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A decision scheme to indicate dominant hydrological flow processes on temperate grassland

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Abstract:

A decision scheme has been developed to indicate the likely dominant runoff forming on temperate grassland hill slopes. The decision scheme was developed from data collected from sprinkler experiments on 60 m^2 plots at a number of grassland sites in Switzerland. The scheme requires input of hydrological properties of the surface and each major horizon of the soil. Worked examples of the application of the decision scheme to determine the dominant hydrological processes and runoff types are given for three actual grassland hill slopes. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS runoff generation; processes; decision scheme; infiltration; sprinkler experiments; macropore flow

INTRODUCTION

The formation of runoff on natural soils after intense precipitation is more complex than originally assumed. According to Horton (1933) runoff occurs when the rainfall intensity exceeds the infiltration rate. However, in many soils where runoff is observed, measured infiltration rates are larger than rainfall intensities even during the most intense storms. Another approach was based on the assumption that all the water infiltrates and runoff starts when saturated soils prevent further infiltration. In such cases, no runoff occurs until soil saturation, and then all the water runs off. The concept of the contributing areas avoided such rarely observed sudden changes in flow, assuming a continuous increase of the saturated areas with increasing rainfall amounts, starting near the brook and extending upwards. Other research showed that a considerable amount of the water can flow laterally below the ground surface, introducing the concept of fast subsurface flow or through flow (Whipkey and Kirkby, 1978).

Infiltration models based on homogeneous or even very heterogeneous soil matrices alone often failed. Beven and Germann (1982) pointed to the influence of macropores on the infiltration process and Mosley (1979, 1982) discussed the role of lateral preferential flow paths for fast subsurface flow. However, the assessment of the role of macropores in infiltration at the plot and the catchment scale proved to be difficult. Studies of a single or a few macropores in the field or in the laboratory revealed very complex behaviour of the flow processes in and around macropores (Jones, 2000). Upscaling this knowledge to the plot, hillslope, or catchment scale proved equally demanding, as the ensemble of macropores often did not react like a multitude of single macropores. Some of these difficulties could be circumvented with investigations at the plot or hillslope scale, where the reactions of many macropores and heterogeneities of the soil matrix are integrated and averaged (Kirkby, 1985).

In the last few decades, research has gathered a wealth of observations and ideas on the processes influencing runoff formation. The question is how to bring these many facets together to decide which process occurs on a given plot and how these processes influence runoff formation at the catchment scale during intensive precipitation events. Some approaches in this direction exist, like the HOST system (Boorman *et al.*, 1995) and

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an approach called FLAB (Peschke *et al.*, 1999). Both infer the hydrologic reaction from soil properties and profiles with the aim of delineating locations of different reactions to precipitation within the catchment. Both can produce high-resolution spatial maps of the dominant runoff processes. However, to be able to upscale available information to the catchment, generalizations have to be made that do not take direct account of the actual processes.

A different approach for inferring the type of runoff process taking place on a plot is presented here. It is based on experience gained with high-intensity sprinkler experiments in Switzerland (Naef *et al.*, 1998) on 18 mostly grass-covered hillslopes. In these experiments, soils with similar characteristics displayed quite different hydrological reactions to the applied precipitation. Some governing factors were identified. It was not possible, however, to isolate these factors, as they exert their influence only in the context of their actual surroundings. A revised understanding of runoff formation is therefore presented in the form of a scheme that follows the flow of the water through the soil profile. In each horizon of the scheme the water can flow differently, depending on the critical factors operating within that horizon. At the end of each possible path, the dominant runoff process occurring in a specific soil is indicated.

INFILTRATION AND RUNOFF PROCESSES

A general overview of the main factors that influence infiltration and runoff formation are presented in the following section, illustrated by results of field experiments. In these experiments a sprinkling apparatus was used to apply high-intensity rainfall (50–100 mm h^{-1}) to hill-slope plots of 60 m^2. Faeh *et al.* (1997) presented a detailed description of these sprinkling experiments and the procedure of process identification. Measurements of overland flow, subsurface flow at the trench at the downslope boundary, and soil water changes using tensiometers, piezometers, and time domain reflectometry probes were made during the experiments. These measurements provide the necessary information to identify dominant runoff processes. In this paper, data from three sprinkled plot sites, all performed on grassland cambisol, are used to demonstrate the identification of the dominant processes leading to the production of runoff from the plots.

