Analysis of Land Use Change in the Eastern Ore Mts. Regarding Both Nature Protection and Flood Prevention

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Abstract: Two different models (WBS FLAB, WaSiM-ETH) were used in the project HochNatur (flood prevention and nature conservation in the Weißeritz catchment in the Eastern Ore Mts. – Erzgebirge) to determine risk areas with quick runoff processes and to simulate the discharge. It was done in different scales, in the mesoscale Weißeritz catchment as well as two selected subcatchments with different natural and urban conditions, the Weißbach subcatchment with a well-structured landscape, the Höckenbach subcatchment with a greater part of arable land. On the basis of selected scenarios, the effect of land use changes on the runoff generation processes of an area and on the hydrograph is described. Land use changes are able to reduce the portion of quick runoff components, the water erosion and the discharge. The effect occurs especially in smaller catchments and with short heavy rains (events with a frequency of occurrence of 5–50 years). Depending on the present situation the changes have to include areas of more than 25% of the catchments area to cause a significant effect. It became apparent that nature conservation and flood prevention agree well in their requirements with the land use. A rich structured landscape proved to be extraordinarily positive for both, flood prevention and nature conservation.

Keywords: hydrological modeling; runoff generation; land use change

The region of the Eastern Ore Mts. (Saxony, Germany) was often affected by heavy rains causing floods. The last spectacular one was the flood of 2002. Therefore different solutions of flood prevention were discussed intensely during the last years. Beyond technical measures preventative measures like land use change can be helpful. An accurate forecast of discharge by precipitation-runoff-models with changed land use is generally possible only with large uncertainties. A substantial problem is how to parameterize the models.

Driven by the flood event of August 2002 the aim of the HochNatur-Project is to develop measures which both prevent floods and support nature conservation. A tight interdisciplinary cooperation between hydrological modeling on one side and landscape ecology studies and conservation assessment on the other (Figure 1) plays the key role in this project (Merta *et al.* 2006; Richert *et al.* 2007).

Scientific analyses to assess the present state and to derive scenarios for future sustainable development have been carried out, for example a stream habitat survey, mapping of biotopes and endangered species, vegetation relevees, analysis of surface hydraulic roughness and hydrological measurements. The results of these comprehensive analyses will be integrated in hydrological models (expert system WBS FLAB and the precipitation-runoff model WaSiM-ETH). As a starting point the

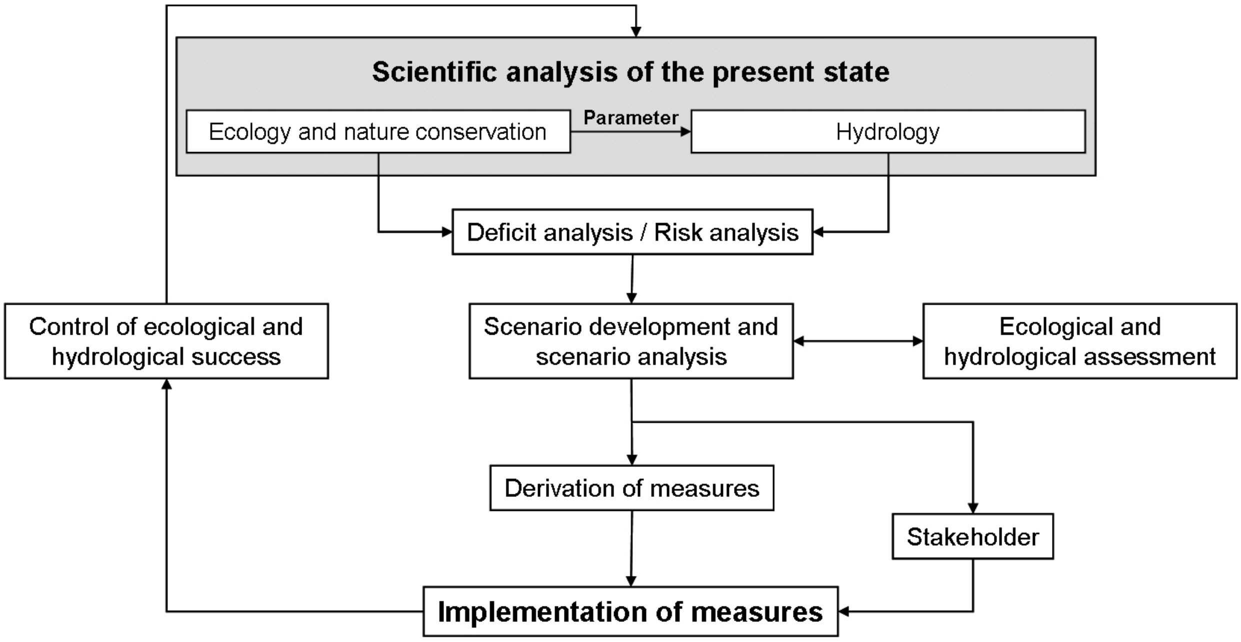

Figure 1. Main steps in the project HochNatur

analyses of the actual state of the Weißeritz catchment with two subcatchments Rote and Wilde Weißeritz (research regions) were used. Major emphasis was on investigations and suggestions of measures for the subcatchments of two tributaries (Weißbach und Höckenbach) of the Wilde Weißeritz (Figure 2). This way it was possible to assess the transferability on other areas. The development of scenarios by the hydrological models focuses on the definition of structures and measures with a high relevance to flood control and includes the outcomes of the assessment of the conservation value including deficits. Measures suggested by the integrative modeling will be implemented in close cooperation with local and regional stakeholders. Another important aspect of this multifunctional approach to flood and nature protection lies in the transfer and generalization of the suggested measures to other mountainous regions within Germany.

