# HYDROLOGICAL PATTERNS AND PROCESSES OF A DEEP SEATED CREEPING SLOPE AT EBNIT, VORARLBERG

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## ZUSAMMENFASSUNG

Massenbewegungen werden häufig durch Niederschlag ausgelöst, dabei spielt einerseits die Infiltration in die ungesättigte Bodenzone eine Rolle, andererseits können Änderungen des Grundwasserspiegels zum Versagen führen. Um den Auslöser von Bewegungen besser verstehen zu können, müssen die hydrologischen und hydraulischen Flüsse besser verstanden werden, die eine Massenbewegung dominieren. Bereits abgegangene Rutschungen verhindern in der Regel die detaillierte, prozeßbasierte Untersuchung hydrologischer Prozesse. Die untersuchte Massenbewegung liegt in den Vorarlberger Alpen und wird durch ein extremes hydrologisches Regime beeinflußt. Eine detaillierte Identifikation hydrologischer Prozesse sowie eine physikalisch basierte hydrologische Modellierung werden hier vorgestellt. Die Felduntersuchungen zeigen, dass die Massenbewegung durch Oberflächenabfluss dominiert ist, eine Tiefenversickerung dahingegen ist unwahrscheinlich. Benachbarte Bereiche zeigen eine schnelle Infiltration und wirken durch eine laterale Druckweitergabe auf das Grundwassersystem der Massenbewegung.

**Keywords:** prozeßbasierte Hydrologie, Hangrutschung, Kriechen, hydrologische Modelle, Vorarlberg

## ABSTRACT

Many mass movements are driven hydrologically through precipitation and infiltration in unsaturated soils and subsequent groundwater fluctuations. For understanding the role of flow paths and flow dynamics of infiltrating water in the subsurface, hydrological active structures are considered responsible for fast preferential flow and transport. In mountainous regions, high relief gradients are an additional factor driving fast hydrological processes. It is also of great importance to understand dominating hydrological thresholds to appropriately account for critical trigger situations, e.g. certain climatic conditions. The mass movement investigated in this study is of a slow creeping type. It is located in the Vorarlberg Alps where high precipitation depths govern surface and subsurface hydraulics. The research is aimed to better understand hydrological processes and triggers of mass movements. The approach is a detailed field investigation coupled with the use of physically based hydrological models. The field investigation, including a geobotanical determination of hydrotopes, revealed that the mass movement body is dominated by surface runoff generation and that seepage to groundwater is inhibited. The reason for fast changes of the groundwater level is found in adjacent areas with high infiltration capacities and a fast pressure propagation towards the mass movement's groundwater system.

**Keywords:** process based hydrology, landslide, creep, hydrological modelling, Vorarlberg

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## INTRODUCTION

Many mass movements are related to extreme hydrological events, for instance think of the Rufi-landslide which failed in May 1999 (Eberhardt *et al.*, 2005) or the August 2005 events in Austria (BMLUFW, 2006) and Switzerland (MeteoSchweiz, 2006). Investigation of the triggering hydrological event and a related landslide mostly starts ex post, i.e. after the landslide event. This hampers of course our understanding of the most important hydrological and geological control mechanisms and how the system evolved to this critical state. Additionally, many studies are hampered through the lack of sufficient hydrological data sets which are needed to close the water balance of the investigated site.

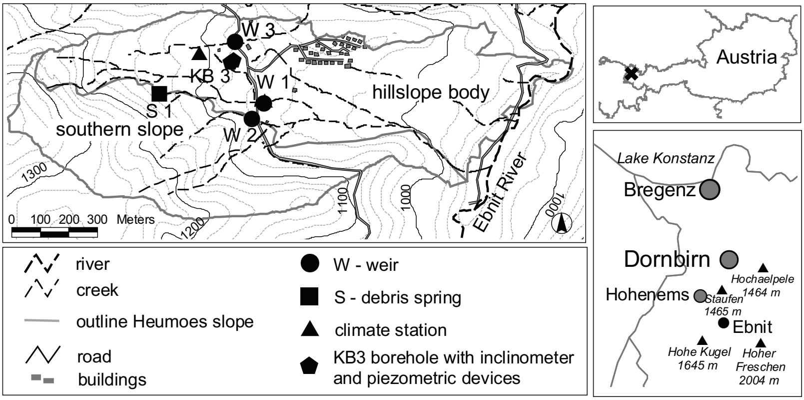


**Fig. 1:** Location and measurement set-up of the Heumös slope south of Ebnit village. A hydrometeorological station, three discharge weirs, one spring discharge weir as well as boreholes equipped with inclinometers and piezometers are located on the slope and in adjacent areas. A small holiday village is located on the Heumös slope as well.