Infiltration processes

Several factors influence infiltration and water retention in a soil and, consequently, runoff formation. The surface–topsoil interface controls if, how, and where rainfall water enters the matrix and macropores (Bouma, 1990; Naef *et al.*, 1998). Infiltration barriers, such as surface sealing or soil crusts, can prevent infiltration and thereby affect macropore and matrix flow. However, if a continuous macropore system leading from the surface into the subsoil exists, macropore flow can still be promoted by a superficial infiltration barrier. Other soil characteristics, like soil compaction, an abrupt increase of bulk density from top- to sub-soil, hydrophobic organic topsoils, or weak soil structure, hinder effective water transport from the topsoil into the matrix of the subsoil. Here too, an effective macropore system can bypass such superficial infiltration hindrances and provide a rapid and efficient path for water into the deeper soil. The interaction between macropore flow and matrix flow, i.e. the intensity of water exchange between macropores and the surrounding soil matrix, determines how much water can be stored in the soil (Faeh, 1997; Weiler and Naef, 2003, this issue). A dense macropore system in a permeable matrix maximizes interaction between preferential flow paths and the soil matrix. Thus, water is distributed throughout the soil and the full storage potential of the soil is used. In contrast, if a less permeable matrix surrounds the macropores, then the flow of water into the soil matrix is limited and the retention capacity of the soil cannot be fully used.

Some soils have effective lateral flow paths that enable rapid water movement. Such structures are formed by soil pipes, produced by decaying roots or soil fauna activities (mouse or mole burrows), or by leaching processes induced by regular water flux above impervious horizons. These lateral flow paths were also observed in the highly permeable weathered bedrock zone lying above compact sandstone strata.

Runoff processes

Table I gives an overview of the runoff processes as defined in the literature and observed during the sprinkler experiments. The processes are subdivided according to the conditions of their occurrence and their runoff response. For example, HOF1 (immediate Hortonian overland flow) occurs on soils with serious infiltration hindrances, on soils with few macropores and extremely high clay content, on soils compacted by heavy agricultural machinery or intense animal confinement, or on bedrock surfaces with low permeability. Such conditions provide low infiltration rates and, therefore, rapid and high rates of runoff. HOF2, a slightly delayed version of Hortonian overland flow, occurs, for example, on soils affected by compaction and low macroporosity or surface sealing, soils susceptible to hydrophobicity, or soils with medium macroporosity and low water exchange to the surrounding matrix. A typical runoff response produced by HOF2 is illustrated in Figure 1, experiment no. 2 *(Heitersberg)*. On moist or wet soils, which can be saturated during a short rainfall burst, immediate saturation overland flow (SOF1) is expected. A very delayed saturation overland flow (SOF3) occurs on thick macroporous soils with a permeable matrix. *Therwil* (experiment no. 3 in Figure 1) is typical of the delayed and weak runoff response produced by SOF3. Such soils contribute to runoff only after prolonged rainfall. Rapid subsurface flow (SSF1) results if an impermeable horizon, e.g. higher bulk density, or impermeable bedrock occurs on a steep slope with very shallow soil and an effective system of lateral flow paths. On less shallow soils with such characteristics, SSF2 occurs. This process produces a moderate runoff response, as was observed at site *Willerzell* (experiment no. 1, Figure 1). Deep percolation (DP) is expected on permeable and thick soils or on permeable shallow soils with very permeable subsoil and bedrock. In such cases the available capacity to store water is very large and is almost never exceeded, even after prolonged heavy precipitation.

Figure 2 shows the soil profiles and characteristics at the three sites that produced the runoff responses shown in Figure 1, together with the graphs of the applied rainfall rates and the measured surface and subsurface flows. The general classification of the soils was undertaken according to the FAO–UNESCO soil classification system (FAO, 1974) and the texture according the USDA classification scheme (Soil Survey Staff, 1975). The first experiment was made in *Willerzell*, on a typical steep grassland hill slope used as

