**Hydrology and
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Use of soil moisture dynamics and patterns for the investigation of runoff generation processes with emphasis on preferential flow

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Abstract

Spatial patterns as well as temporal dynamics of soil moisture have a major influence on runoff generation. The investigation of these dynamics and patterns can thus yield valuable information on hydrological processes, especially in data scarce or previously
5   ungauged catchments. The combination of spatially scarce but temporally high resolution soil moisture profiles with episodic and thus temporally scarce moisture profiles at additional locations provides information on spatial as well as temporal patterns of soil moisture at the hillslope transect scale. This approach is better suited to difficult terrain (dense forest, steep slopes) than geophysical techniques and at the same time less
10 cost-intensive than a high resolution grid of continuously measuring sensors. Rainfall simulation experiments with dye tracers while continuously monitoring soil moisture response allows for visualization of flow processes in the unsaturated zone at these locations. Data was analyzed at different spacio-temporal scales using various graphical methods, such as space-time colour maps (for the event and plot scale) and indica-
15 tor maps (for the long-term and hillslope scale). Annual dynamics of soil moisture and decimeter-scale variability were also investigated. The proposed approach proved to be successful in the investigation of flow processes in the unsaturated zone and showed the importance of preferential flow in the Malalcahuello Catchment, a data-scarce catchment in the Andes of Southern Chile. Fast response times of stream flow
20 indicate that preferential flow observed at the plot scale might also be of importance at the hillslope or catchment scale. Flow patterns were highly variable in space but persistent in time. The most likely explanation for preferential flow in this catchment is a combination of hydrophobicity, small scale heterogeneity in rainfall due to redistribution in the canopy and strong gradients in unsaturated conductivities leading to
25 self-reinforcing flow paths.

1   Introduction

Identification of patterns of soil moisture response to rainfall and especially the vertical dynamics of soil moisture at the hillslope or plot scale can be useful for the investigation of runoff generation processes in a previously ungauged or data scarce catchment. When investigating runoff generation processes in a previously ungauged catchment it becomes obvious from the start that the equipment we are about to install is insufficient. There will be neither enough data points in time nor in space to characterize these processes in their temporal and spatial variability. A possible way to overcome this problem is the approach where a multitude of experimental methods is applied within a relatively short time frame, producing a data set that highlights a multitude of angles and aspects of catchment functioning. This type of study was carried out in the Malalcahuello Catchment in the Chilean Andes and is described in Blume et al. (2007a)[1].

One important aspect of the Malalcahuello study was the question whether a combination of spatially scarce soil moisture profiles with high temporal resolution, additional episodic measurements of soil moisture along two hillslope transects and continuously monitored dye tracer irrigation experiments can provide useful insights into the processes of runoff generation in young volcanic ash soils. The young volcanic ash soils of Chile are little understood in their hydrological characteristics and no studies of high temporal resolution soil moisture dynamics were found in our literature search. However, in other parts of the world such as New Zealand or Japan the soil moisture dynamics of volcanic ash soils has been investigated to some extent: Hasegawa (1997) used hourly TDR data to investigate soil water conditions and movement, Musiake et al. (1988) used tensiometric observations and a numerical model to study infiltration and drying behaviour of these soils and Van't Woudt (1954) used 19 small lysimeters

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[1]Blume, T., Zehe, E., Reusser, D., Bauer, A., Iroumé, A., and Bronstert, A.: Investigation of runoff generation in a pristine, poorly gauged catchment in the Chilean Andes. I: A multi-method experimental study, Hydrol. Process., in review, 2007a.

to investigate subsurface stormflow.

Soil moisture data has been used as a means to understand runoff generation in other parts of the world (e.g. Kienzler and Naef, 2007; Meyles et al., 2003; McNamara et al., 2005; Frisbee et al., 2007; Germann and Zimmermann, 2005; Zhou et al., 2002; Hino et al., 1988) or for the investigation of the effects of changes in land use or management on hydrological processes (Williams et al., 2003; Starr and Timlin, 2004). In most studies soil moisture was measured either with high spatial or with high temporal resolution, thus producing either spatial soil moisture patterns (Bardossy and Lehmann, 1998; Brocca et al., 2007; Meyles et al., 2003; Williams et al., 2003; Western et al., 2004; Rezzoug et al., 2005; Nyberg, 1996) or information on the dynamics (e.g. McNamara et al., 2005; Starr and Timlin, 2004; Frisbee et al., 2007). A combination of both can only be achieved with either a large number of probes measuring continuously such as in Starr and Timlin (2004) and Taumer et al. (2006) or with geophysical methods such as described for example in Zhou et al. (2001), where electric resistivity tomography was used to investigate soil moisture dynamics on a 3.5×3.5 m plot at hourly resolution. However, the first of these two options is cost-intensive while the second is predominantly carried out on grassland, fields or bare soils with little topography and is not feasible in complex terrain. Combining high temporal resolution soil moisture profiles at few points in space with episodic manual measurements at additional locations thus might be a viable cost-efficient alternative for difficult terrain.

At the Malalcahuello Catchment soil moisture was measured on two steep hillslope transects. Data was collected with a data logger at high temporal resolution at three points and manually at irregular intervals at 11 additional points. Each measurement produces soil moisture data for 6 different depths along a vertical profile. While this is still a pitiful number of data points it is nevertheless possible to get a general understanding of the major processes occurring within the unsaturated zone of this catchment. Data was analyzed using different graphical methods allowing for data exploration at different spatio-temporal scales. By carrying out rainfall simulation experiments using a dye tracer over each of the continuously measuring probes

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it was possible to corroborate our perception of flow in the unsaturated zone at these locations. This combination of high temporal resolution soil moisture measurements, rainfall simulation experiments and the use of dye tracers to corroborate the conclusions gained from the soil moisture time series is noteworthy and only one other study (Weiler and Naef, 2003) using a slightly different layout was found in our literature search. The study at the Malalcahuello catchment furthermore included the analysis of response times at the event scale, yearly soil moisture dynamics, spatial patterns and their long-term dynamics for 14 locations and 6 depths and the investigation of small scale soil moisture variability at the decimeter scale.

The four main questions of the study in the Malalcahuello Catchment were:

1. Can soil moisture data be used to investigate the dynamic patterns of unsaturated flow and can these patterns be attributed to runoff generation processes?

