Integrated Process Studies to Simulate Hillslope Hydrology and Interflow Dynamics Using the HILLS Model

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Abstract Research studies about the hydrological dynamics of hillslope drainage by interflow have been carried out on test slopes in the Bröl catchment, located in the region Bergisches, Rheinisches Schiefergebirge. The overall objective was to simulate soil moisture, interflow and groundwater level with a high resolution in time and space using different measurement stations distributed along a cross section of a test slope. For the modelling study the two-dimensional numerical hillslope model HILLS was applied. By using a detailed time-series of measured data for evapotranspiration (ET), precipitation, runoff and groundwater such rainfall events producing interflow could be identified and analysed, revealing insight into the complex process structure of the hillslope hydrology. The results from the modeling exercise clearly demonstrate the ability of the model to simulate interflow and to reproduce the measured field conditions. However, extreme hydrometeorological periods such as summer storms falling on very dry soils were simulated dissatisfying. This is probaply caused by the generalization of the soil-physics in the model if compared to the complex structure of the permeable and impermeable of the test slope.

1. INTRODUCTION

Interflow is considered to be of high importance for generating river runoff in mountainous catchments (Flügel, 1995). To investigate the dynamics of interflow in the slopes of the Rheinische Schiefergebirge, a research project was initiated in 1994 and first results from the intensive field investigations and modelling exercises are presented in this paper. In 5-minute time intervals at seven selected hillslope locations of a test slope (Kiefer-slope) soil moisture measurements were carried out and all relevant hydro-meteorological parameters were monitored in a wea-ther station. The data base was then used for validating the simulations obtained with the HILLS model (Herbert and Smith, 1992).

2. STUDY AREA

The test slope (Kiefer-slope) area is located in the Bergische Land approx 30 km northeast of Bonn within the catchment of the River Broel, Rheinisches Schiefergebirge (Figure 1). The catchment is located in the lee of the Köln-Bonner-Bucht and is about 216 km² in size. The underlying geology is Devonian shale and Grauwacke, considered as being impermeable for deep percolation. Its climate is oceanic influenced and characterized by a mean annual (i) precipitation of 1039 mm, (ii) calculated evapotranspiration 536 mm ,and (iii) temperature of 8.5°C. Land use of the catchment consists of 50 % grasing, 34% forest, 4% farmland and 12 % settlements (Bende, 1994).

2.1 The Kiefer Test Slope

The Kiefer-slope represents the typical hillside form to be found in the catchment: a convex head changes into a slope with even gradient which in turn changes into a convex foothill and flat valley floor. The grass of the slope is cut twice a year and no grazing takes place.

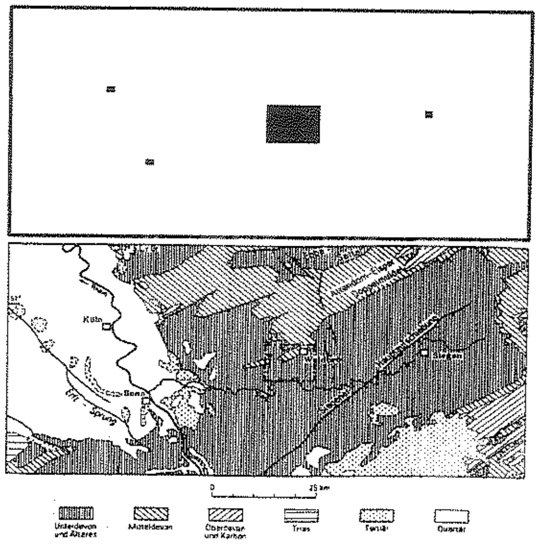

FIGURE 1: Geological map of the study area.