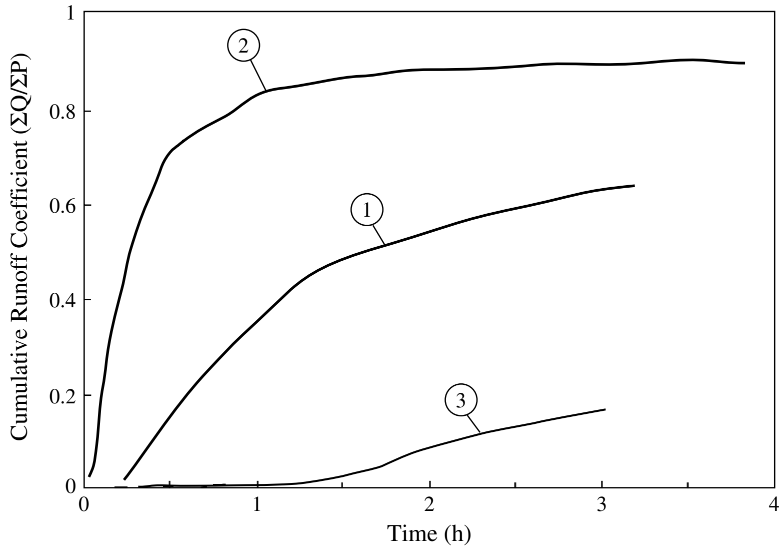

Figure 1. The observed runoff coefficients at three selected hillslopes where artificial rainfall of high intensity (55–100 mm h^{-1}) was applied. Experiment 1 (*Willerzell*) is dominated by delayed subsurface flow (SSF2). At experiment 2 (*Heitersberg*) a slightly delayed Hortonian overland flow (HOF2) dominated runoff formation. The runoff response of experiment 3 (*Therwil*) is generated mostly by a delayed version of saturation overland flow (SOF3). (Q: runoff; P: precipitation; the numbers refer to the experiment)

Table I. An overview of the different flow processes considered in the process decision schemes (urban areas are not included)

Process	Type	Abbreviation	Intensity of runoff process	Process criteria: characteristics and conditions
Overland flow processes	Hortonian	HOF1	Immediate Hortonian overland flow due to infiltration hindrance (infiltration excess overland flow)	Soil or surfaces with serious infiltration hindrances: soils with extremely high clay content, compacted soils by agricultural machines or cattle; bedrock surfaces with low permeability
		HOF2	Delayed Hortonian overland flow due to infiltration hindrance (infiltration excess overland flow)	Hydrophobic soils (soils with extremely dense root network near surface similar to fur), compacted soils with low macropore density, sealed and crusted soils, macroporous soils with small water exchange (interaction) between macropores and soil matrix
	Saturation	SOF1	Immediate saturation overland flow due to soil saturation (saturated overland flow)	Soil water level near surface combined with good permeability of soil layers (macroporous, permeable matrix), which enable infiltration and saturation after short rainfall, absence of lateral flow structures
		SOF2	Saturation overland flow due to slowly saturating soils (saturated overland flow)	Permeable, shallow soils with a low permeable subsoil, e.g. bedrock, soils with a water level in the subsoil, absence of lateral flow structures
		SOF3	Delayed overland flow due to very slowly saturated soils (saturated overland flow)	Thick macroporous soils with permeable soil matrix, which can only be saturated after extensive rainfall
Subsurface flow processes	Lateral flow	SSF1	Subsurface flow	Lateral flow in steep and shallow hill-slope soils due to effective lateral flow paths (macropores, pipes, highly permeable layers) in combination with low permeable underground (bedrock, impermeable layer), thicker soils with small interaction between macropore flow and soil matrix
		SSF2	Delayed subsurface flow	Lateral flow in the soil due to lateral flow paths (macropores, permeable layers) with medium water exchange to the surrounding soil matrix and low permeable underground (impervious bedrock, impermeable layer)
		SSF3	Strongly delayed subsurface flow	Delayed lateral flow controlled by lateral flow paths in thick soils (macropores, highly permeable layers)
	Vertical flow	DP	Deep percolation	Permeable and thick soils or permeable soils with a permeable geological underground

pasture. This site is located in the Swiss pre-alps near Einsiedeln (33 km south-southeast from Zurich). The shallow, sandy loam Cambisol is situated at the lower end of a 400 m, steep hillside (slope of 55%). The geological substratum of the macroporous soil is sandstone of the Upper (Sub-Alpine) Freshwater Molasse. The C-horizon represents the weathered bedrock and contains sand, stones, and boulders (Figure 2). Below this horizon, rather compact and impervious sandstone was observed. The soil profile has a depth of between 0·5 and 0·9 m. The B-horizon varies from 0·1 to 0·45 m, displaying very small oxidized zones caused by percolating water. The macropores are mostly generated by earthworms and extend down to the weathered zone. The soil bulk density ranges from 1·2 g cm^{-3} (A and B horizons) to 1·5 g cm^{-3} (C-horizon) and the high matrix porosity (55%) decreases slightly with soil depth. This site was selected to investigate the influence of the steep topography on the runoff generation processes. HOF is usually expected on such steep slopes during high-intensity rainfall events, such as was simulated by applying rainfall at 55 to 70 mm h^{-1} for 3 h.