2. Are moisture patterns persistent in time and space?

3. What are the causes for the observed moisture/flow patterns?

4. How important are these patterns for the entire system/catchment response?

2 Research area

2.1 The Malalcahuello catchment

The research area is situated in the Reserva Forestal Malalcahuello, in the Precordillera of the Andes, IX. Region, Chile. The catchment is located on the southern slope of Volcán Lonquimay (38°25.5′–38°27′ S; 71°32.5′–71°35′ E). The catchment covers an area of 6.26 km^2. Elevations range from 1120 m to 1856 m above sea level, with average slopes of 51%. 80% of the catchment is covered with forest of the type Araucaria (*Araucaria araucana*) (with Lenga (*Nothofagus pumilio*) and Coigüe (*Nothofagus dombeyi*)) at higher elevations and Roble (*Nothofagus obliqua*) – Raulí

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(*Nothofagus alpina*) – Coigüe (*Nothofagus dombeyi*) at lower elevations. These types of native forest have a dense understorey of bamboo (*Chusquea culeou*). There is no anthropogenic intervention. Due to this dense vegetation interception losses become significant: on average only 80% of total precipitation reaches the forest floor as throughfall (measured with a raster of throughfall collectors with a diameter of 10.5 cm). However, throughfall amounts are highly variable and can in places also exceed total precipitation (measured outside the forest) by a factor of 2 or even 3 (Blume et al., 2007a[1]). Above the tree line (20% of the catchment area) there is no significant vegetation cover.

The soils are young, little developed and strongly layered volcanic ash soils (Andosols, in Chile known as Trumaos) (Iroumé, 2003; Blume et al., 2007a[1]). High permeabilities (saturated and unsaturated), high porosities (60–80%) and low bulk densities (0.4–0.8 g/cm^3) are typical for volcanic ash soils. They also usually show a strong hysteresis and irreversible changes (e.g. in water retention) with air-drying (Shoji et al., 1993). Soil hydraulic conductivities for the soils in the Malalcahuello catchment were determined in the lab with the constant head method and range from $1.22 * 10^{-5}$ to $5.53 * 10^{-3}$ m/s for the top 45 cm, with an average of $5.63 * 10^{-4}$ m/s (42 samples). The mean conductivity for the fine gravel and pumice layers is $1.88 * 10^{-3}$ m/s (9 samples). Porosities for all horizons sampled range from 56.8% to 82.1%. The mean porosity for the top 45 cm is 71.7% with a standard deviation of 6.6% (16 samples). Layer thickness is also highly heterogeneous, and can range from 2–4 cm to several meters. Depth to bedrock is unknown, however manual augering to depths of 2–3 m, at one occasion even 7 m was possible (Blume et al., 2007a[1]). At the locations of the 4 wells at the lower end of this slope (Fig. 1) groundwater was found in depths of 1.8–3.2 m below the surface. However, at many other locations on this slope no groundwater was found in auger holes of similar depths. Grain size distributions for the upper horizons resulted in an average of 66.5% sand, 30.4% silt and 3% clay. In the coarse layers the grain size fraction ≥2 mm ranges from 38–86% (Blume et al., 2007a[1]). For a more detailed description of the Malalcahuello Catchment see Blume et al. (2007a)[1].

The climate of this area can be described as temperate/humid with altitudinal effects. There is snow at higher elevations during winter and little precipitation during the summer months January and February. Annual rainfall amounts range from 2000 to over 3000 mm, depending on elevation. Event runoff coefficients are low, with 1–10 % for 17 events analyzed in 2004/2005, of which a third are smaller than 2% (Blume et al., 2007c). (The method of baseflow separation used in this analysis is described in Blume et al., 2007c.) On the other hand, yearly runoff coefficients (>60%) as well as the baseflow index (>75%) calculated for the years 2004 and 2005 are high (Blume et al., 2007a[1]).

An overview of catchment layout and topography as well as instrumentation is given in Fig. 1.

3 Approach and methodology

3.1 Approach

The approach of this study is based on the measurement of spatially scarce but high temporal resolution soil moisture profiles on the one hand and additional episodic and therefore temporally scarce soil moisture profiles on the other hand. These two datasets combined with additional experiments described below were used to investigate different aspects of soil moisture response patterns and thus flow in the unsaturated zone. These aspects included the analysis of event response patterns resulting in the deduction of flow processes, the use of rainfall simulation experiments with dye tracers to corroborate these deductions, but also the analysis of response times at the event scale as well as yearly soil moisture dynamics. The episodic measurements along the hillslope transects allow for the analysis of spatial patterns and their long-term dynamics for 14 locations and 6 depths and for the investigation of small scale soil moisture variability at the decimeter scale.

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3.2 Soil moisture profiles

Soil Moisture was measured at two transects with FDR (frequency domain reflectometry) profile probes (Delta-T) in 10, 20, 30, 40, 60 and 100 cm depth. Both transects are located on the eastern slope close to the main stream gauging station S1 (Fig. 1).
These profile probes do not measure within a purely circular field as the sensor only extends about two thirds around the probe. By taking three measurements, turning the probe by 120° each time, the full circle is covered. At each depth soil moisture is measured in a soil volume of about 2.5 L, a cylinder with a radius of 10 cm. The absolute measurement error of about 3% (manual of the profile probe) is for the measurement of the dynamics of soil moisture of less importance. The error of the measured dynamics, i.e. the error of the values relative to each other is likely to be smaller than the absolute error. As a result of the special characteristics of the volcanic ash soil, such as the extremely high porosities and the fact that volcanic glass is a primary constituent, the built-in standard calibrations were not applicable. It was thus necessary to calibrate the probe specifically for this type of soil with gravimetrically determined water contents of 19 soil samples of the upper horizons.

Three profile probes were connected to a data-logger and were measuring continuously with a temporal resolution of 10 min. The data set extends from March 2003 to May 2006 for the lowest probe and from December 2004 to May 2006 for the two upper probes. For easier reference the three probes are numbered: probe 1 is located at the lower end and probe 3 at the upper end of the hillslope transect. A fourth probe was used for manual measurements at 11 points along the transects. 5 of these measurement locations supplement the transect of the continuously measuring probes, while the remaining 6 form the second transect located to the north of the first (Fig. 1). The points on the transects were evenly spaced. These manual measurements were carried out at 41 occasions at irregular time intervals during field campaigns (December 2003–February 2004, October 2004–December 2004, November 2005–December 2005 and April–May 2006).