Deep seated landslides are often considered to be triggered by groundwater level changes which are induced by long lasting wet periods over several months (Schuster & Wieczorek, 2002; van Asch *et al.*, 1999). This might be true for the majority of systems, but might also be an effect of observation inter-vals ignoring fast processes.

The objective of our study is to pro-vide insights on how slow geo-mechanical pro-cesses are affected by relatively fast hydrological and geo - hydrological processes that could lead to a critical system state. We employ a twofold study approach:

- Set-up of a nested observation network to observe hydro-meteorological key variables, geological setting, and identify patterns of key parameters in the subsurface. Additionally, the movement was and is monitored at the surface and subsurface. The field investigations started with mapping of areas with specific hydrological dominant characteristics (hydrotope delineation) and were followed by detailed plot-scale investigations.
- Combine these data with process model studies to shed light on the spatial patterns of key processes such as infiltration and subsurface flow dynamics. The application of a physically based hydrological model (CATFLOW, Zehe et al. (2001)) helps to understand the dominating processes and to close the water balance of the subsurface system.

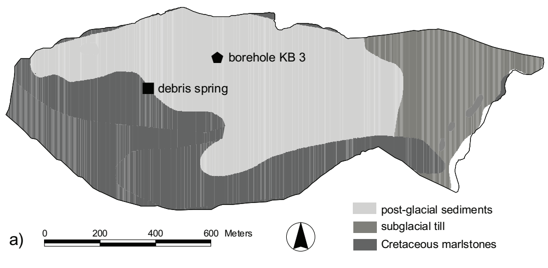
This case study will show that detailed hydrological investigation of deep seated landslides is needed to understand the fast hydrological processes which might be the mechanism that switches the slow shear zone development of an unstable hillslope into the fast failure process of a catastrophic landslide.

## STUDY SITE

The study site is located in the western Vorarlberg Alps at Ebnit village near Dornbirn, Austria (fig. 1). The so called “Heumös slope” extends from 960 to 1360 m above Adria; it is about 1800 m long and up to 500 m wide. The slope can be parted into two major areas: the 7“southern slope” has very steep angles, rock outcrops and otherwise a thin soil cover. It belongs to the hydrological catchment area of the Heumös slope but is not the major moving part. The actually eastwards moving part is located north of the southern slope. This area is called the “hillslope body”. It is less steep and exhibits a thick sediment cover of up to 30 m.

### Geological setting

The geological setting favours the development of mass movements. Cretaceous marlstones and limestones surround the Ebnit area and the Heumös slope (fig. 2). Glaciation left several meters of subglacial till in different states of compaction and stability. Post-glacial development means erosion through the Ebnit River and the removal of the counter bearing of the slope in the east. It also means accumulation of debris material on top of the subglacial till and bedrock. These post-glacial sediments have their origin in the steep slopes of marlstones and calcareous marlstones of the Amden and Wang formations, which are exposed in rock scarps in the south of the hillslope body. It is the composition of the marlstones and their high susceptibility to physical and chemical weathering which helps to develop a critical composition of the post-glacial sediments that makes it prone for movement.



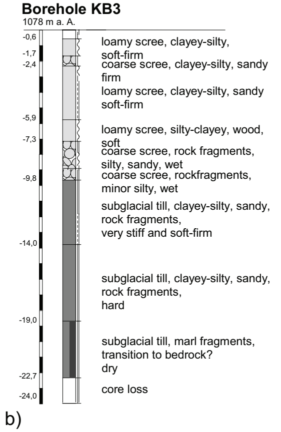


**Fig. 2:** Overview of geological units and layers in borehole KB 3 a) and b). A weak shear zone is observed in the coarse scree layer in 7.5 to 8.5 m depth. Technical reasons inhibited drilling into the bedrock, which is located below 24 m.