MATERIAL AND METHODS

Research area

The Weißeritz catchment (384 km^2) is located in the Eastern Ore Mts. (thereof 12.3 km^2 in Czech Republic) and it extends from the crests at the German-Czech border over middle and lower mountain region as well as the hilly country down to the lowland of the Dresdener Elbtalweitung. The rock structure of the study area is dominated by gneiss and acidic magmatic rocks (granite, granite-porphyry (micro-granite) and quartz-porphyry. Soils were mainly formed on periglacial debris. Therefore the soils, especially in the upper areas, are shallow and skeleton rich. According to the geological initial situation sandy loamy Cambisols are widespread in the research area (Figure 2a). In the upper areas poor Podzols and shallow skeletal Umbrisols are dominating, on loess silty Cambisols and Stagnosols. The valleys are usually characterised of holocene sediments. Only in the upper mountain region in the south of the Weißeritz catchment some few Fibric Histosols can be found (Mannsfeld & Richter 1995).

At present a third of the Weißeritz catchment is covered by forests (Table 1). Forest stands mainly consist of spruce, on sandstone pinewood forests also share great parts of the area (Mannsfeld & Richter 1995). Only some small woodlands consist of deciduous tree communities. Almost half of the area is used agriculturally, with considerably more agricultural cropland than grassland (Figure 2b). Agriculture dominates in the lower and middle regions. The northern part of the catchment is particularly marked by the settlement areas (cities of Freital and Dresden).

The research areas Weißbach (7.4 km^2) and Höckenbach (16.7 km^2) differ a lot from each other in the actual land use and land relief. The soils

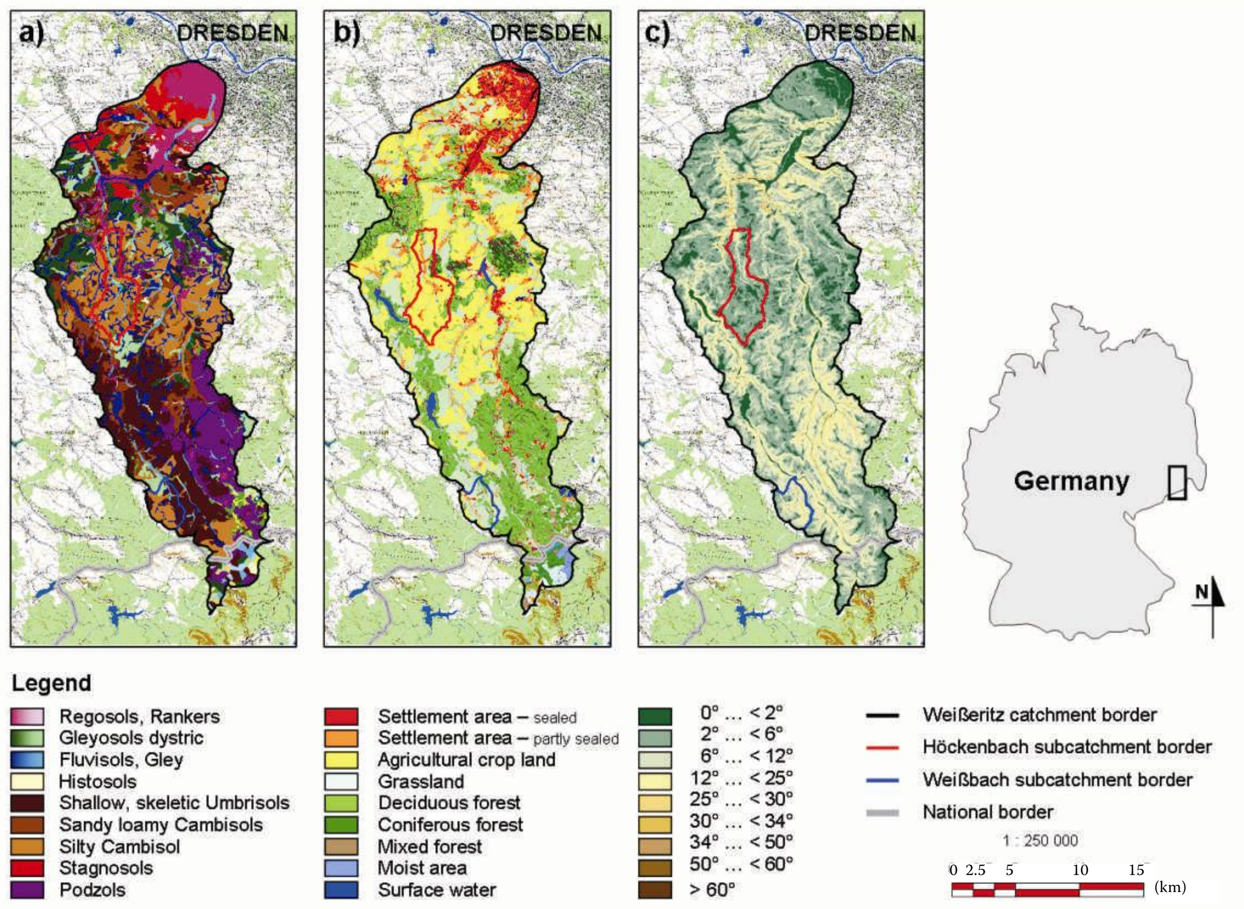

Figure 2. Weißeritz catchment; (a) soil types – soil concept map 1: 200 000; (b) land use – Color-Infrarot-(CIR)-Biotope type and land use mapping; (c) slope – DGM 20

of the two subcatchments consist in large parts of stratified cohesive soils. A high proportion of shallow cambisols is recorded in the Weißbach subcatchment (Figure 2a). In contrast to the Weißbach subcatchment the terrain of the Höckenbach subcatchment has predominantly flat slopes nevertheless it is strongly endangered by erosion.