The runoff observed during the experiment is also displayed in Figure 2. After 20 min, subsurface flow started in the trench at the lower end of the plot. Water was observed flowing from macropores and the highly permeable weathered bedrock. The subsurface flow rate increased rapidly, whereas overland flow remained low and constant. With the increase of rainfall intensity after 2 h, the overland flow rate also increased. However, most of the overland flow originated from a mouse hole near the lower end of the plot and should be called return flow.

It is obvious, that very high infiltration rates can occur on steep slopes if an effective system of vertical macropores, is available. Lateral flow paths, such as highly permeable strata of weathered bedrock and lateral macropores, drain the shallow soil efficiently so that soil saturation is not achieved. The experiment demonstrated that subsurface flow can contribute significantly to runoff during intense rainfall storms. However, the rapid subsurface flow was a surprise. It was expected that the sandy soil matrix would need to be saturated first. In the experiment, the matrix was bypassed by the effective macropore system. This observation led to the initiation of a study to investigate the mechanisms governing flow in macropores and the exchange of water with the soil matrix (Weiler and Naef, 2003).

The *Heitersberg* meadow site is located 15 km northwest of Zurich, where a loam Cambisol developed over a loamy moraine of the Riss ice age. A 0·3 m thick A-horizon with rather high bulk density (1·35–1·55 g cm^{-3}) overlies the stony subsoil. A dense network of earthworm channels was visible to a depth of 0·7 m. The plot was sprinkled with an intensity of 100 mm h^{-1} and reacted quite differently from that at *Willerzell*. After only a few minutes overland flow occurred and increased rapidly. Subsurface flow was minor, beginning after about 20 min. Most subsurface flow emanated from some macropores in the profile. Within 1 h, more than 80% of the applied rainfall rate was running off. The process was identified as slightly delayed Hortonian overland flow (HOF2). The existing macropores enabled water to infiltrate the soil, but the weak interaction between macropores and the loamy, low permeability matrix limited distribution of water into the soil profile. During intense storms, such sites rapidly contribute to runoff formation.

The third site, near *Therwil*, is located in the northwestern part of Switzerland, 10 km south of Basle. On the 23% slope used as pasture, a thick, macroporous Cambisol soil has developed. Neither weathered bedrock nor the compact sandstone rock (Tertiary) was reached when excavating the trench (1·5 m). The bulk density of the A- and B-horizons (1·4–1·5 g cm^{-3}) is higher than in *Willerzell* and the soil matrix consists of sandy clay loam. A combination of earthworm channels and soil cracks provide an extended macropore system.

A sprinkling intensity of 100 mm h^{-1} was applied for nearly 5 h. During the first hour, 100 mm of rainfall infiltrated without providing any significant runoff. Then overland flow increased continously, and after 1·5 h minor subsurface flow started. The extended macropore system enabled an effective vertical water transport into the subsoil. The measurements from several soil moisture sensors demonstrated that water flowed rapidly into the deeper subsoil. The sandy soil matrix provided good interaction between the vertical flow channels and the matrix, resulting in an efficient distribution of water in the soil. The observed response was characterized by very delayed saturation overland flow (SOF3). Such sites contribute to runoff only during extended and very extreme rainfall events. The efficient vertical macropore system and the permeability of sandstone strata