Several processes led to a very heterogeneous build up of the post-glacial sediments during the last 10000 years: accumulation of debris from the adjacent hillslopes (e.g., rock fall, mud flows), erosion by creeks or small scale slides and different weathering conditions over time (e.g., freezing or soil development). Basically, coarse scree material was deposited in earlier times and then soil development lead to the development of loam in more temperate climate. The post-glacial sediment composition is very heterogeneous and can be best described with two end members concerning grain size distribution: on the one side, there is a coarse scree consisting of sub angular marlstone clasts. On the other side, there is a gravel free loam, comprised of silty clay. The clay sized material consists mainly of clay minerals (illite, kaolinite, smectite), carbonates (30-40 %) and quartz. Stronger weathered samples have a higher smectite content. Soft or stiff clay layers might be underlain by very soft clay layers which enhances the susceptibility for movement (Lindenmaier, submitted).

### Hydrological environment

The nearby Ebnit climate station (Hydrographischer Dienst Vorarlberg, Austria) records an average yearly precipitation depth of 2100 mm. The data shows the influence of the westwards opening Vorarlberg Alps which enhance precipitation through orographic lifting. The Bodensee (Lake Constance) further enhances convective storm events, which is reflected in higher precipitation depths in the months April-September with average monthly depths of 150-250 mm. October-March have average monthly depths of less than 150 mm. Storm events in summer have a high precipitation intensity and a considerable precipitation depth. Events with 30-40 mm of precipitation in less than 12 hours are common. On the other side of extremes there are long lasting events with high precipitation depths, e.g. the May 1999 events with two times more than 210 mm in 3 to 5 days (10.05.1999 and 20.05.1999). The long lasting events readily lead to the development of small scale and shallow slides and small scale mudflows in the Ebnit river area. Considerable movement at the deep seated shear zone could not be observed during or after such events, but this is also in relation to observation intervals of movement. We rather think that a succession of small high intensity events do have a larger effect on deep seated movement than long lasting precipitation periods or a snow cover.

### Movement characteristics

Surface deformation was measured during three campaigns each year (Depenthal & Schmitt, 2003) with GPS equipment from 1995-2001. Measurement intervals gap between 3 and 6 months (May, August, November). About 25 points were marked and measured with GPS equipment on the meadows and 15 points were marked in the forested eastern part for terrestrial measurement. Surface movement is about 10 cm per year west of the borehole KB 3 (fig. 1). In the mid part, near the holiday village, movement is less with 0 to 5 cm per year. The terrestrial points east of this village show higher yearly movement rates of more than 10 cm. Lateral movement is more pronounced than vertical movement. For several points, a periodicity with maximum movement rates per day peaks in November and is at minimum in August. A relation to long term hydrological signals cannot be established as these are on faster process scales.

Subsurface movement was measured with an inclinometer device in KB 3 and is approximately 0.7 cm a year in 7.5 to 8.5 m depth (Schneider, 1999, fig. 2b). This is the transition between post-glacial sediments and subglacial till. A second shear zone is assumed to be at the transition between subglacial till and bedrock, but technical reasons inhibited measurement there. This will be overcome with recently drilled boreholes equipped with inclinometer and piezometer devices. A relation between surface and subsurface movement could not be established yet as data sets are not exhaustive enough. But likely, different processes lead to movement at different locations.

## OBSERVATION NETWORK AND FIELD METHODS

A hydro-meteorological observation system has been established in 1998 (Lindenmaier *et al.*, 2005). Besides climatological variables and precipitation, soil moisture in several depths as well as creek discharge and spring discharge are observed (fig. 1). Debris transport and clogging of the weirs of the three observed creeks (W 1-3) often hampers exact discharge measurements due to changing rating curves. Nevertheless, by excavating the weirs regularly, time periods with good quality observation could be achieved.