The Eastern Ore Mts. can be considered as a hydro-geologic unit. The above-ground and below-ground catchments are largely identical within the research area. The springs are mostly scree slope springs with a flow of < 1 l/s, which strongly react to rain fall. This is caused by interflow, which plays an essential role within the research area. However within the middle and lower regions, the arable land with silty soils shows bad infiltration conditions, which in connection with the partly very steep slopes (Figure 2c) often results in overland flow. The receiving streams, dependent on the system status (soil moisture), react quickly to precipitation events.

Models

Landscape-ecological and hydrological system analyses and models were used as methods for analysis. At the same time data was taken from the terrain for biotype and vegetation structures (actual state) and used for hydrological system analyses, which are based on the expert system WBS FLAB (Peschke *et al.* 1999; Zimmermann *et al.* 2001) and the precipitation-runoff model WaSiM-ETH (Schulla & Jasper 2006). The two models were coupled, which firstly takes the advantage of a functional spatial structuring of the catchment, regarding the processes of runoff generation, which is taken into account for the quantitative modelling of runoff situations. In addition, risk areas can be identified for high water emergences by this procedure. A deficit or risk analysis followed the analysis of the actual state to build and judge different land usage scenarios.

Table 1. Actual land use in Weißeritz catchment (Color-Infrared-(CIR) biotope type and land use mapping) and in Weißbach subcatchment und Höckenbach subcatchment (biotope type mapping, Foltyn 2006)

Land use	Weißeritz catchment	Höckenbach subcatchment	Weißbach subcatchment
	proportion of area (%)		
Forest	34	12	16
Afforestation areas		< 0.5	8
Hedges, groves, tree rows	< 0.1	1.5	1.5
Grassland, bushes, moorland	24	7	44
Agricultural crop land, horticulture	26	69	21
Surface water	1	< 0.5	< 0.5
Settlement areas, industry, infrastructure	15	9	9
Other areas	< 0.5	< 0.5	< 0.5

A knowledge-based system was developed to identify similar runoff components (Expert System – Area of Equal Runoff Components) and to regionalize the runoff generation processes (Figure 3) (Zimmermann *et al.* 2001). Starting with general available information about the area (land use and vegetation, soil types or geology, stream network and DEM) the WBS FLAB subdivides a catchment into areas in which a certain runoff process dominates. Here the quick runoff generation processes are in the focus of consideration for the high water emergences. If-then rules and factual knowledge are essential components of the WBS FLAB. The set of rules is independently usable for geographical regions and climatic conditions. "Expert knowledge" was used to derive the set of rules, which is based on a generalisation of the measured and observed processes in catchments of different physiographies, geographic regions and climatic conditions. The factual knowledge are a kind of data base, which contains detailed information and parameter lists of maps, e.g. physical soil parameters, soil horizons, rooting depth, root system structure and coarse root and fine root.

The concept based, deterministic area-distributed precipitation-runoff model WaSiM-ETH (Schulla & Jasper 2006) for natural streams was used for the quantitative description of the runoff processes. For urbanely modified streams the program SWMM (Rossmann 2005) was used in first place. The model WaSiM-ETH represents a balanced symbiosis of physical and conceptional hydrological approaches since it also allows the modelling in different time levels in mesoscale areas. Among the presently existing precipitation-runoff models, this model has very good prerequisites in order to comprehend the effects of land use on the high water discharge, e.g. (Niehof 2001)

RESULTS AND DISCUSSION

Integration of vegetation parameter into the Expert System

Information about the soils is necessary in order to derive the rules for the expert system. Since soil properties are strongly influenced by the plant root system (porosity, hydraulic conductivity, storage capacity, macropores etc.), a visual assessment procedure was developed to characterize the attributes of root systems (depth, intensity) for a soil profile and applied to root distribution pictures of various soil profiles. This procedure requires knowledge about the vegetation type and the species composition (dominant species). By means of this scheme new rules on the impact of root systems on the soil were derived and integrated in the WBS FLAB. The improved system allows considering the influence of vegetation on the runoff processes in more detail. Most of the roots are normally thicker than soil pores, so they can only partly use the soil pores. During their growing period they themselves form pores. Hair roots and hyphas create medium pores and can enlarge the soil storage capacity. Medium and strong roots form macropores assuring a better percolation.