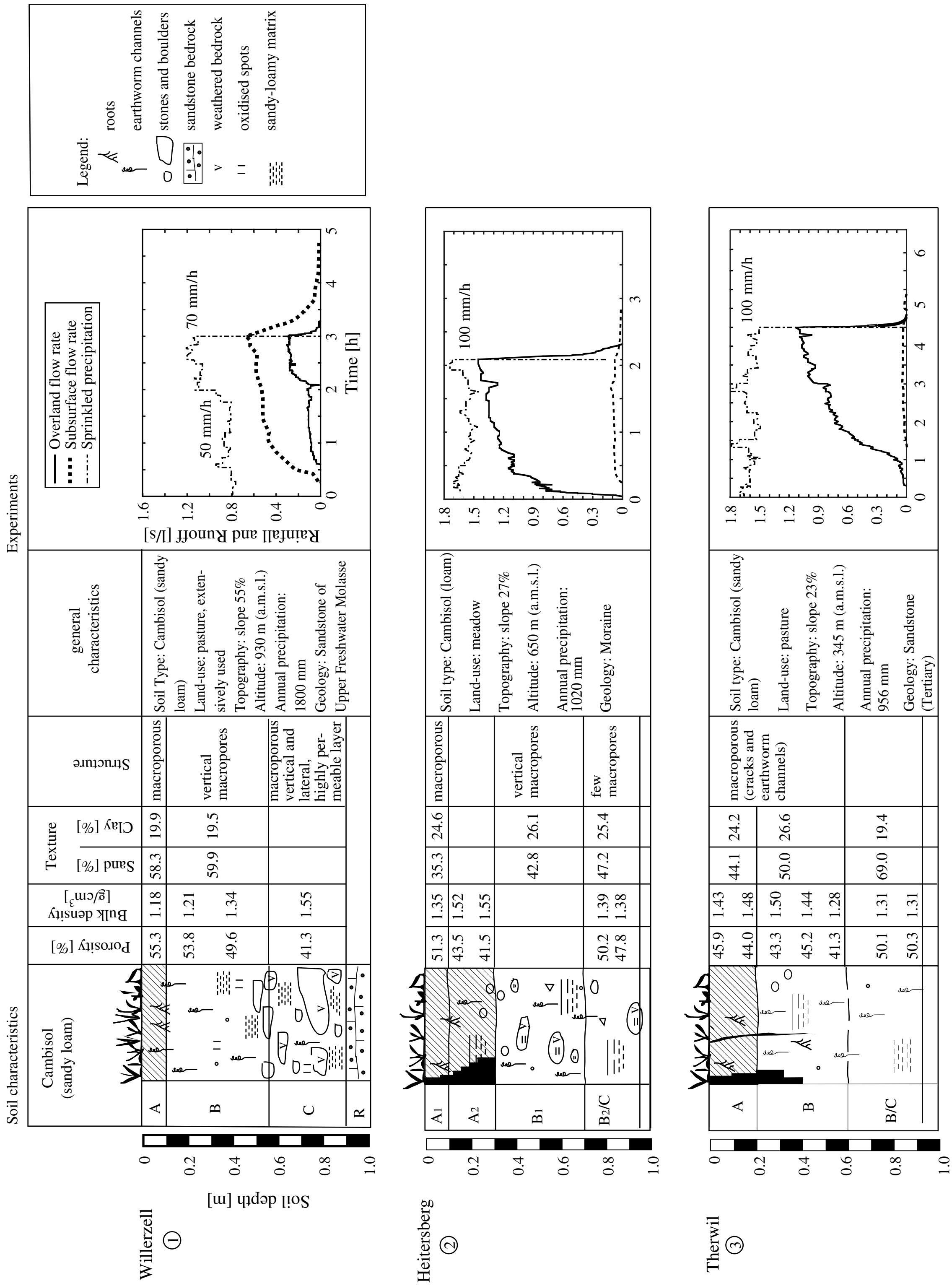

Figure 2. The site and soil characteristics and the hydrographs observed at the experiments performed at *Willerzell*, *Heitersberg*, and *Therwil* (Scherrer, 1996; Faeh, 1997)

provide a high infiltration rate for a prolonged time. The applied rainfall rate of 100 mm h^{-1} over a time period of 5 h is rather extreme. It can be supposed that lower intensities would percolate into the deeper underground (DP) without forming any significant runoff.

DECISION SCHEME TO INDICATE THE DOMINANT RUNOFF PROCESS AT A SITE

In the preceding section it was shown how certain criteria determine which runoff processes actually occur at a particular site. In this section a process decision scheme is presented, which aims to connect the relevant factors. The scheme allows the identification of the dominant runoff processes at the plot scale, using transparent and objective criteria.

Structure and conception of the scheme

Hill slopes have a large diversity of soils and site characteristics. Earlier studies showed that soil type, as an integral classification, cannot be used to explain runoff formation (Scherrer, 1996). Soil type classifications are usually a qualitative assessment based on genesis and particle size distribution or stratification and typically do not consider hydrologically relevant properties. The aim was to develop a scheme to account adequately for the range of processes and characteristics that can operate and interact to produce the runoff observed at a given site.