The Kiefer slope is exposed north-northwest, having a cross profile length of 174 m (Fig. 2). At the upper and middle part of the slope former agriculture has resulted in eroded brown soils. In addition a small hollow has formed which clearly was depicted from the cross profile drilling. It will be shown below that this hollow is also of importance for the interflow dynamics generated within the hillslope. The foot slope is covered by colluvial sediments eroded from the hillslope during the past agriculture usage. Deep hydromorphic brown soils are changing over to groundwater influenced gleyic soils in the small valley floor. Here the groundwater level is close to the surface and is draining directly towards the Breidenbach as the nearby receiving creek.

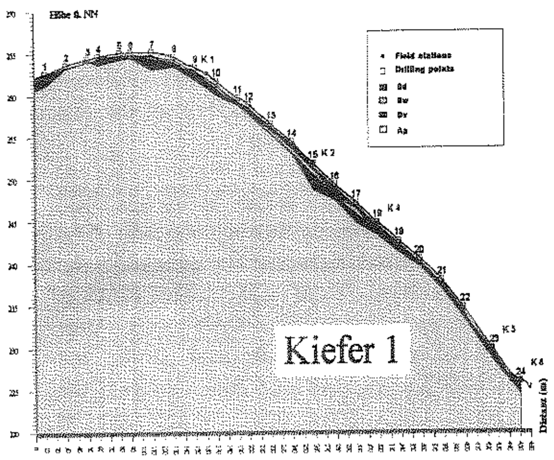

FIGURE 2: Cross section of the test hillslope.

2.2 Instrumentation

Altogether seven field stations **K1 - K6** (Figure 2) have been installed along the cross profile and data-loggers are recording soil moisture, groundwater level and meteorological parameters such as rainfall, temperature, radiation wind speed and humidity at 5-minute intervals. The meteorological station **K1** (Figure 2) is situated on top of the profile and here soil tempratures have been recorded as well. Soil moisture was measured using pressure transducer tensiometers which were prepared in such a way that also during the winter season measurements could be recorded.

2.3 Field Station K6

Soil physical parameters of the station K6 in the foot slope of the cross section are listed in Table 1. This station was used to calibrate the simulation results and the HILLS-model parameterizations. However, similar parameters have also been collected for the other stations along the slope cross section. They are in line with data given by Scheffer and Schachtschabel (1989) for similar soil profiles. Based on this literature review, the physical parameters derived from the test slope can also be regionalized for the Bröl Catchment as such.

TABLE 1: Soil physical parameters at station K6

soil horizon	text-ure	PV (%)	BD (g/cm^3)	kf (m/s)	FK (%)
Ah	lU2	54,1	1,12	1,55E-05	49,3
Bv / Go	lU2	54,1	1,10	3,80E-05	46,8
Go / Gr	lU2	43,0	1,46	3,46E-06	39,3
Gr	lsU	41,7	1,50	2,23E-07	35,6

PV = Pore Volume; BD = Bulk Density; kf = Saturated Conductivity; FK = Field Capacity

3. HYDROMETEOROLOGICAL DATABASE

The meteorological database was generated from data recorded in station **K1** on top of the hillslope (Fig. 2). The database will briefly be discussed by using the hydrological year 1995 as an example. Beside the measured data ET was calulated by means of the Penman-Monteith model (ASCE 1990), which was inbuilt into HILLs for this simulation study.

3.1 Climate

According to (Flügel 1981, 1993, 1995; Schroeder 1990) precipitaion as major water input controls the soil water and interflow dynamics of a hillslope system. The sum of precipitation in the hydrological year 1995 amounts to 1176 mm with a daily maximum of 58.2 mm (December 1994). Altogether 63 % (746 mm) of the annual total was received on the slope during the winter halfyear between November 1994 and April 1995.

In comparison to the rainfall input, output by evapotranspiration during the entire hydrological year 1995 was calculated at about 672 mm of which the vegetation period (May - October) accounts for 80% (537mm).