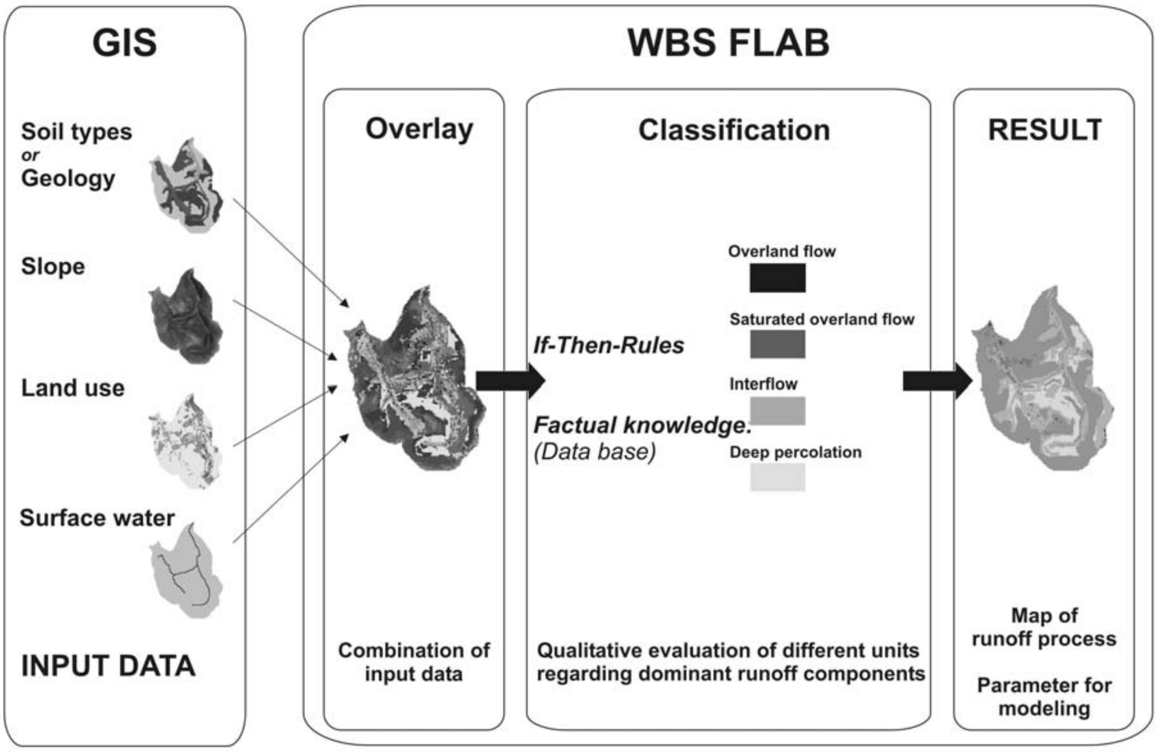

Figure 3. Structure of the Expert System FLAB

Medium roots and strong roots together are called coarse roots. The description in Table 2 exemplifies possible modifications of the soil properties by the vegetation. This information is the basis to derive new rules. Together with the already integrated information on the different soil types, this results in new soil properties. Thus a better assessment of the vegetation influence on the runoff generation processes is achieved.

Analysis of the actual state

The spatial distribution of runoff generation processes shows potential overland flow from areas with bad infiltration capacity especially on loess soil (Figures. 4a, b, c). This mainly concerns agricultural cropland and the so far intensively used grassland (Zimmerman *et al*. 2006). The plough furrow sole can also cause surface-near quick interflows (Schobel *et al*. 2001). As soon as the soil storage capacity is exhausted and the soil is saturated, overland flow occurs. The intensively used grassland has a higher root density within the upper 10–15 cm only, with vastly fine roots (0.3 ... 0.7 mm). Due to that fact the storage capacity within the upper layers can increase (Sloboda & Leuschner 2002). Because of cattle track and frequently driving with agricultural

Table 2. Relevance of root density for soil properties

Low root density without coarse roots	Low root density few coarse roots	High root density many coarse roots
Sandy soils		
Without modification	– slightly increasing storage capacity – no change of conductivity	– increasing storage capacity – no change of conductivity
Cohesive soils		
Without modification	– slightly increasing conductivity – no change of storage capacity	– growing part of macropores – no change of storage capacity – increasing of conductivity