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3.3 Rainfall simulation experiments

By carrying out rainfall simulation experiments using a dye tracer over each of the continuously measuring probes it was possible to test our perception of flow in the unsaturated zone at these locations. The dye tracer experiments were carried out in May 2007. The plot size was $1.2\,m^2$ with the probe situated in the center. For all experiments the dye tracer Brilliant Blue with a concentration of $4\,g/l$ was used. The dye was applied with a hand pressurized pesticide sprayer in order to simulate rainfall. 30 liters of the dye were sprayed over a period of $3\,h$. This corresponds to a total of $25\,mm$ at application rates of $8.3\,mm/h$ on average. Profiles of the plots were excavated the following day and photos of the dye patterns were taken with a digital camera.

3.4 Streamflow, groundwater levels and rainfall

Water levels in stream and groundwater were measured with capacitive water level sensors (WT-HR Trutrack) at 5–10 min time intervals. Stream water levels were converted to discharge with the help of a rating curve. Rainfall was measured with a tipping bucket rain gauge with a resolution of $0.27\,mm$. A climate station maintained by the Universidad Austral de Chile is located in a nearby forest plantation at $1270\,m$ elevation. This climate station has been logging the parameters rainfall, temperature, relative humidity, wind direction and velocity as well as global radiation at hourly intervals since 1999. During the winter of 2005 an ultra-sonic snow height sensor was also installed at this climate station. For more details on the experimental methods applied in the Malalcahuello Catchment see Blume et al. (2007a)[1].

3.5 Response times

Response times were calculated from the time series of rainfall, soil moisture, groundwater levels at well W1 (Fig. 1) and streamflow (all with 10 min resolution). Response

time in this case was defined as the time period between begin of precipitation and first response of soil, ground- and stream water. The following threshold values were used to identify the point of first response in the time series: an increase of 0.2 Vol% in soil moisture, an increase of 0.005 m in groundwater level and an increase of 0.01 m^3/s in stream flow.

3.6 Data analysis

Data was analyzed at different space-time scales using various graphical methods. The space-time scales analyzed included event and longterm scale, point and hillslope scale. Event scale datasets with high temporal resolution were analyzed with the help of colour maps which included temporal dynamics similar to those used by Weiler and Naef (2003). Here, time is plotted on the x-axis while depth is plotted on the y-axis. Soil water content at each depth and point in time is visualized by color, changing from blue to red with increasing wetness. For additional information the response of streamflow and groundwater, as well as the rainfall intensity at each point in time were also included. Color scales were adapted from one event to the next in order to get the best "color resolution" possible, producing clearer patterns of response. It thus becomes possible to explore and identify patterns in moisture response, patterns in space and time that are much more difficult to identify in the classical line plots of soil moisture dynamics. In a next step flow processes were deduced from these patterns.

Soil moisture patterns at the hillslope scale are investigated with the help of indicator maps for each depth. These maps show locations where soil moisture is above/below a certain threshold, here the median value for that depth or the 75% quantile, respectively. Additionally, the temporal aspect of these patterns is also included by plotting location on the slope on the y-axis and time on the x-axis, thus giving an idea of pattern persistency.

Simple line plots were used to analyze annual dynamics as well as small scale variability of soil moisture.

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3.7 Unsaturated conductivities

In order to obtain unsaturated conductivities for the top horizons it was necessary to estimate the Van Genuchten parameters by fitting the Van Genuchten equation to the soil moisture characteristic curves. Soil moisture characteristic curves were determined with a pressure chamber for the first two horizons below the humus layer (3 samples each). The Van Genuchten parameters were then used to determine the unsaturated conductivities for a chosen matric potential.

3.8 Hydrophobicity

Potential hydrophobicity was measured with the Water Drop Penetration Time (WDPT) test as described in Dekker and Ritsema (1994) for 12 air dried soil samples from 4 different locations and depths from 5 to 80 cm. The WDPT test is a simple test for water repellency where a water drop is applied to a soil sample and the time between application of the water drop and its penetration into the soil is measured. Water drop penetration times for air dried soil have been classified by Dekker and Ritsema (1994) into 5 classes of water repellency: wettable (<5 s), slightly water repellent (5–60 s), strongly water repellent (60–600 s), severely water repellent (600–3600 s) and extremely water repellent (>3600 s). After testing if a soil sample was wettable soil samples showing water repellency were submitted to 12 repetitions of the WDPT, each test carried out with a different subsample.

4 Results and discussion

4.1 Soil moisture dynamics on event basis

The soil moisture response was analyzed with the help of space-time maps for 34 rainfall events during the period from December 2004 to December 2005. The temporal resolution of these plots is 10 min. The analysis included some events influenced by

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snow, either directly by snowfall or by rain on snow events. While snowfall will reduce the amount of water infiltrating at the time of the event, rain on snow events will have the effects of flow on or within the snowcover as well as infiltration of meltwater. However, as snow water equivalent was not measured, these effects could not be measured
5 directly.

Three typical events are shown in Fig. 2. Probe 1 is located at the lower end and probe 3 at the upper end of the hillslope transect. Details of event response and antecedent conditions are listed in Table 1.

For the first event, the event on March 3rd 2005 (Fig. 2a), total precipitation amounted
10 to 52 mm with a highest intensity of 8.6 mm/10 min. The maximum change in soil moisture was high with 8.6 Vol%, which is due to the fact that this event was the rainfall event with the lowest antecedent moisture content of all events studied. The most prominent patterns found for this event are a) extremely fast vertical water transport (arrow 1 in Fig. 2a), due to high rainfall intensities and high hydraulic conductivities, and b) very
15 little reaction at the 10 cm depth for probes 1 and 3 (arrow 2 in Fig. 2a). This is probably due to hydrophobicity resulting from the dry antecedent moisture conditions. This pattern was observed only for the 3 driest occasions. Soil moisture increase below the hydrophobic layer must be due to lateral inputs, either at the the decimeter scale or at the hillslope scale. Potential hydrophobicity of soil samples from 5 to 80 cm depth
20 was tested with the Water Drop Penetration Time test. It was found that while the top horizons show strong to extreme water repellency, samples from greater depths are wettable (Table 2). However, this test determines only potential hydrophobicity, measured in air dried soil. Water repellency under field conditions is likely to be less pronounced.
25 The rainfall event on April 6th 2005 (Fig. 2b) has a total precipitation of 28 mm and only low rainfall intensities. The maximum increase in soil moisture, as well as streamflow and groundwater levels are low with 3.8 Vol%, 0.06 m^3/s and 3 cm, respectively (Table 1). The major patterns found here are: a) fast vertical water transport, due to high hydraulic conductivities (arrow 3 in Fig. 2b), and b) late but persistent response at

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100 cm depth for probes 2 and 3, while no such reaction can be seen at the 60 cm sensor (arrow 4 in Fig. 2b). As water is apparently not transported to this point vertically, this seems to be the result of lateral water input, causing a slow trailing "wave" at this depth.