Groundwater level changes were recorded with piezometer devices in 1998 in borehole KB 3, which is located on the central hillslope body, in about 280 m distance from the debris spring S 1 (fig. 1). Piezometers are set in 5.5 m and 12 m depth. The devices failed in September of 1998. Unfortunately, surface runoff recording in the three weirs (fig. 1) and the debris spring started just afterwards. Overlapping time series are almost non-existing, due to the early failure of the piezometer devices.

**Fig. 3:** Map of ecological moisture index. Hydrotopes 1-4 were delineated with the help of topography, ecological moisture index and soil type definition.

A detailed soil and vegetation analysis was conducted with 49 soil cores, which were identified after the German soil classification system (AG Boden, 1996). At each soil core a vegetation analysis was undertaken for the major plants after Ellenberg (1996) and an ecological moisture index was calculated for vegetation patches. The vegetation distribution and soil definition was used to develop an ecological moisture index map (fig. 3).

Soil hydraulic conductivity was determined with constant head permeameter tests after a method of Amoozegar (1989) in 12, 20 and 50 cm depth. Two key areas, one in the forested southern slope and one on the hillslope body which is mainly covered by meadows were chosen. Additionally, hood infiltrometer tests were conducted on the surface to get information about the infiltrability on the surface. The hood infiltrometer device (UGT, Germany) is designed to allow infiltration on the undisturbed soil surface with zero tension (Zimmermann *et al.*, 2006). A saturated hydraulic conductivity of the surface layer is measured. Slug tests (Butler, 1998) were conducted in 1-2 m depth in window sampling holes.

To better understand small scale flow behaviour we stained soil patches with a dye tracer (Brilliant Blue FCF) and removed the stained soil layers in 5 cm steps to visualize flow paths in the soil column (Flury & Flühler, 1995; Zehe & Flühler, 2001). On the hillslope body, 30 litres of stained water were applied on a steep grass covered plot (1 m²). On the southern slope the same amount of stained water was applied on a 1 m² plot of forest floor.

## IDENTIFICATION OF DOMINATING PATTERNS AND PROCESSES

### Soil and vegetation distribution

The Heumös slope catchments are covered with meadows and mixed forests of spruce and alder. Soil identification revealed stagnic and gleyic gleysols on the hillslope body and clay-rich leptosols on the steep southern slopes. The dominance of clay bearing fast weathering source rocks means that all soils have a more or less similar grain size distribution. This complicates the identification of dominating hydrological processes of specific soil systems on the slope as grain size distribution is classically used to determine heterogeneity of an area. This is why a key role in process identification was given to a combined soil and vegetation analysis. A moisture index which describes the water demand of a specific plant was used (Ellenberg, 1996). The ecological moisture index represents the long term water budget of the root zone in a single value, and thus allows for comparison of different ecohydrological regimes (fig. 3). Vegetation patches with dry ecological moisture indicate fast preferential infiltration, e.g., on steep slopes. Patches with wet ecological moisture distribution indicate soils with stagnic properties where surface runoff generation is dominating.

With the help of the ecological moisture distribution combined with topography, four hydrotopes with specific characteristics could be identified (fig. 3). Focus here will be on hydrotope #1 and #2. Hydrotope #1 is dominated by leptosols, rock outcrops and is very steep. Hydrotope #2 is the upper part of the moving hillslope body which features stagnic gleysols on a less steep surface and which has significantly higher ecological moisture values than hydrotope #1. The different moisture distribution in hydrotope #1 and #2 show that there must be also different hydrological processes dominating the soils, as soil texture is quite similar for all soils.

**Variability of hydraulic conductivity**

The sampling number for the hydraulic conductivity ($K_{sat}$) measurements is not high enough to conduct geostatistical analysis, but some major findings can be concluded from the measurements (fig.4). 1) The surface infiltrability is high on the meadow: an average of $9*10^{-3}$ m/s indicates a high conductivity layer in the uppermost soil surface. Observation verifies this finding as a thin organic layer functions as a very shallow interflow layer there (see next section). 2) Towards depth, the hydraulic conductivity decreases. The constant head permeameter values indicate this. Very low conductivities of $1*10^{-9}$ m/s are found in 1-2 m depth. 3) The variability of the hydraulic conductivity is large, it can range over 4 orders of magnitudes (forest, 12 cm; fig. 4). This high variability is in contrast to the clay rich soils encountered both in hydrotope #1 and #2. It shows that these soils must be dominated by preferential flow paths, and that matrix water flow is only of secondary importance. A closer look on the soil structures will be taken in the following to get a better idea of water flow in these clay rich soils.