According to this rainfall-ET distribution over the hydrological year the winter half-year is characterized by high precipitation and continuously small ET-rates, and the summer season by high ET-demand by almost the same amount of rainfall input. Consequently groundwater recharge by interflow is concentrated in the winter half year and was observed frequently during this period. During the winter season the soil water content is high and the almost saturated soils have high conductivity rates (Hartge and Horn 1991). These initial conditions directly affect groundwater recharge and the generation of river runoff by interflow as discussed in section 3.2.

The water balance for the winter halfyear (Figure 3) shows a surplus of 611 mm resulting as difference between the 746 mm precipitation input and the 135 mm output by ET. This surplus infiltrates into the soil, as surface runoff was not observed on the slope, and fills up the soil storage till field capacity is reached. Excess water infiltrates and percolates till it is reaching the underlaying impermeable Devonian shale generating interflow which flows laterally downwards towards the valley floor. Here it recharges the groundwater aquifer and generates the runoff of the Breidenbach.

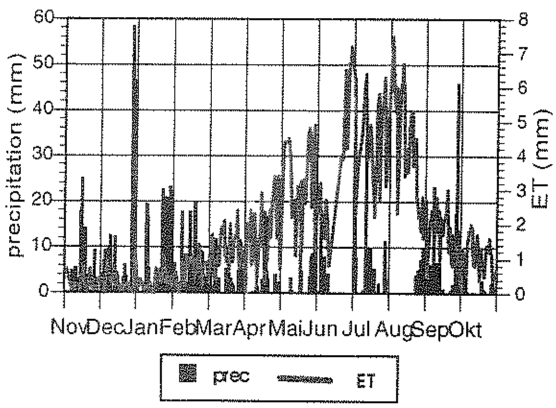

FIGURE 3: Precipitation and ET during the hydrological year 1995.

In the summer period 430 mm precipitaion are received but potential ET is about 537 mm. Therefore most of the precipitation evaporates, with the exception of summer storm periods with high rainfall input into the system. However, according to Kutilek and Nielsen (1994) such periods are rather seldom and not characteristic for the summer interflow dynamics.

The potential ET of the summer season is accounted for by the soil water stored in the soil during the winter halfyear. Precipitation input received from summer storms only disturbs the drying dynamics on a short-term basis without generating considerable interflow. Such storms mainly fill up the available soil water storage for the consecutive consumption by the vegetation (Flügel 1993, 1995; Richter 1986).

3.2 Groundwater level and runoff

Station **K5** at the footslope and **K6** in the valley floor (Figure 2) also record the levels of the groundwater and in the Breidenbach creek. By means of such measurements the lateral inflow as interflow and the runoff generation can be analysed. Interflow is mainly restricted to the winter half-year (Flügel 1993, 1995). By using the soil physical parameters (Table 1) interflow is computed by the HILLS model and is calibrated in this study by means of the measurements obtained from stations **K5** and **K6**.

The process dynamics of soil moisture, groundwater level and runoff will be represented by using the interflow event observed in January 1995. By using the concept of the of the interlinked unsaturated/saturated zone termed "dynamic storage" (Barsch and Flügel 1988; Flügel 1993) an insight into the process structure active on the test slope can be derived.

During a rainfall event, water infiltrates and vertically moves downwards through the soil. The response of the various tensiometers indicating the advancing infiltration front (Richter 1986) is delayed according to the depth of installation. After percolation through the unsaturated zone the infiltration front hits the saturated zone on top of the Devonian shale and a lateral interflow dynamics is generated which is almost parallel to the slope.

At the foothill zone the gradient controlling this flow dynamics decreases considerably and interflow is recharging the groundwater as well as increasing the storage of the unsaturated overlying soil zone. As groundwater cannot flow as fast into the Breidenbach the inflowing interflow is dammed up and the groundwater aquifer starts to extend from the valley floor into the footslope zone. This can be seen by a delayed increase of groundwater levels measured in station **K5** a compared to such measured in station **K6**. The runoff of the Breidenbach creek receives direct inflow from forest roads as well as interflow. The latter can be observed by a distinct peak as shown in Figure 4.

