in runoff are limited.

### 3.5 Stream valleys and flood plains

To delay discharge as long as possible, water retention management must focus on retaining water in sufficiently-dimensioned retention areas such as stream and river valleys. They are natural flood areas (KOEHLER 1998). Flood plains in uninhabited areas have a good natural retention capacity if peakflow water can spread over the whole valley bottom during the flood development phase in order to delay flood propagation downstream. Hence, land-use in the flood plains should reflect the water level dynamics in the valley. Furthermore, water retention management should avoid the runoff from several retention areas converging simultaneously in one or several tributaries.

The water-flow lines, river-bed structure, and the state of the banks and the vegetation in the valleys should be as natural as possible to maintain and support the retention and delay capacity. Natural streams and rivers often have an irregular meandering course, a riverbed with rich and varied structures, and associated riparian vegetation. Water flow will be delayed by driftwood or rock debris in the riverbed. The obstruction with living willow switches in breakwaters and groins to support the meandering of streams and rivers is a biological-technical measure to restore a close-to-nature state of rivers and flood plains and to regain the river valley as a retention space (SCHÜLER 2003).

Forest roads on flood plains restrict their retention capacities. If new roads following river courses are to be built, they should be far enough away from the river to avoid any conflict between river development and road structure (Forest Administration Rheinland-Pfalz 2002). Old roads following the course of rivers should be de-activated and rehabilitated over the long-term.

### 3.6 Close-to-nature retention basins in the forest

In practice, some water administrations consider retention basins to be the most effective measure (MUTH *et al.* 2001; WESTRICH and SIEBEL 2004), provided that the basins can be drained at different times from the peak in runoff from a particular event (ASSMANN and GÜNDRA 1999). To ensure effective water retention, the basins must be connected to a terraced network. Even smaller artificial retention basins prevent or delay discharge when present in sufficient numbers. This is possible in deep narrow valleys. Small close-to-nature retention basins make use of natural structures such as cross-river road embankments and former fishponds. Here the retention space can be used by reducing the passage capacity of drainage pipes.

## 4 Efficiency of precautionary forestry water retention measures

The efficiency of precautionary water retention measures in forests must be discussed in the context of the particular level of observation. GRANT (2005) discussed the effects of forests on flood events. He found that forest harvesting and deforestation has only limited effects on big flood events at the mesoscale. At the microscale, each additional flood precautionary measure makes the flood discharge curves diverge from their starting points, and meet on the flood frequency curve at a higher flood return period (Fig. 5). If all small catchments in a larger watershed are managed with a view to water retention, the occurrence of damaging floods may be reduced. The key word is reduced, because large scale climatic situations are responsible for the generation of infrequent, damaging floods. Above a certain threshold of

flood return period, only technical flood-protection measures are effective (e.g. dams). This threshold is defined by the point of intersection, when the reduced discharge curve meets the “normal” flood frequency curve. It depends strongly on the magnitude of the climatic event, and on the site, soil, geology, land-use, and landscape characteristics. It should be the objective of spatial flood-protection planning to predict the particular threshold of danger, depending on the damage potential in catchment areas.

Flood precautions should not only be restricted to forestry management concepts. Flood precautions require the cooperation of water, agriculture, and viticulture sectors as well as land and infrastructural planning and management in residential area and traffic systems, combined with spatial planning and domestic policy, all to be integrated into a truly eco-hydrological approach. All precautionary measures that effectively enhance water retention in small watersheds are suitable.

A digital tool is under development within the European WaReLa-project to determine the efficiencies of the various precautionary measures (SCHÜLER 2005). Measures will be validated on the basis of ecology, cost, and benefit impacts. This eco-efficiency tool will allow the evaluation of land-use measures relative to the specific site and landscape characteristics.

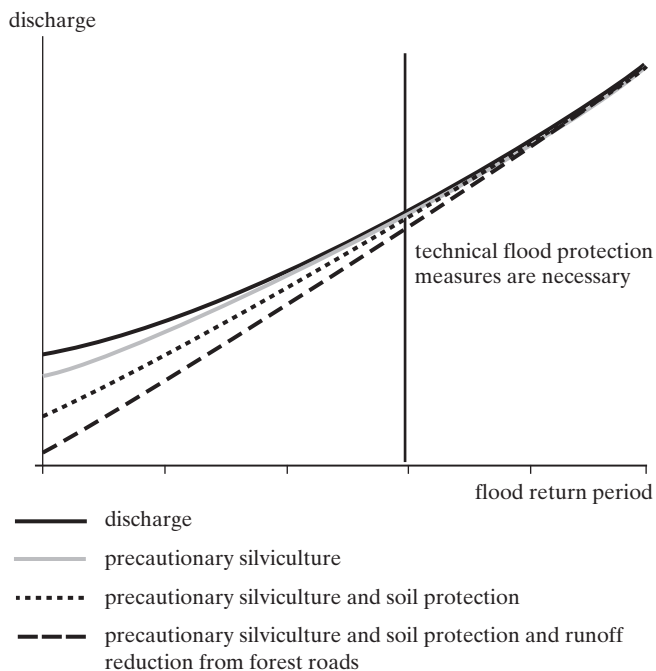


Fig. 5. Effects for discharge reduction by precautionary forestry management are shown in this unscaled graph. Different discharge curves vary according to the site and landscape structures. Intersection points and their assignment to a certain flood return period depend on the particular efficiency of the precautionary measures.



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