The event on 27 May 2005 (Fig. 2c) has a very high total precipitation of 124 mm with a highest intensity of 3.2 mm/10 min. However, as this event is probably a rain on snow event, it is difficult to estimate the actual amount of water entering the soil. While the response of discharge (3.22 m^3/s increase), and ground water levels (120 cm increase) is extremely strong, soil moisture shows a much less pronounced reaction. This is explained by the fact that this is not only an event with high rainfall amounts, but that snow was also present in the catchment at this time (30 cm of snow were measured at the climate station just outside of the research catchment at 1270 m elevation, while the soil moisture transect is located at about 1140 m elevation.). Therefore some of the runoff might be generated at the snow surface or within the snow layer. Furthermore, as all water in excess of field capacity is likely to be transported quickly to greater depths, soil moisture increases most for dry antecedent conditions and less in conditions of high antecedent wetness, which was the case during this event. The most prominent patterns for this event are: a) slow vertical water transport, probably due to lower rainfall intensities (arrow 5 in Fig. 2c) and b) strong response at 40 cm depth for probe 1, very local and short-term (arrow 6 in Fig. 2c). This reaction might be due to an underlying capillary barrier, causing the water to pond above it until breakthrough. This pattern was observed at this location quite frequently (for 15 events out of 34).

4.2 Dye tracer rainfall simulation

In May 2006 rainfall simulation experiments with blue dye were carried out at the locations of the three continuously measuring probes. The soil moisture dynamics of these three experiments are shown in Fig. 3. As the same amount of dye was applied over the same amount of time during each of these experiments, the three experiments were plotted in one single figure as if corresponding to a single rainfall event. The

time period and intensity of dye application is plotted in the top bar. The same colour scale was applied for the intensity of application as for the rainfall intensities in Fig. 2. Neither streamflow nor groundwater level dynamics are plotted as there was no reaction to these small scale experiments (small in comparison to the size of the hillslope). The mean antecedent moisture content for the top 30 cm was 27.7 Vol%. The dynamic moisture patterns show fast/preferential vertical flow for probes 1 and 2 and slow vertical water transfer for probe 3 (Fig. 3). One day after the beginning of the sprinkling experiment, crossections of the infiltration plots were excavated and the dye stain patterns marking the flow paths of the dye in the unsaturated zone were photographed. The three photos of the crossections at the locations of the soil moisture probes are shown in Fig. 4. Preferential flow is found at all three plots. Flow occurred in plumes, which are separated by distinct areas of little or no flow and thus are not marked by blue dye.

Figure 4a shows the flow paths of probe 1 (located at the bottom of the slope). While blue dye can be seen in the top 5 cm, hardly any dye stains could be found in depths of 5–ca. 30 cm (arrow 1 in Fig. 4a). This is most likely the suspected zone of hydrophobicity which was also found in the analysis of the time-space maps of soil moisture response to rainfall events. This zone of hydrophobicity or water repellency is most pronounced after summer dry periods but is still visible at the time of the sprinkling experiment where only little reaction was seen at the 10 cm sensor of probe 1 (Fig. 3). Distinct plumes of dye can be found at depths of ca. 30–60 cm (arrow 2 in Fig. 4a) (also at the location of the soil moisture probe), just above a very pronounced layer interface between the silty sand layer above and the gravelly layer below (arrow 3 in Fig. 4a). This confirms the hypothesis that a capillary barrier could be the cause of the ponding at the 40 cm sensor which was seen in the event response analysis (Fig. 3, arrow A). The dye stains also indicated the locations were water leached into the capillary barrier (arrow 3 in Fig. 4a). The maximum depth of dye infiltration was about 1 m. Probe 1 is thus intersecting a preferential flow path, which is in part due to roots and in part probably due to flow patterns caused by water repellency of the soil. In late summer

the 10 cm and sometimes also the 20 cm sensor are surrounded by hydrophobic soil (Figs. 2a and b).

The crosssection at probe 2 (Fig. 4b) shows as most distinct feature the saprolite layer (weathered bedrock) starting at the location of the 60 cm sensor (arrow 1 in Fig. 4b). The 100 cm sensor is thus located within the saprolite. It was also found that the probe is located within a preferential flow path coinciding with a concentration of fine roots (arrow 2 in Fig. 4b). Maximum infiltration depth is about 80 cm in the three major plumes. A hydrophobic layer with very little staining can be seen in the crossection (arrow 1 in Fig. 4b). However, this layer was not identified in the soil moisture data, as the probe is located within the preferential flow path and not in a hydrophobic patch. The high velocity of flow and the strong response in this preferential flow path is also visible in Fig. 3 (arrow B) and was also a feature of the soil moisture response space-time maps at this location.

The soil at probe 3 (Fig. 4c) differed compared to the two others as the vegetation at this plot included a thicket of low shrubs, causing a higher density of roots in the top 20 cm (arrow 1 in Fig. 4c). The probe was here located in between dye stained preferential flow paths. While blue dye is found in the vicinity of the probe at depths 10–20 cm, very little of it is found close to the probe at greater depths. The 60 cm sensor is located just at the interface between the silty sand and layer of fine gravel (arrow 2 in Fig. 4c), thus probably measuring in both layers, while the 100 cm sensor is situated in a layer of more compacted silty sand starting at a depth of approx. 75 cm. Maximum depth of infiltration is 80 cm. The fact that the layer at the 100 cm sensor is more compacted might explain why reaction at this sensor occurs delayed and prolonged. This would correspond to lower hydraulic conductivities in the compacted layer causing a delay in response and a prolonged peak. However, as the response at the 60 cm sensor is often very weak, the water causing the peak at 100 cm depths is most likely transported to this point not vertically but laterally. The dense root zone in the top 20 cm explains the strong reaction at the 20 cm sensor (Fig. 3, arrow C). Probe 3 shows a slower reaction to rainfall compared to the other two probes (Fig. 3 and also Fig. 2),

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which is explained by the fact that this probe is not situated within a preferential flow path.