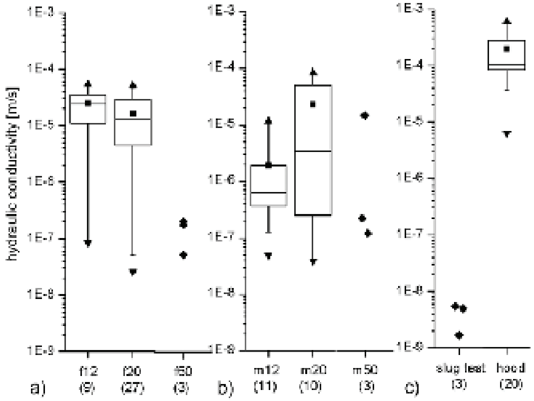


**Fig. 4:** Soil hydraulic conductivity (Ksat) and infiltrability in box plot display: a) Ksat of constant head permeameter measurements in the forest in 12, 20 and 50 cm depth; b) Ksat of constant head permeameter measurements on the meadow in 12, 20 and 50 cm depth; c) Ksat of slug tests in 1-2 m depth and hood infiltrability values at the soil surface. Number of samples in brackets.

Box plots present essential aspects of a sample distribution. The box shows the spread of the central 50 % of a distribution, where the lower limit is the first quartile and its upper limit the third quartile. The middle bar represents the median. The square represents the average of the sample distribution. The whiskers are the 5 and 95 percentiles. The box plots also show the 1 and 99 percentile, represented by triangles. There are no outliers.

**Observation of flow patterns**

Figure 5 shows pictures of stained plots. In hydrotope #1 the water flew in a distinct network of shrinkage cracks and seeped between soil column and bedrock. The preceding dry weather resulted in shrinkage cracks with an aperture of more than 1 cm in 25 to 50 cm depth. In wet conditions, these cracks are more closed but still function as a hydraulic active fissure system. In addition, macropores and soil pipes with diameters of up to 10 cm enhance fast infiltration and preferential flow there. In hydrotope #2, all stain stayed in the upper 10 cm at the vegetation /soil transition. Here, the upper organic and vegetation layer functions as the most dominant flow path for water, although cracks, macropores and soil pipes were found readily on the meadows as well, yet in smaller quantities than in hydrotope #1.

Shrinkage cracks do play a major role in subsurface flow despite high precipitation values on the Heumös slope. Many soil patches are fully saturated throughout the year. But dry periods lead to soil moisture decrease, which then easily leads to the evolution of shrinkage cracks due to volume change of pores in the clay soils (Chertkov, 2003; Wilding & Tessier, 1988). Shrinkage cracks enhance drying of the soil column on the one hand but also function as a fast flow pathway with the onset of precipitation. Macropores and cracks can be washed out and might form soil pipes which are hydraulic active during precipitation events.

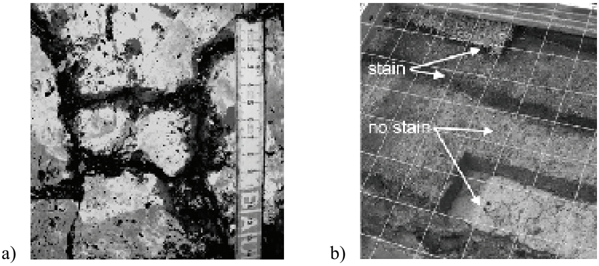


**Fig. 5:** Dye tracer experiments, a) shows stained plot in forest, which is dominated by shrinkage cracks in 25 cm depth. Black and dark grey are stained; b) shows stained plot on the meadow, only the uppermost vegetation-soil layer is stained.