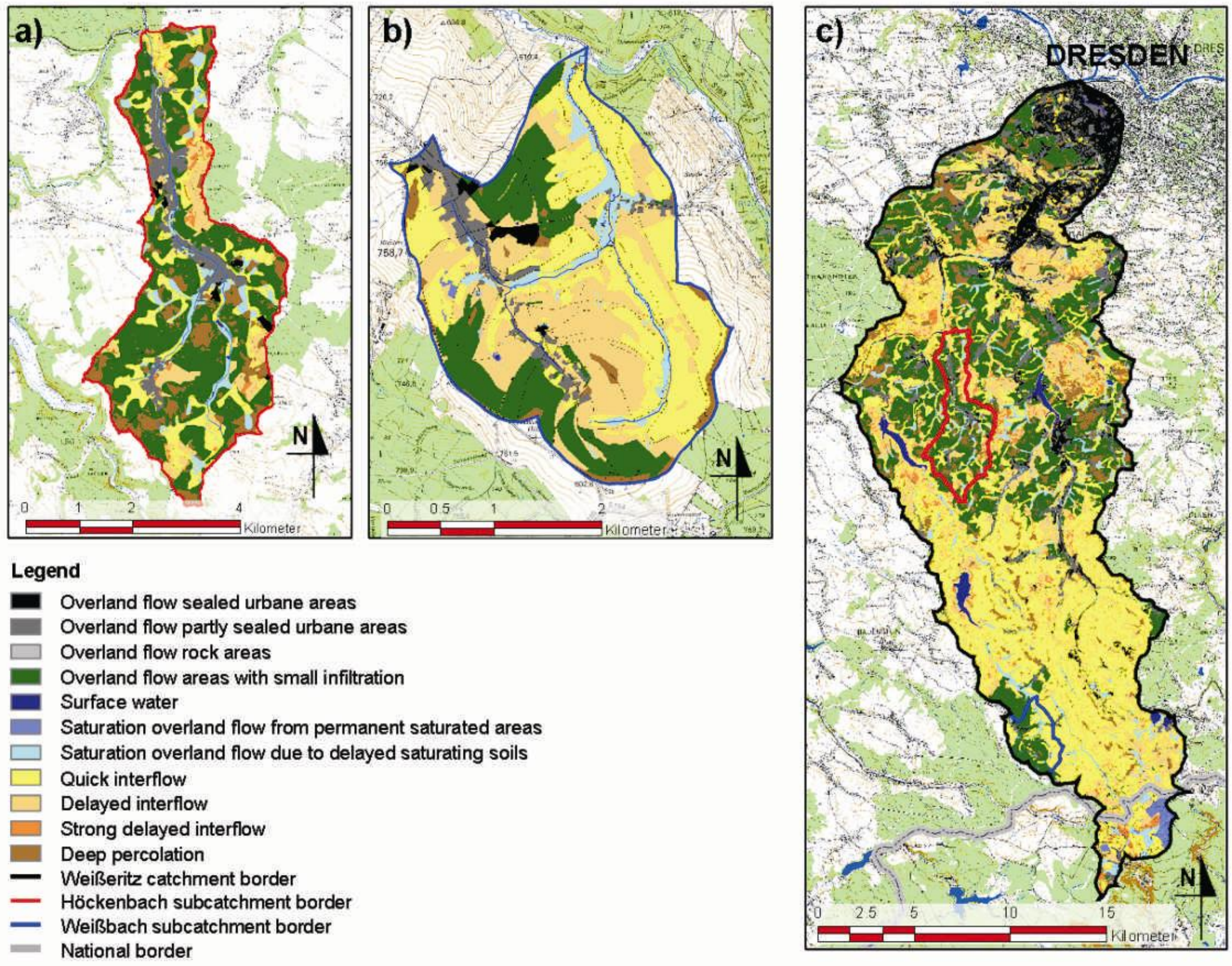

Figure 4. Spatial distribution of runoff generation processes resulting from the application of the Expert system FLAB; actual state; (a) Höckenbach subcatchment; (b) Weißbach subcatchment; (c) Weißeritz catchment

vehicles the soil compaction arises and therefore also an infiltration barrier, which leads to an overland flow (e.g. Kurz *et al.* 2006; Zimmermann *et al.* 2006). The discharge measurements show that with intense rain events all streams in this catchment react very fast with high discharges within very short periods.

The quick interflow occurs particularly on steeper slopes and forested (spruce) shallow soils (Figures 2 and 4). Shallow soils above impermeable subsoil generally show small storage capacities (Andreassian 2004). It is possible to increase the storage capacity of those soils slightly with afforestation due to the developing organic surface layer. Additionally a minimally higher interception loss and a more intense evapotranspiration lead to a stronger exhaustion of the soil water content on average (Johnson-Maynard *et al.* 2002). Nevertheless the soil storage capacity of those soils cannot reduce the discharge significantly for heavy rain events causing floods (Lüscher & Zürcher 2003; Hegg *et al.* 2004).

The vegetation types affect these processes strongly. For instance the shallow root system of spruce shapes a more slope-parallel macropore system benefiting the generation of quick lateral runoff (quick interflow) on the shallow soils (e.g. Uchida *et al.* 2005). Afforestation of those areas will influence the discharge only slightly, especially under wet conditions. Depending on the size of forested areas and other local conditions, a reduction of peak discharge from small to medium can be expected during heavy summer rainfall, which is confirmed by application of the model WaSiM-ETH (Pöhler 2006). Due to the current knowledge it can be assumed, that forests on soils with layers of low hydraulic conductivity in depths between 30 and 50 cm, force flood generation (e.g. Andreassian 2004; Hegg *et al.*

2004). From areas with minor slopes and loess or deep soils below extensively used grassland (Figures 2b, c) mainly delayed interflow originates. This species-rich vegetation type is characterized by an intense well-structured root system that is able to increase the porosity. Root hairs as well as fine roots in the upper layer (up to 30 cm) create fine and medium sized pores increasing the soil storage capacity. The large portion of middle and coarse roots and the deep root penetration together with numerous tubes of soil organisms provide for better infiltration and percolation (Doussan *et al.* 2003). Thus, the water flows laterally with time lag above deeper dense horizons.

In floodplain areas saturation overland flow from gleyic or fluvio genic soils are common runoff components (Figure 2a). Slow runoff components as delayed interflow, strongly delayed interflow and deep percolation occur generally on areas with minor slopes (0° ... 2°) as well as deep Cambisols and forest on 25% of the total catchment area (Figure 4).

Land use scenarios

All land use scenarios were evaluated based on the detailed analysis of the actual state (Table 3). In both of the above mentioned subcatchments an area-wide biotope mapping was realised (Foltyn 2006).