The 'key points' evaluated by the experimental investigations outlined above provide the framework of the process decision scheme. The structure of the scheme corresponds to a soil column with vegetation cover, topsoil, subsoil, and bedrock. The scheme allows for the combination of different soil and site characteristics. It traces the path of the rainfall water impacting the surface, moving vertically and horizontally into and across the topsoil, and through the subsoil and bedrock. As one moves along the scheme network, decisions are needed concerning which criteria are fulfilled. At the end of a branch, a particular runoff process is defined. Different combinations of physical process criteria can lead to the same form of runoff. As an example, Figure 3 shows the scheme for grassland sites affected by intense rainfall for soils not permanently saturated and not significantly influenced by groundwater. Schemes not discussed here were also developed for other land uses (e.g. arable land or forest).

Application of the decision scheme to a steep pasture hill slope at Willerzell

The *Willerzell* site is again used to demonstrate the application of the scheme. The evaluation path for this site is indicated with a grey dashed line in the decision scheme (Figure 4). The path starts at the surface. In the section of the scheme marked 'surface', the dense grass vegetation cover found at the site leads to the section 'topsoil'. Following the marked path through non-hydrophobic humus to the non-compacted matrix and macropores leads to the criterion of subsoil depth. As the depth of the subsoil does not exceed 1 m, the category 'shallow soils' is reached. The sandy soil shows an intense macropore network and good matrix permeability, which permit vertical flow of water. The impermeable geological substratum and significant lateral flow paths in the weathered bedrock, however, cause an intense lateral flow. Hence, a slightly delayed version of subsurface flow (SSF2) with a significant runoff response is expected.

The evaluation of the dominant runoff process at *Willerzell* is an illustrative example of how site characteristics influence runoff formation. The effective vertical and lateral flow paths induce rapid subsurface flow. In the region of *Willerzell*, however, the geological strata of the Freshwater Molasse is not only overlain by sandy loam but also has regions of clayey marls and conglomerate. How would production change if a typical loamy–clayey macroporous soil had developed at this site on a marl substratum?

The application of the scheme for such a site starts at the same point as for the *Willerzell* site. In the subsoil the same soil depth ($<0{\cdot}5$ m) and low permeability of the bedrock would also be affirmed. The decision path would follow the same trace to slope ($>5\%$) and the question of macropores would also be