## Groundwater, spring discharge and surface runoff generation

The piezometer in 5.5 m depth shows a pressure high stand during winter and spring months (fig. 6a). This is followed by groundwater level changes reacting to precipitation events. A relatively quick rise of the groundwater level in the 5.5 m device can be observed about 6 hours after the start of a certain precipitation event, followed by a long tailing afterwards. Not all precipitation events lead to a pressure rise. The deeper device shows a more damped reaction. The debris spring S 1 is located at the transition of the southern slopes towards the hillslope body, namely at the border of hydrotope #1 to hydrotope #2. It shows a quick reaction to precipitation events, within the first 15-30 minutes after precipitation started (fig. 6b). The reaction time is soil moisture dependent (Lindenmaier, submitted), according to the dependence of the aperture of shrinkage cracks to the soil moisture state. It is remarkably that a long tailing of discharge prevails after the fast first reaction ceded. This tailing is very similar to the piezometer reactions in 280 m distance.

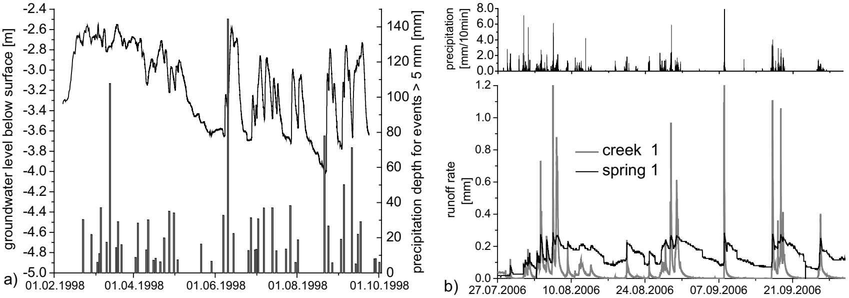


**Fig. 6:** a) Piezometer time series in 1998 and cumulative precipitation depth of selected events show that a certain threshold of precipitation is needed to trigger piezometer level rise. The piezometer is installed in 5.5m depth. b) Comparison of spring and creek discharge in 2006, note the tailing of spring discharge. Creek 1 catchment has a size of 209.000 m², the spring catchment has an approximate size of 1100 m².

In contrast, the discharge in the creek gauges shows a fast reaction to precipitation events but also a fast decline after maximum discharge (fig. 6b). This is in accordance with the overall wet soil moisture regime on the hillslope body. During rainfall events, a connection of saturated and nearly saturated patches is quickly established to the creek channels. Retention in the uppermost soil zone is low. It can be stated that the hillslope body is dominated by surface runoff generation. Fast, shallow interflow plays a major role during precipitation-runoff events, while deeper interflow or groundwater discharge is negligible. These two process types also influence baseflow in precipitation free periods.

**Soil moisture**

Soil moisture observation with time domain reflectometry (TDR-rods) in a profile show that the soil moisture is dominated by evapotranspiration. In winter and wet periods, soil moisture is at saturation, and precipitation events do not result in soil moisture changes. Only after long dry periods, the soil moisture drops to values below saturation (fig. 7). A precipitation event then can lead to a fast rise of soil moisture, even in the deeper soil column. This is an indication for preferential infiltration through shrinkage cracks. The saturated conditions throughout most times indicate that deep infiltration is not a major process on the hillslope body.

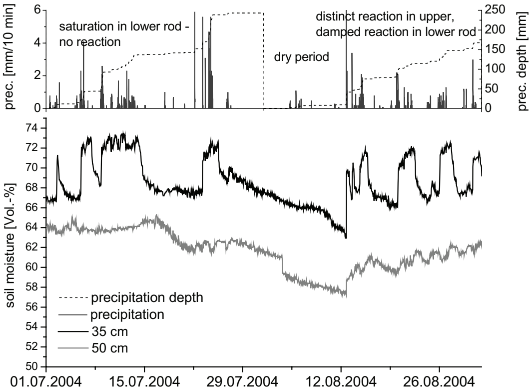


**Fig. 7:** Soil moisture variation ~~du~~ring summer 2004. The lower rod shows saturated condition, whereas the upper one is driven by evapotranspiration. During winter, soil moisture is at saturation. TDR-rods do not give plausible measurements in high saturation conditions in such clay-rich soils. For a yearly record, see also Figure 9.