On the basis of these investigations common guidelines are developed and synergies are used between the issues of flood protection and nature conservation aiming at the demonstration of land use effects on runoff generation. Besides feasible scenarios based on the wishes of local stakeholders, reference scenarios (land use changes of areas with quick runoff components) and extreme scenarios (complete afforestation) were analysed. From the position of flood prevention the scenarios had to reduce the quick runoff components (surface runoff and quick interflow) as well as to delay the runoff concentration and to increase the soil storage capacity. Therefore particularly arable land was changed into extensive grassland or mixed forest. In the Höckenbach catchment conservation tillage plays an important role. The nature conservation scenario aims at a well-structured landscape with different biotopes to preserve biodiversity, including extensification of grassland, preservation of species rich meadows, hedges and ecological transformation of forests or creating new mixed forest etc.

Assessment of land use scenarios

The runoff components identified by the WBS FLAB are subdivided into two groups according to their relevance to flood formation. The group "quick runoff components" contains surface runoff, saturation overland flow and quick interflow, the group "slow runoff components" delayed and strongly delayed interflow and deep percolation.

Table 3. Compilation of the land use scenarios, their abbreviations and the area percentages affected by land use changes in comparison to the present state in the subcatchments Höckenbach (HB) and Weißbach (WB)

Land use change	Abbreviation	HB	WB
Present land use (2004/2005)	pres	–	–
Complete afforestation	c-aff	89.7	90.8
Arable field into grassland	a-g	69.0	16.3
Conservation tillage, intermediate crop	c-till	69.0	21.0
Ecological transformation of forests	tr-for	12.6	24.3
Partial afforestation (areas with quick runoff components)	p-aff	25.9	24.9
Extensification of grasslands	g-ext	n.a.	9.8
Nature conservation measures	nat	83.7	53.8
Flood protection measures	flood	82.2	51.8
Combination of nature conservation and flood protection measures	comb	82.9	51.3

n.a. = scenario not analyzed

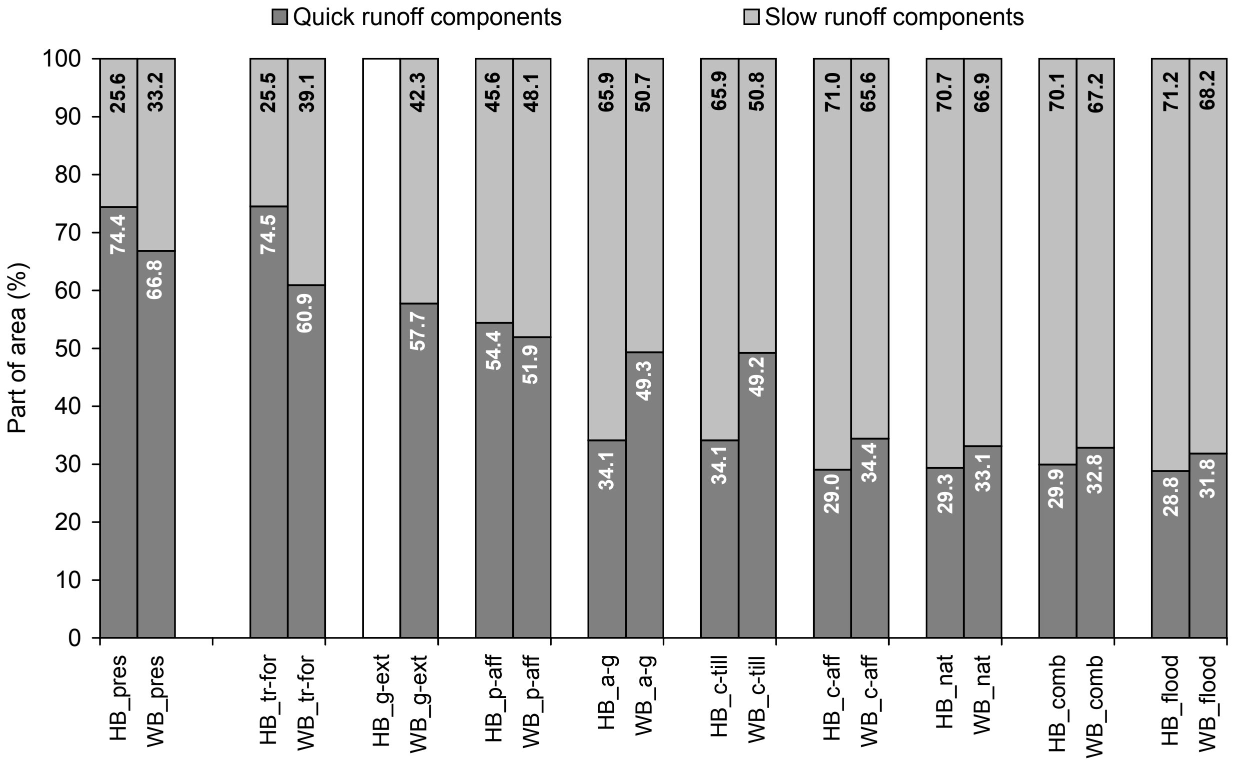

Figure 5. Comparison of the portion of area with slow runoff components and quick runoff components for the actual state and land use scenarios; Höckenbach subcatchment (HB) and Weißbach (WB) subcatchment

In the study areas Weißbach subcatchment and Höckenbach subcatchment the scenarios WB_flood und HB_flood are of high significance related to flood prevention. In the Weißbach subcatchment the area proportion with quick runoff components was reduced by 35% and in the Höckenbach subcatchment by 45% (Figure 5). The land use changes by the scenarios HB/WB_comb, HB/WB_nat and HB/WB_c-aff enclose a large proportion of the research areas and therefore they are very effective concerning flood prevention in these regions. The differences between the several scenarios (< 3%) are in between the error range of the model.