4.3 Response times

A comparison of response lags for 27 rainfall events between December 2004 and April 2006 is shown in Fig. 5. S20, S30, S40 are the response lags of the soil moisture sensors at 20, 30 and 40 cm depth, GW is the response lag of ground water level at well W1 (Fig. 1) and Q is the response lag of stream flow. Response lags of all parameters show similar behavior over time: response times are short from January to April (summer and early fall) when compared to the winter months. This is probably the result of a) enhanced preferential flow due to hydrophobicity and b) higher rainfall intensities. Groundwater response is generally slower than stream flow response. (At this hillslope the groundwater surface at well W1 in the vicinity of the stream is generally about 60 cm below the stream bed.) Surprisingly, the soil moisture sensors often react slower than stream flow. This could either mean that rainfall is not uniformly distributed over the catchment or that these sensors are bypassed by preferential flow paths. Surface runoff is unlikely, due to high infiltration rates and porosities and has not been observed during field campaigns.

4.4 Annual dynamics of soil moisture

The annual dynamics of soil moisture, in Fig. 6 shown exemplary for probe 3 (October 2004–May 2006), are little pronounced in comparison to the event dynamics. Only during the summer months (January and February) a short drying period can be observed (circled in Fig. 6). However, as soon as the first rainfalls start in autumn, soil moisture values rebound to their previous level. The fact that soil moisture values for the 20 cm depth are high compared to the 10 and 30 cm depths is either due to textural differences or to a root found close to this sensor during the excavation of this profile (Fig. 4c).

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4.5 Soil moisture spatial patterns at the hillslope scale

Soil moisture patterns at the two transects are depicted in Fig. 7. It was found that patterns are quite persistent over time. There seems to be a correlation with position on the slope for the 10 cm sensor, but not for the sensors at greater depths. At 10 cm depth the lower part of the slope is generally wetter than the upper part of the slope. This is probably due to shading effects: the deeper in the steep valley the fewer hours of direct sunshine. The northern transect is wetter than the southern transect, which is probably due to denser vegetation.

4.6 Variability of soil moisture at the decimeter scale

Profile probes measure predominantly in a certain direction. By taking three measurements, turning the probe by 120° each time, the full circle is covered. Figure 8 shows the small scale variability in soil moisture measured by twisting the probes at the manual measurement points H4 and H5. Differences in soil moisture around the probe can be very pronounced, e.g. it is wetter/drier in one direction than in the others. These patterns of small scale variability are quite persistent over time while the temporal variability of soil moisture at this time resolution (irregular time intervals during field campaigns) is generally low. It can be seen that while for measurement point H4 only the 20 and the 40 cm sensor show a stronger directional variability of 2.3 Vol% and 4.3 Vol%, respectively, this phenomenon is found for all depths but the 100 cm level at location H5. Overall 68% of the sensors show directional variability (median variability $\geq$1.8 Vol%) when counting each sensor along the probes separately (i.e. 6 depths times 11 locations). 29% of all sensors have a variability $\geq$3 Vol%, 18% have a variability $\geq$4 Vol% and 6% show a variability of more than 5 Vol%. As the profile probes have a range of only 10 cm, this observed variability of soil moisture occurs on a very small scale, the scale of decimeters. A possible explanation for these strong gradients in water content over such a small distance is the presence of preferential flow patterns which were found during the dye tracer experiments (see Fig. 4), as well

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as during a more extended dye tracer study in this catchment (Blume et al., 2007b[2]). If a sensor is located near the interface of such a preferential flow path, soil moisture will differ considerably depending on the direction of the measurement. The scale or width of these flow paths is in the order of <3 decimeters, thus matching the scale of the measurement. A sensor showing no directional variation must therefore be located either in the center of a flow path or in the center of the matrix with no flow path within reach of the measurement. Ritsema and Dekker (1996) also used small scale (5–10 cm) variability of soil moisture as a measure for preferential or finger flow. In their study moisture gradients between flow paths and non-flow areas ranged between 3 and 6 Vol%. Assuming small scale soil moisture variability does indeed indicate the presence of a preferential flow path, the fact that in Malalcahuello 68% of all sensors show this type of variability also gives us a measure of the importance of preferential flow in this catchment. There are five possible explanations for the surprising persistency of these soil moisture patterns (or preferential flow patterns) over the course of more than one and a half years (Fig. 8).

1. These patterns might be caused by air gaps between access tube and the surrounding soil due to faulty installation. However, special care was taken to avoid this problem, by using the auger supplied by the manufacturer of the probes. Furthermore no noticeable air gaps were found during excavation of the probes at the end of the field study, on the contrary, probes were sitting tightly in the soil.

2. They might also be due to textural differences. However, as the sensors have only a range of 10 cm the measured volume is likely to be located within a single layer.

3. These patterns might also be induced by roots, which are not likely to change position on this time scale. However, roots were only found in some instances were these preferential flow patterns were observed during dye tracer experiments.

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[2]Blume, T., Zehe, E., and Bronstert, A.: Investigation of runoff generation in a pristine, poorly gauged catchment in the Chilean Andes. II: Qualitative and quantitative use of tracers at three different spatial scales., Hydrol. Process., in review, 2007b.

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4. They might be due to hydrophobicity in some parts of the soil, which would produce self reinforcing patterns likely to persist if not subjected to long periods of saturation.

5. These patterns could also be self reinforcing due to the strong gradient in soil moisture itself, leading to faster vertical transport within the wetter area (the flow path) than lateral flow into the drier area as a result of the strong gradient in matric potential.

This last possibility was investigated by calculating the unsaturated conductivities for a number of gradients in soil moisture and thus matric potential: from 20 to 25 Vol%, from 25 to 30 Vol% and from 30 to 35 Vol%, thus covering the range from 20 to 35 Vol% of soil moisture, where most of the variability was observed. The gradient of 5 Vol% chosen to investigate this phenomenon was in the upper range of gradients observed in the field (as the profile probes are not measuring unilaterally in one direction, the gradients perpendicular to a flow path interface are likely to be even higher than the gradients obtained from these measurements). In order to compare flow within the flow path with flow perpendicular to the flow path interface a three step calculation was carried out: First, the Van Genuchten parameters were obtained through fitting the Van Genuchten equation to the soil moisture characteristic curves. Then the gradient in matric potential was determined for the above gradients in soil moisture from the soil moisture characteristic curves. The Van Genuchten equation can then be used to determine the unsaturated conductivities for the chosen matric potential. As the longitudinal distance a length of 10 cm was chosen, as this is the range of the instrument. The ratio of the gradients in potential (across interface/within flow path) was then compared with the ratio of the unsaturated hydraulic conductivities (within the flow path/ across the interface). The effective unsaturated hydraulic conductivity across the flow path interface was calculated by treating the interface as two layers of differing conductivity (due to the differences in water content) and therefore using the harmonic mean for its calculation. The gradient in potential within the flow path is assumed to be equal