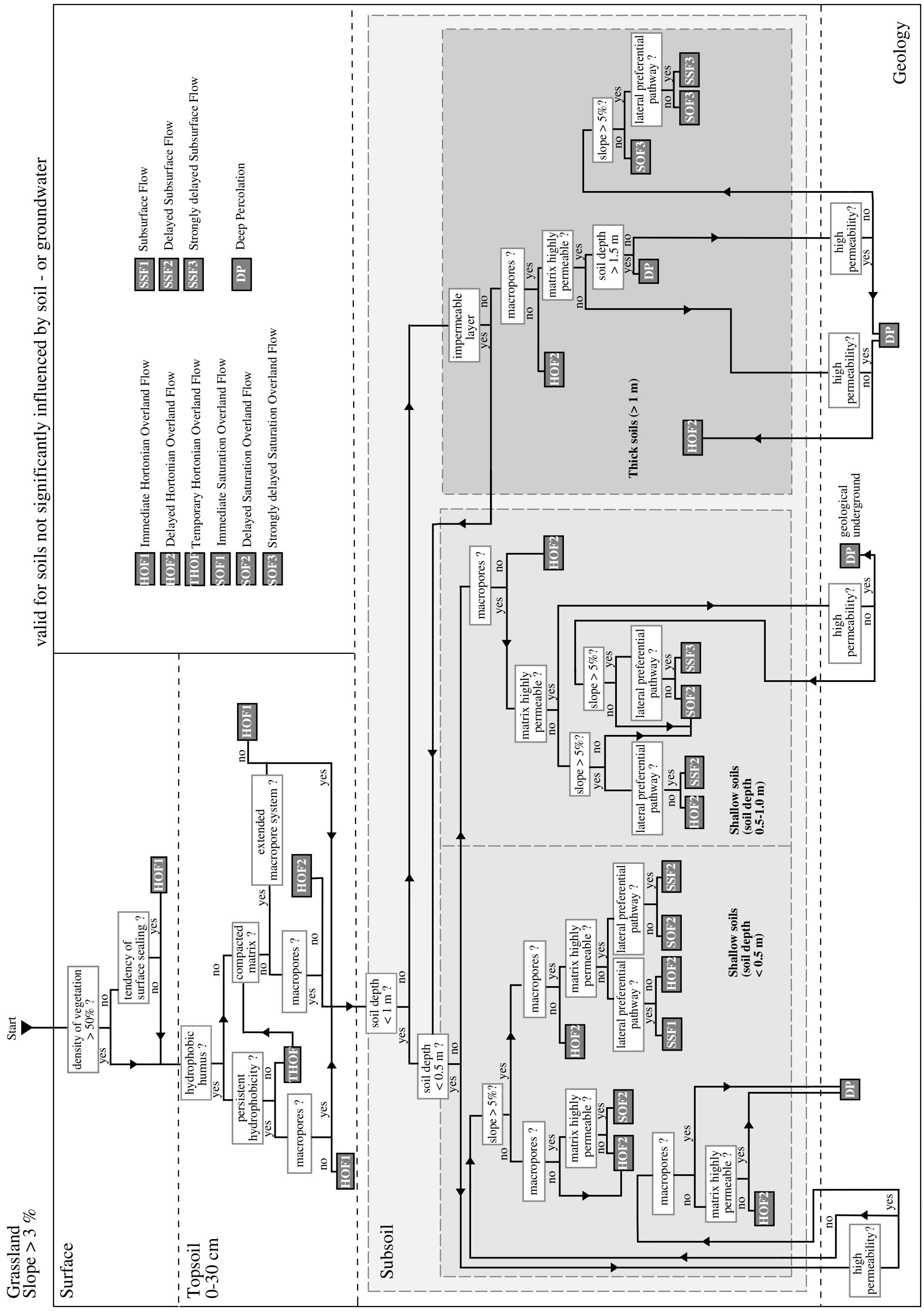

Figure 3. Decision scheme for grassland sites (slope >3%) to evaluate dominant runoff process at the plot scale