## MODEL APPLICATION TO ENHANCE HYDROLOGICAL PROCESS UNDERSTANDING

The model CATFLOW is designed to use the pressure based form of the Richards equation (Richards, 1931; Zehe *et al.*, 2001) and is equipped with an extended soil-vegetation-atmosphere-transport module (SVAT). It is build up on a quasi 2½-dimensional network of surface runoff channels and connected hillslopes. The hillslopes are represented by a single line for surface processes but is extended into the depth to present the soil profile. This has the advantage that surface runoff processes as well as subsurface hydraulics can be represented. In this paper, we want to present a model for the weir 3 catchment with a size of 0.05 km². It lies completely on the hillslope body (fig. 1). A simple soil catena was taken which is supposed to represent a two layered gleysol with higher conductivities at the top and lower conductivities at the bottom. The soils are parameterised as a silty clay after Carsel & Parrish (1988) with conductivities of $6.40*10^{-07}$ m/s (top) and $1.70*10^{-07}$ m/s (bottom). To decide whether deep infiltration is a considerable process on the hillslope body or not, the lower boundary condition was either chosen to be of a no-flow or a gravity-flow.

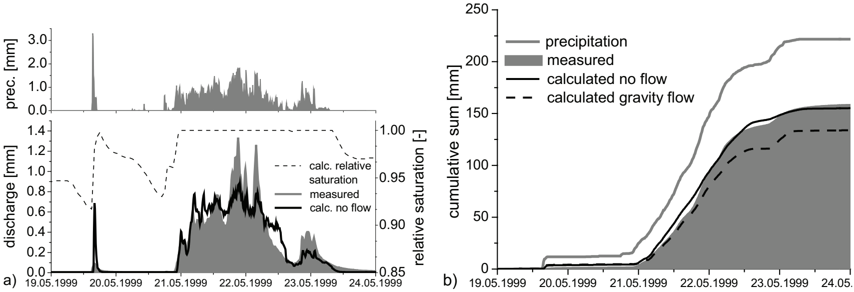


**Fig. 8:** Precipitation event in May 1999 with a sum of 210 mm. High initial saturation leads to a high runoff coefficient (>0.7). The overestimation of the small first precipitation peak (a) results from low hydraulic conductivities in the uppermost soil column of the model and so to infiltration excess runoff generation in contrast to reality. The cumulative sum (b) shows that the gravity flow boundary condition has a higher bias than the no flow boundary condition.

Long lasting precipitation events combined with wet soil moisture condition give good quality simulations (fig. 8a). High intensity precipitation events are overestimated, the reason is a missing implementation of shrinkage crack behaviour in the model. Figure 8b shows that the no-flow boundary condition results in a better water balance for this event. This is similar for long term studies as well, as CATFLOW runs on a time continuous base. To underline the results shown in figure 8, the measured soil moisture is compared to the calculated soil moisture at the same spot in the model. Figure 9 shows a good relation of soil moisture changes in the field and in the model for the summer period.

The no-flow boundary condition inhibits water seeping from the lower boundary, so that the water in the hillslope can only be removed through return flow into the creek or lost to evapotranspiration. The significant soil moisture changes in the summer indicate that evapotranspiration is the major process which dominates the soil moisture state. The model application shows that deep infiltration on the hillslope body is not a dominating process and so cannot contribute to the fast groundwater level changes.

## DISCUSSION AND CONCLUSIONS

Both a detailed field observation of hydrological measures and processes as well as the application of a highly distributed physically based hydrological model show that fast hydrological processes dominate the surface as well as subsurface hydraulic system of the mass movement. The similar behaviour of the debris spring and the piezometer rise the question whether a lateral pressure propagation can function as trigger for the movement.