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to 1 [cm H$_2$O/cm]. In case the ratio of the of the unsaturated hydraulic conductivities is much larger than the gradient in matric potential across the interface (Eq. 1), these flow paths are likely to persist over time.

$$\frac{K_\theta(\text{flow path}) \left[\text{m/s}\right]}{K_\theta(\text{interface}) \left[\text{m/s}\right]} \gg \frac{\Delta\psi(\text{interface}) \left[\text{cm H}_2\text{O/cm}\right]}{1 \left[\text{cm H}_2\text{O/cm}\right]} \tag{1}$$

5   It was found that this would indeed be the case for a pure sand (with a ratio of K_θ up to 11 times larger than the ratio of $\Delta\psi$), however, in these soils, which have a fraction of at least 20% silt, it is very difficult to achieve these conditions (the ratio of K_θ is less than half that of the ratio of $\Delta\psi$). It is thus unlikely that solely the gradient in soil moisture causes the flow paths to persist in time. Nevertheless, if the unsaturated conductivity across the interface is further diminished by the effects of hydrophobicity a persistant pattern becomes more probable. Furthermore this type of soil is known to be hysteretic (Shoji et al., 1993; Musiake et al., 1988) thus causing a shift in the wetting curve compared to the here used draining curve, which could also change the outcome of this rough estimation. Persistent fingers as a result of hysteresis of the soil moisture characteristic curves were described by Selker et al. (1996) and Nieber (1996). Nieber (1996) explains that fingers will persist if the water entry pressure on the main wetting curve is smaller then the air entry pressure on the main drainage curve. However, due to lack of information on the main wetting curve, this effect cannot be assessed for the soils in the Malalcahuello Catchment.

5   Conclusions

The soil moisture data obtained in this study provided diverse insights covering different aspects of runoff generation processes in this catchment. It was shown that high resolution time series in combination with manual measurements at irregular time intervals can be a valuable addition to time series of precipitation and discharge when

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investigating runoff generation processes. This is especially true for catchments where only short time series of data are available, as in the Malalcahuello Catchment. The approach of combining high temporal but spatially scarce data with episodic additional measurements allowed for the investigation of soil moisture dynamics as well as patterns and proved to be less expensive than high density installation of continuously logging sensors while also being applicable to difficult terrain, i.e. densely forested and steep hillslopes.

By analyzing the dynamics of soil moisture response to rainfall events with the help of space-time maps it was possible to identify a number of patterns which can be attributed to different phenomena of flow in the unsaturated zone. The very subdued response of soil moisture in the upper soil horizon at two locations during the driest period (late summer) was attributed to the formation or reinforcement of hydrophobicity in this layer. The accumulation/ponding of water at certain depths was assumed to be due to the effect of capillary barriers. This was confirmed by the dye tracer experiment carried out at this location. Strong response at certain depths while the layers just above show little reaction indicate the importance of lateral flow processes.

It was furthermore found that infiltration dynamics differed from summer to winter, which could be due to differences in rainfall intensities as well as the amplification of preferential flow due to hydrophobicity in the top layer. Potential water repellency was tested with "Water Drop Penetration Time"-method (e.g. Dekker and Ritsema, 1994) and was found to be strong to extreme for the upper horizon. Hydrophobicity has been observed in these Chilean young volcanic ash soils by other researchers (Bachmann et al., 2000; Ellies, 1975) and is also of importance in volcanic ash soils of Ecuador (Poulenard et al., 2004). Differences in flow patterns from dry to wet period were also found in the Malalcahuello Catchment during a more extensive study involving a total of 10 dye tracer experiments (Blume et al., 2007b[2]). The change in flow pattern observed in this study further supports the theory that preferential flow in this catchment is reinforced by hydrophobicity. Similar flow patterns also attributed to hydrophobicity were observed in other studies (Ritsema and Dekker, 2000; Ritsema et al., 1998; Rit-

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sema and Dekker, 1994; Dekker and Ritsema, 2000; de Rooij, 2000). The fact that throughfall amounts are highly heterogenous in this catchment (Blume et al., 2007a[1]) is likely to be the reason why some locations (probably on the decimeter scale) are drier than others and thus more likely to develop water repellency. Spots of high water input are therefore likely to become preferential flow paths. These observed patterns in dynamics were found to be spatially and temporally persistent insofar as the event pattern dynamics of soil moisture observed in Fall 2005 (Fig. 2) matched well with the flow patterns found during the dye tracer experiments one year later. The persistency of the spatial patterns of soil moisture for 14 locations and 6 depths (Fig. 7) shows that spatial variability is much higher than temporal variability and that wetter locations are likely to remain wet. Furthermore the patterns of soil moisture variability at the decimeter scale, which were also attributed to the presence/absence of preferential flow paths, were found to be persistent over a period of more than one and a half years. While in the case of the larger scale soil moisture patterns the spatial differences in water content could also be attributed to differences in soil texture, the small scale variability is most likely located within a single soil layer and thus not caused by textural differences.

Other possible causes for the observed flow patterns/finger flow apart from hydrophobicity are: flow along roots or preferential flow paths maintained purely by the strong gradient in soil moisture and thus also in unsaturated conductivity. However, roots were found only in some cases of preferential flow patterns. Furthermore, a simple back-of-the-envelope calculation of unsaturated conductivities within and in between flow paths and their corresponding gradients in matric potential showed that these flow paths might be self-reinforcing in pure sand but not in this type of soil. Hydrophobicity is therefore still the most likely explanation for the flow patterns found here. However, the effects of hydrophobicity are likely to be aggravated by root channels, strong gradients in matric potential and the hysteresis of the soil moisture characteristic curves of volcanic ash soils as described by Shoji et al. (1993).