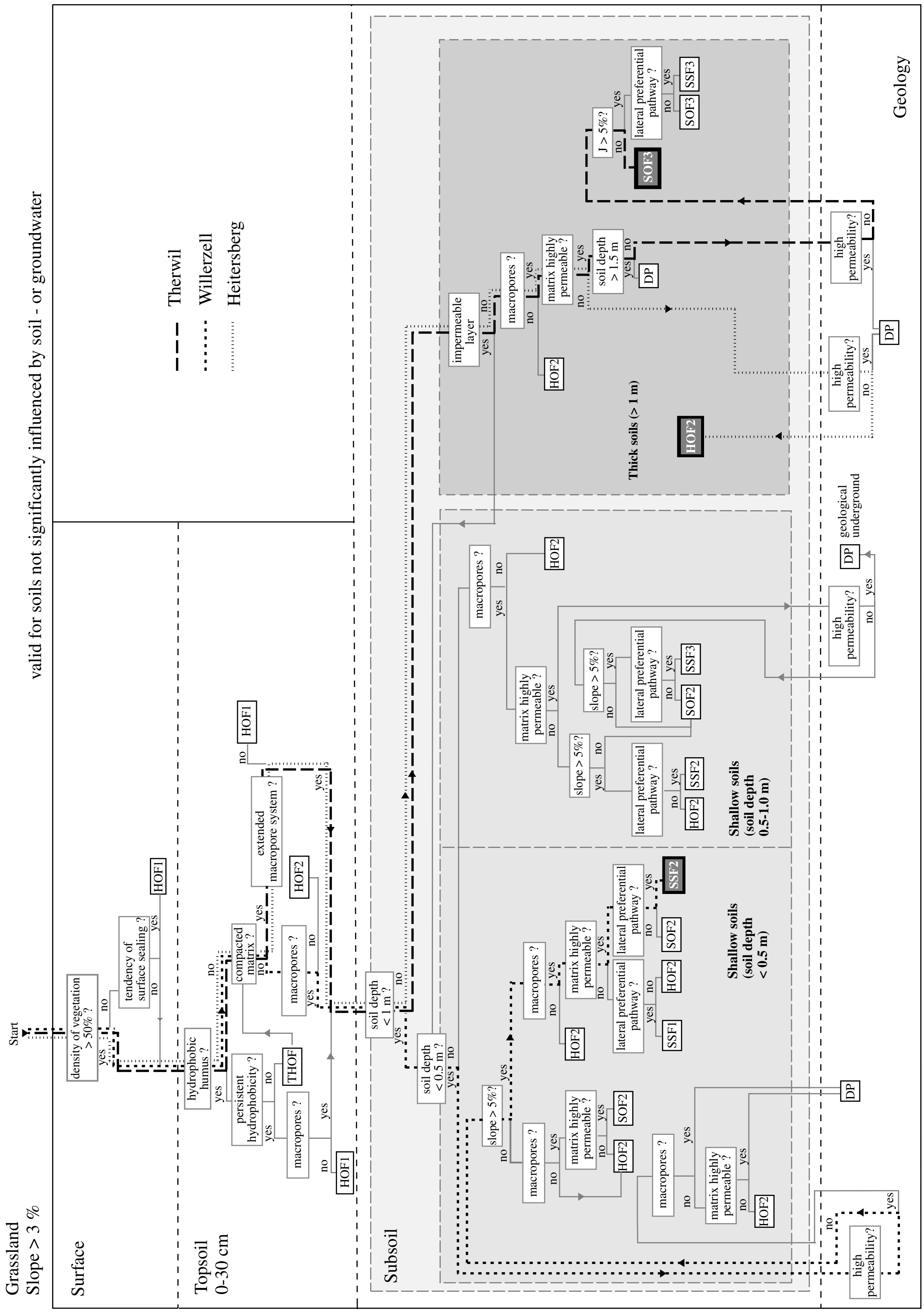

Figure 4. The paths taken when the decision scheme is applied for plots 1–3; ('Normal soils' comprising soils showing no gleying characteristics)

answered positively. However, the permeability of the soil matrix is much lower, and the weathering of clayey marl rock does not produce highly permeable strata. Thus, the lack of lateral preferential flow paths would end the questioning with HOF2 as the dominant runoff process. The well-developed macropore system could transport water deep into soil, but, in contrast to the *Willerzell* site, the low matrix permeability would not allow significant water exchange between the vertical macropores and the matrix. Thus, the subsoil storage would not be filled to capacity, and because lateral flow paths are not present and little water could exit the vertical macropores, Hortonian overland flow due infiltration excess (HOF2) would result.

Application of the decision scheme for Heitersberg and Therwil

The ***Heitersberg*** site had considerably compacted topsoil. The observed macropores were extensive and provided a bypass of the compacted matrix. The macropores in the subsoil were surrounded by a low permeability soil matrix, which limits the exchange of water between macropores and the matrix. The low permeability moraine leads to Hortonian overland flow (HOF) as the dominant runoff process.

The soil developed at ***Therwil*** is similar to that at *Willerzell* with respect to cover, soil texture, and macroporosity. Soil depth, lateral flow paths, permeability of the local sandstone, and the slope angle, however, vary considerably from those at the *Willerzell* site. At *Therwil* the matrix of topsoil was slightly compacted and the infiltrating water bypasses this infiltration hindrance by an extended system of cracks and earthworm channels. These preferential flow pathways enable rapid water transport through top- and sub-soil. The subsoil matrix is permeable, which provides for distribution of water. Bore-holes driven down to the bedrock showed varying weathered sandstone strata. The degree of decay varied from deeply weathered (high permeability) to moderately weathered sandstone (not permeable). Continuous macropores, a permeable soil matrix, and the moderate permeability of the bedrock enable slow saturation overland flow (SOF3). Where there are deeply weathered substrata, DP could be expected.

Limitations of the decision scheme

Rains of low intensity infiltrate into the soil predominantly by matrix flow and the scheme presented does not apply to such conditions. The matrix–macropore system probably only becomes active during rainfall of higher intensities (Faeh, 1997).

Field experiments emphasized the important role of the nature of the surface–topsoil interface for infiltration and runoff formation. As this interface is more complex on arable land (soil compaction, plough pans, surface sealing effects, etc.) and in forests than on grassland, special decision schemes are required for these other land-use types.

CONCLUSION

Sprinkling experiments have allowed development of an improved understanding of hydrological flow processes during intense precipitation. Complex interactions between rainfall, soil, and site characteristics at the hill-slope-scale were responsible for widely differing types of runoff from soils that have similar characteristics. Factors such as the structure of the soil, the stratification, depth, macroporosity, and matrix characteristics influence the formation of runoff. These, however, have to be considered in the context of their actual setting. For example, the permeability of the bedrock influences the occurrence of surface runoff only in a soil with a network of active macropores. Without such a network, bedrock permeability usually plays a minor role. The decision scheme presented here, which is structured like a soil profile, contains the important concepts and physical interdependencies and represents the current understanding of the authors of the main runoff formation processes at the plot scale. Currently, the scheme is under test in different catchments by workers not involved in its development. To this end, guidelines have been prepared to make possible an objective assessment of the parameters in the field.

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