Relating to the restructured area the efficiency of the scenarios WB_a-g, WB_c-till and WB_p-aff is very high. For the whole Weißbach subcatchment these measures reduce the quick runoff components by only approximately 16% compared to the actual state. A similar trend can also be observed with scenario WB_g-ext but with a reduction of only 10% of the quick runoff components it plays a minor role. The transformation of forests enhances the actual state by less than 6%, because of the steep slopes and the shallow soils. At such sites a transformation of spruce monoculture is not a big advantage. In contrast agricultural cropland (69% of the total area) dominates in the Höckenbach subcatchment, thus the scenarios HB_a-g and HB_c-till (Figure 5) are of great relevance from the position of flood prevention. The quick runoff can be reduced by approximately 40% of the area. The partly afforestation (HB_p-aff) reduces the portion of areas with quick runoff components by 20%. Due to the currently small forests their transformation (HB-WU) does not affect the discharge compared to the actual state. From the position of erosion prevention the following scenarios are outstanding: HB_flood, HB_comb, HB_nat, HB_c-aff, HB_a-g and HB_c-till, because a near complete elimination of surface runoff can be achieved.

The model WBS FLAB analyses the runoff generation processes and assesses the effectiveness of all scenarios in a qualitative way whereas the precipitation-runoff-model WaSiM-ETH calculates the discharge in the river quantitatively, including the position of the runoff areas to the river, ground and soil water conditions and river structure.

Several land use scenarios were simulated with WaSiM-ETH for some heavy rain events of different

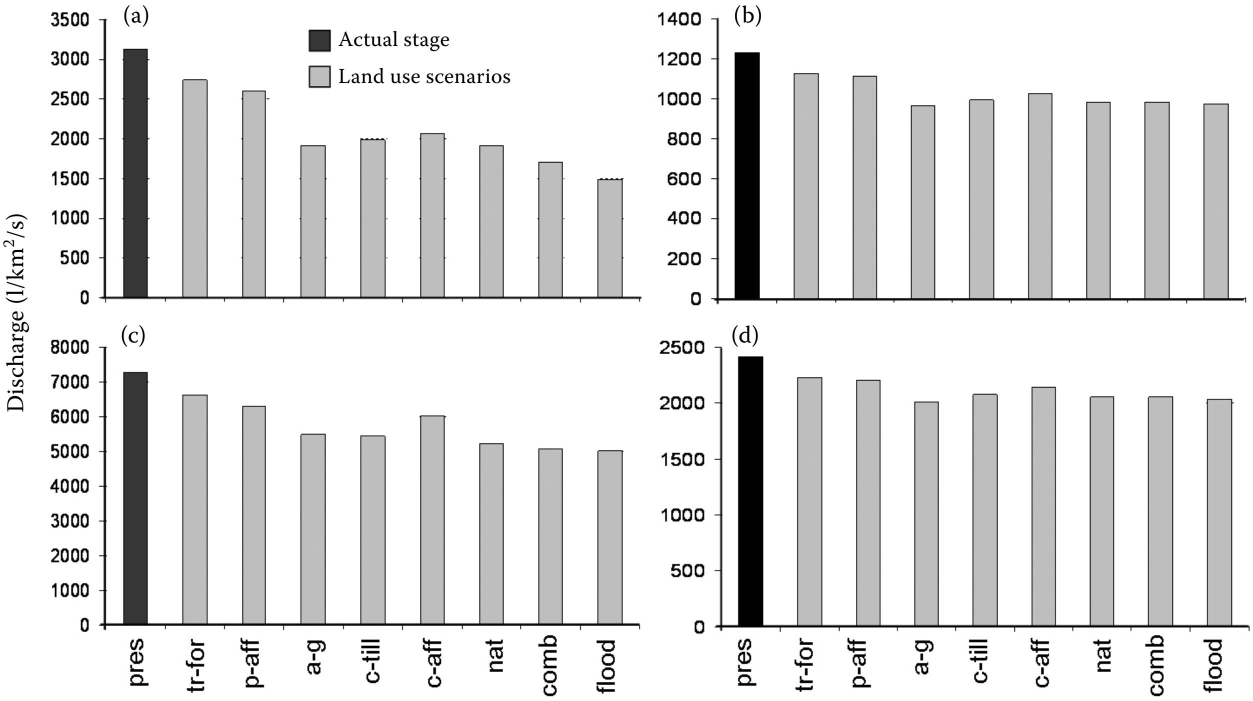

Figure 6. Comparison of the mean discharge of the Höckenbach subcatchment; (a) HQ5 – precipitation 10 min, 17.4 mm; (b) HQ5 – precipitation 24 h, 78.8 mm; (c) HQ100 – precipitation 10 min 31.6 mm; (d) HQ100 – precipitation 24 h, 142.4 mm

duration (10 min until 48 h), different intensities (KOSTRA-DWD-2000 2005) and temporal variability of a likelihood of 1 year until 100 years. Some selected examples fort the Höckenbach subcatchment are discussed in detail (Figure 6). Due to deep soils in this subcatchment (Figure 2a) measures that increase the soil storage capacity, decrease surface runoff and stream discharge.