The last and maybe the most important question is the question of how important this locally observed preferential flow is for the system as a whole, i.e. runoff re-

sponse/runoff generation at the catchment scale. Several findings indicate that while preferential flow was only observed at the plot scale it might indeed be important factor of runoff generation at the catchment scale. That preferential flow occurs throughout the catchment is indicated by the fact that additionally to the three tracer experiments
5   shown in this study all 9 dye tracer experiments carried out under forest at various locations in the catchment showed preferential flow patterns (Blume et al., 2007b[2]). The fact that 68% of the sensors at the 11 manual measurement points showed small scale soil moisture variability is another indicator for the importance of these preferential flow paths. Last but not least the analysis of response times for soil moisture, groundwa-
10   ter and streamflow reveiled that response lags are generally much shorter during the summer months were preferential flow is also likely to be further enforced by stronger hydrophobicity. Interestingly streamflow often shows faster response than both groundwater and soil water. This might be due to non-uniform rainfall distribution (i.e. earlier onset of rainfall further up in the catchment causing stream levels to respond while soil
15   moisture at the slope close to the catchment outlet remained unchanged). However, as our data points in space are restricted to only three locations it is also likely that there are other preferential flow paths with even faster response than the ones measured by our instruments. In this case preferential flow in the vertical and then a fast reaction along a horizontal layer interface might be the reason for the short response lags of
20   streamflow found in this catchment. (Finger flow is known to cause faster breakthrough as investigated by de Rooij and deVries (1996) in a modelling study.) The question whether or not these preferential flow processes are important for catchment response could be investigated further by application of a physically based hydrological model either on the hillslope or on the catchment scale.
25   To summarize the main conclusions in short:

1. the combination of high temporal resolution but spatially scarce soil moisture data with episodic additional measurements proved to be useful for the investigation of runoff generation processes, especially with respect to preferential flow. While being less expensive than measuring at higher spatial resolution with a high num-

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ber of continuously logging probes it is also suitable for difficult terrain (i.e. very steep slopes) where geophysical techniques are problematic. The use of continuously monitored rainfall experiments with subsequent excavation of soil profiles adds additional insights into the flow processes in the unsaturated zone.

5   2. soil moisture/flow patterns were shown to be persistent in time and highly variable in space

3. the most likely explanation for the observed flow patterns is a combination of hydrophobicity with strong gradients in unsaturated conductivities, were flow paths are caused either by the presence of roots or the highly heterogeneous distribu-
10   tion of throughfall and thus water input

4. the flow patterns observed at the local scale are likely to be important for runoff response at the catchment scale.

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Table 1. Response characteristics and antecedent conditions for the three events shown in Fig. 2 (P_{tot} = rainfall amount, P_{Int} = maximum rainfall intensity, antec.θ = antecedent mean soil moisture content for the top 30 cm, max.$\Delta\theta$ = max. increase in soil moisture of all sensors, antec.Q = antecedent streamflow, max.ΔQ = max. increase in streamflow, antec.GW = antecedent groundwater level at well W1, max.ΔGW = max. increase in groundwater levels).

Date	P_{tot} (mm)	P_{Int} (mm/10 min)	antec.θ (Vol%)	max.$\Delta\theta$ (Vol%)	antec.Q (m^3/s)	max.ΔQ (m^3/s)	antec.GW (m)	max.ΔGW (m)
03/03/2005	52	8.6	21.6	8.6	0.13	0.45	0.08	0.11
06/04/2004	28	1.6	26.8	3.8	0.13	0.06	0.01	0.03
27/05/2004	124	3.2	29.1	5.5	0.29	3.22	0.42	1.20

Table 2. Results of the Water Drop Penetration Time (WDPT) test. If a sample showed water repellency the WDPT test was carried out with 12 repetitions, i.e. with 12 sub-samples. Shown are the number of tests per sample falling in the different classes of water repellency. Samples "forest 1-3" were taken at the slope of the soil moisture transect, while samples named "pine" were taken in a pine plantation downstream of the catchment outlet.

location	depth (cm)	wettable	slightly water repellent	strongly water repellent	severely water repellent	extremely water repellent
forest 1	5–10	no	–	–	5	7
forest 1	10–15	no	–	2	3	7
forest 2	10–20	no	–	12	–	–
forest 2	20–60	yes	–	–	–	–
forest 2	60–80	yes	–	–	–	–
forest 3	10–20	no	3	9	–	–
forest 3	20–60	yes	–	–	–	–
forest 3	60–80	yes	–	–	–	–
pine	0–5	no	–	–	–	12
pine	5–20	no	12	–	–	–
pine	20–60	yes	–	–	–	–
pine	60–80	yes	–	–	–	–
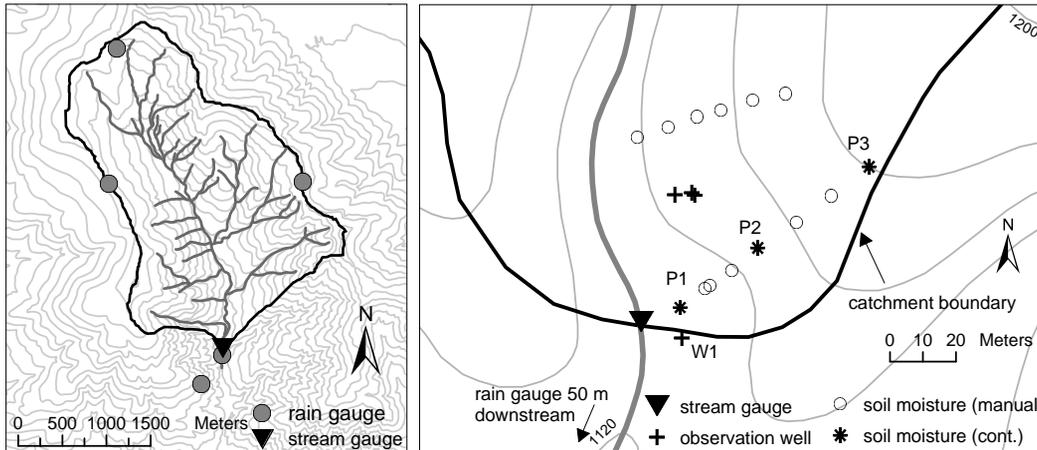
Fig. 1. Left: The Malalcahuello Catchment including the positions of rain gauges and the gauging station. The vertical resolution of the isolines is 50 m. Right: The slope close to the catchment outlet. Shown are the positions of the continuously measuring soil moisture probes (P1–P3) as well as the locations of the manual soil moisture measurements. The position of the groundwater observation wells is also included. The vertical resolution of the isolines is 20 m.