The temporal sequence discribed above is a typical response of the "dynamic storage" in the valley floor and was frequently observed during the three winter half-years.

4. MODELLING

Modelling of the interflow dynamics was carried out by means of the two-dimensional HILLS-model. It is a numerical simulation model which links surface runoff, unsaturated and saturated subsurface flow into a two layer and two dimensional hillslope (Hebbert and Smith 1992).

The time interval used was 5 minutes and was obtained from the hydrometeorological project database. Potential ET was calculated according to the Penman-Monteith equation. The soils of the slope are defined by two layers, of which the lower one is regarded as almost impermeable generating interflow from the percolating rainfall.

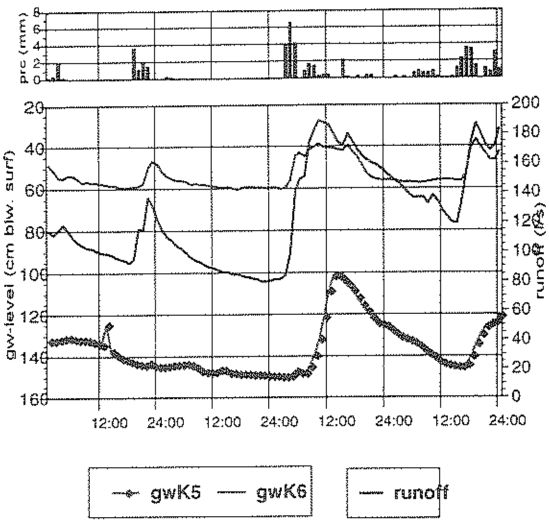

FIGURE 4: Groundwater and runoff at the stations K5 and K6 between 26. - 29.01.1995.

The upper soil layer was physically described by using the soil survey carried out on the slope cross section. The most important control parameters to which the calibration of the model is sensitive to are: (i) soil porosity; (ii) saturated vertical hydraulic conductivity of the surface soil; and (iii) anisotropy factor, which relates the horizontal to the vertical hydraulic conductivity and (iv) the depth of the perched water table at the bottom end of the hillslope.

The hillslope geometry can be set by up to 20 junctions, at every individual one the position on the slope, the thickness of the unsaturated soil and the inclination must be defined. Along the slope HILLS permitts the setting of two checkpoints at which the changes of the perched watertable in relation to the impermeable layer are calculated. These points are essential for the the calibration of the model and were set in the simulations according to the locations of the groundwater levels installed in station **K5** and **K6**.

The modelling of a 4-month time period in the winter season is given in Figure 5 and shows a pretty accurate simulation of the measured groundwater dynamics at **K6**. The measured groundwater peaks are reproduced fairly well. A temporal delay according to the precipitation input is hardly to be seen except of the extreme rainfall event at the end of Janaury 1995. Here HILLS simulates the groundwater peak which was not observed as such.

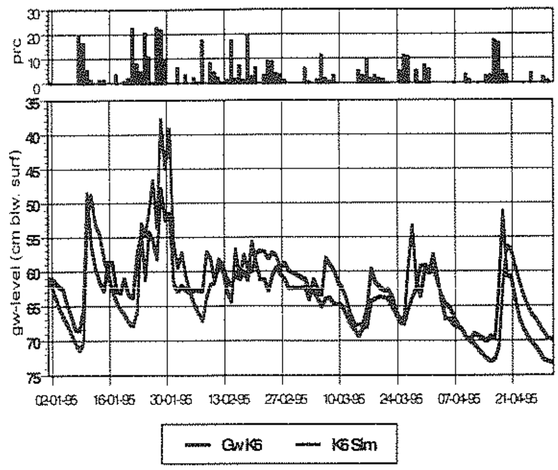

FIGURE 5: Simulated groundwater level at station K6 between 01.01. - 30.04.1995.