Deep percolation of water is not a favoured process on the hillslope body, where sediments with low hydraulic conductivities mean a surface runoff dominated hydrological system. Saturation excess runoff generation is considered the dominating process on the hillslope body. On steeper meadows, the uppermost soil column functions as a fast preferential runoff system. But the lower soil column, especially on flatter areas, is water saturated most of the year.

This is different on the steep southern slope (hydrotope #1). Pronounced shrinkage cracks and macropores dominate the hydrological system through preferential infiltration and flow. This also indicates the dry ecological soil moisture index. The debris springs fast reaction and long tailing are similar to the groundwater level changes. This is why a hydraulic connection from the southern slope towards a confined groundwater system of the hillslope body is considered the most plausible trigger for groundwater level rises, which, in turn, might be responsible for movement. As deep infiltration of water or vertical pressure propagation in the soil column is not plausible due to soil characteristics, a complex three dimensional pressure propagation has to be considered responsible for groundwater changes in the hillslope body. It is clear that such a system responds on a faster process scale than it is usually found and suggested for deep seated mass movements (Schuster & Wieczorek, 2002; van Asch *et al.*, 1999).

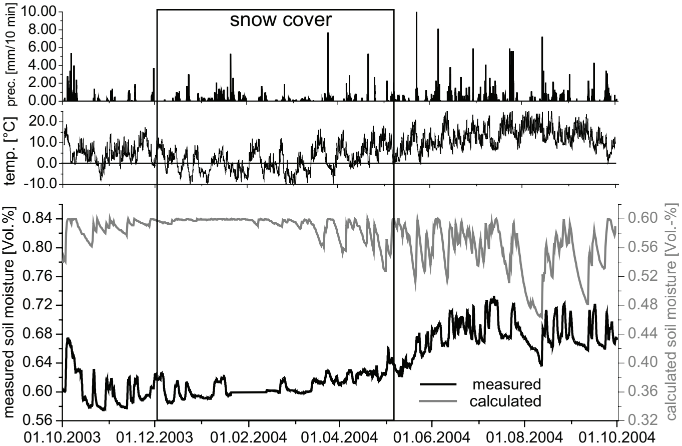


**Fig. 9:** Soil moisture time series for 2004. From top to bottom: precipitation in 10 min time interval; average daily temperature to estimate temperature-influenced measured soil moisture (soil moisture values drop due to lower soil temperature); a good relation for model vs. measured is met in summer. The soil moisture values differ a little for the measured and calculated time series, which is a matter of chosen maximum porosity for the calculated time series and possible influence of charged clay minerals on the measured signal.

Up to now, the slope movement was monitored in intervals of several months. These do not correspond to the time scale of relevant hydrological processes in this case. The observed hillslope creep with time steps of 3-6 months rather belongs to a series of small jerky movements than a continuous creep (Lindenmaier, submitted; Walter, 2006). These could likely be induced by the fast groundwater level changes in summer time rather than by continuous high groundwater levels in winter.

Process based hydrology in landslide research needs further attention as mass movements have an especially complex hydrological and hydrogeological system as similar studies show (Bonomi & Cavallin, 1999; Malet *et al.*, 2003; Malet *et al.*, 2005). Process identification and understanding the heterogeneity of structures is necessary to understand the dominant processes of unstable hillslopes. In our view, a closed water balance is one of the important issues which still need more attention in landslide hydrology (Bogaard *et al.*, 2007).

During our research, it was especially astounding to find a preferential flow system of shrinkage cracks in the clay rich soils. Clay soils, especially in very wet conditions are supposed to have low hydraulic conductivities, but the opposite is the case as shrinkage cracks and macropores, as well as soil pipes dominate the subsurface hydraulics. Soil pipes might function as trigger for movement as well (Uchida *et al.*, 2001). Shrinkage cracks are supposed to have a threshold character for hydrological processes (Zehe *et al.*, 2007). Representing preferential flow in cracks and other macropores is one of the key efforts which will be followed in ongoing research. In addition to movement measurements with higher measurement frequencies and new methods (Singer *et al.*, 2006; Wust-Bloch & Joswig, 2006), the coupling of surface and subsurface hydraulics with movement processes (Hinkelmann & Zehe, 2007) is part of our research effort as well.

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