During summery intense but short rain events, the land use scenarios HB_a-g, HB_c-till, HB_c-aff, HB_nat, HB_comb and HB_flood reduce the maximum peak discharge from 10 to 30%, depending on the dimension of the affected areas (Figures 6a, c). In case of rain events with longer duration and a more frequent reoccurrence interval (HQ 5) the peak discharge can be also reduced by 20% (Figure 6b). In contrast the measures effect the runoff generation process and the discharge only a little for longer lasting rain events with high intensity and long reoccurrence interval (HQ 100) (Figure 6d).

To compare the effects of all scenarios from the different positions of nature conservation and flood prevention, the results of the application of both models WBS FLAB (reduction of areas with quick runoff components) and WaSiM-ETH (reduction of peak discharge) are correlated. Correspondingly there exists a significant relationship between these two parameters and the measures particularly for short intense precipitation events (HQ100/10min and HQ5/10min).

From the position of nature conservation all simulated land use scenarios come to an improvement (without total afforestation) compared to the actual state (Figure 7; Merta *et al.* 2006; Richert *et al.* 2007). The afforestation of the whole research area leads to a loss of biotope diversity.

The integrative assessment of scenarios of land use changes aimed at both flood prevention and nature conservation in a mountainous area has shown that through a wide spectrum of measures on varying area proportions of individual subcatchments, dramatic improvements in both objectives can be gained. Even scenarios with measures directed exclusively to nature protection yielded in a reduction in the extent of areas with fast surface and sub-surface flow and reduce flood peaks in rivers. Similarly, land use management designed with respect to flood prevention had positive effects on nature protection. Highest effects were associated with land use changes on large area proportions. However, also single measures like the

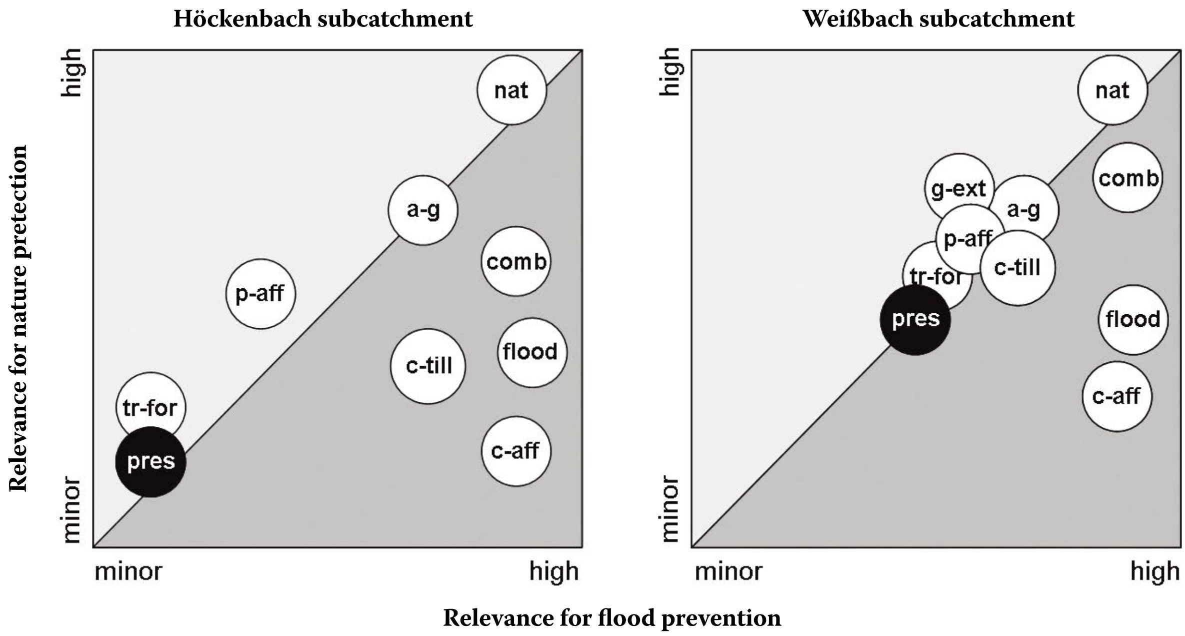

Figure 7. Combined assessment of land use scenarios with respect to flood prevention and nature conservation (for abbreviations of scenarios refer to Table 3)

establishment of hedgerows may be positive both from the nature conservation and flood prevention perspective. They affect especially the local habitat, for example by reducing soil erosion.

The analysed effects of land use changes were the greatest in small to medium sized catchments and in the case of precipitation events with 5 to 50 years reoccurrence intervals. A reduction of as high as 5 to 10% on average and 25% at the most is possible. Based on these results and in relation to the present state, land use changes and alterations in cultivation practises are necessary on 25 to 50% of the catchment area. Further positive synergetic effects include improved soil protection, balanced water supply as well as enriched natural scenery.

In large catchments, the temporal and spatial multiplicity of processes in the different parts overlap and therefore it depends on these interactions whether the discharge of the whole catchment is influenced or not. Several measures in some subcatchments affect the discharge of the whole catchment only slightly. Finally the flow processes in the riverbed itself become more important.

The effect of land use changes heavily depends on the specific conditions of the landscape such as the presence of habitat and landscape elements with high relevance for nature conservation, and such as vegetation structure (density, height, root depth etc.) with relevance for flood prevention. Therefore results from the individual scenarios developed for the two subcatchments cannot be transferred to other catchments. On the other hand, the methods developed for the assessment both from the nature conservation and flood prevention perspective can be transferred to other regions as long as necessary data such as a digital landscape model, land use type and distribution and soil characteristics are available.

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