Using daily data calculated from the 5-minute values the hydrological dynamics of the Kiefer-slope was simulated for a time period of ten months, and the results are shown in Figure 6. During this 10-month simulation period different hydrometeorological conditions were observed which are described by constant model parameters throughout the simulation.

During the summer period the soils were drying out and the interflow dynamics almost completely ceased. In the case of high rainfall events the model tends to overestimate the corresponding groundwater rises. The drying out of the soil during the summer period was not reproduced by the model in a accurate way. However, again short time peaks in the groundwater dynamics resulting from lateral interflow out of the slope were fairly accurately reproduced temporal and according to their dynamics.

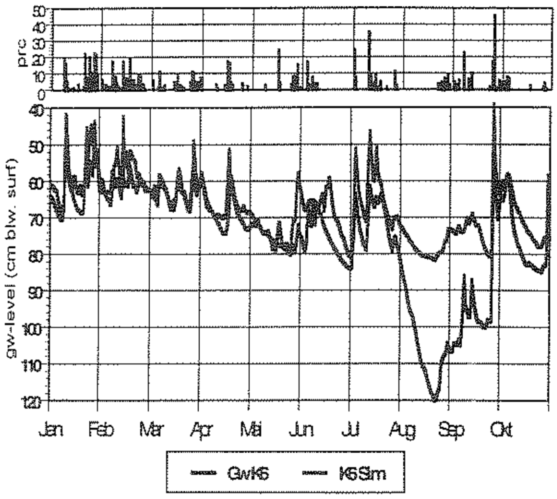

FIGURE 6: Simulation of groundwater levels at K6 between January and November 1995.

The interflow dynamics on the slopes of the entire catchment area of the Breidenbach creek measured in **K6** seems to be completely controlled by the draining of interflow out of the adjacent slopes.

This can be deduced if the modeled interflow output of HILLS is compared with with the measured runoff in the Breidenbach creek as is done in Figure 7. From Figure 7 it can be seen, that both graphs are showing a good agreement between the simulated interflow seepage and the measured runoff of the Breidenbach.

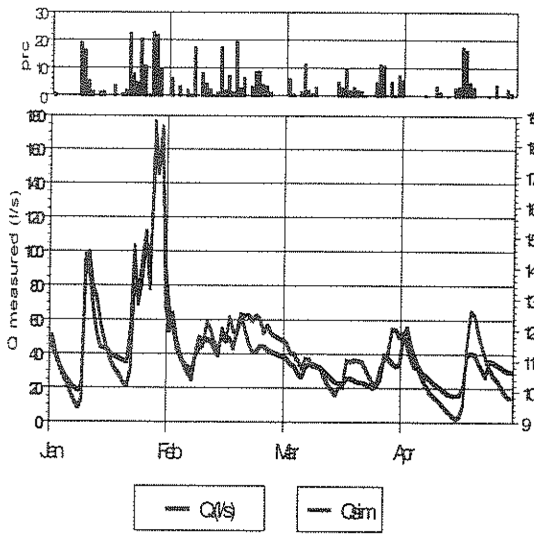

FIGURE 7: Comparison of measured runoff and simulated outflow from the Kiefer test-slope.

5. CONCLUSIONS

The modeling results presented above indicate that the HILLS model simulates the observed dynamics of the test slope quite well. The water balance of the Kiefer-slope was reproduced correctly and its observed interflow dynamics could be reproduced. Extreme events still have to be looked at in more detail considering the findings of Hebbert and Smith (1990).

However, the study also indicated that such results can only be obtained if intensive data recording on representative test slopes is carried out. It will be a future research task to evaluate the potential of the results obtained for regionalization to the catchment of the River Bröl or even the River Sieg to which the Bröl is a tributary.

The description of the distributed physiographic heterogeneity of such catchments will be adressed in more detail in future studies. Soil physical parameters used will be especially looked at and statistical distributions describing their spatial variabilities will be evaluated.

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