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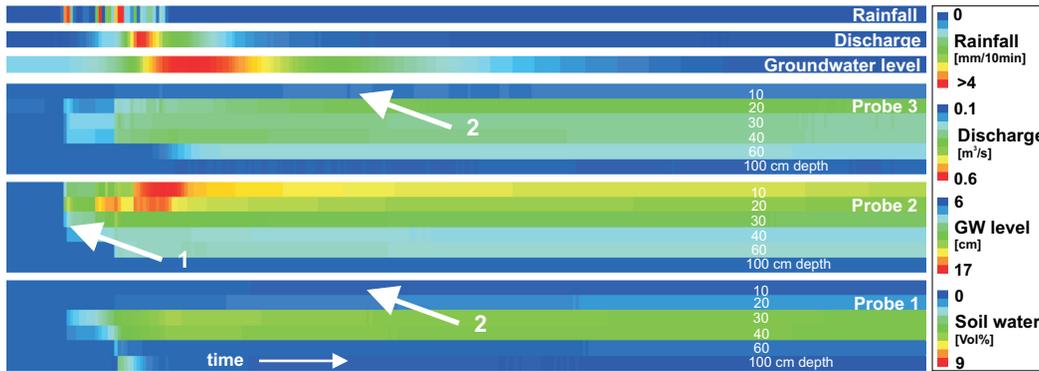
(a) Rainfall event 3 March 2005.
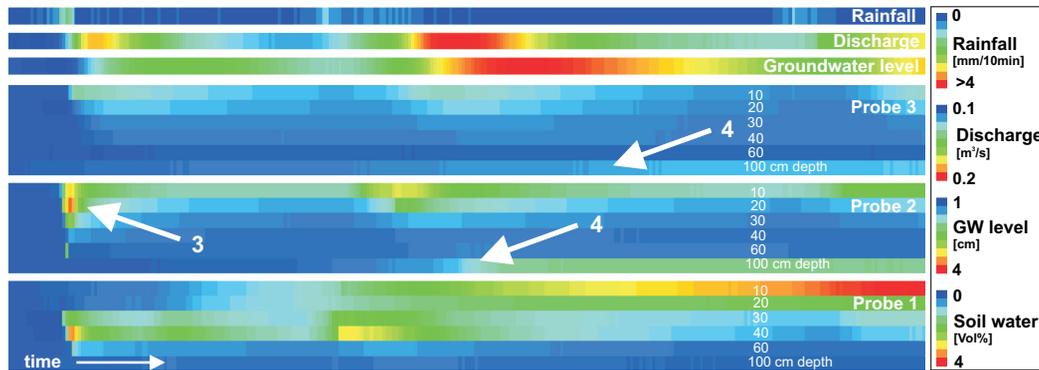
(b) Rainfall event 6 April 2005.

Fig. 2. Continued on the next page.
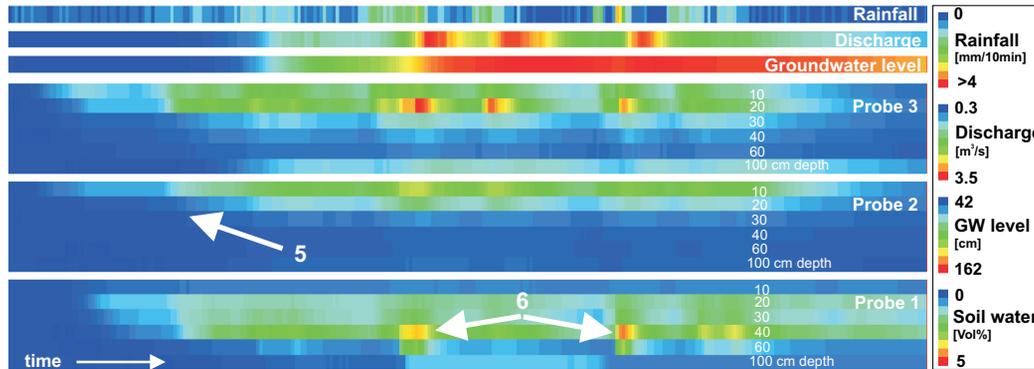
(c) Rainfall event May 27th 2005.

Fig. 2. Event response patterns of soil moisture for three rainfall events. Time is plotted on the x-axis. All plots show a two day period. Explanation of color bars from top to bottom: The uppermost bar shows 10-min rainfall intensity: dark blue is equivalent to 0 mm/10 min, dark red is equivalent to ≥6 mm/10 min. The two following bars show the increase of discharge and of groundwater level (at well W1), respectively. The color scale is stretched from minimum to maximum values. Down below follow the three wide bars representing the soil moisture response at the hillslope transect. The upper bar corresponds to the profile probe at the upper end of the slope (P3), the middle bar to the mid-slope probe (P2) and the lowest bar to the profile probe at the lower end of the slope (P1). Within these three wide colour bars, each stripe corresponds to a certain depth: 10, 20, 30, 40, 60 and 100 cm. 0 on the soil water color scale corresponds to antecedent moisture content. The arrows indicate the most prominent features and are numbered for easier reference.
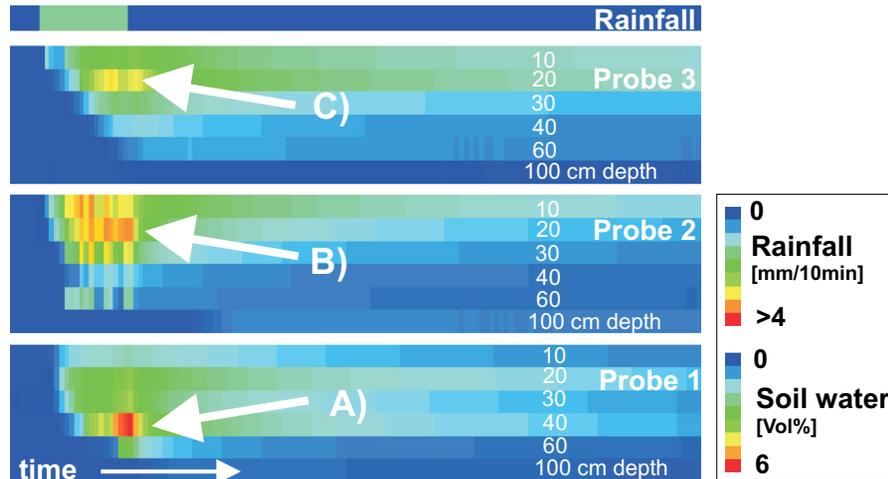
Fig. 3. Rainfall simulation with dye tracer at the locations of the soil moisture probes: amount of dye applied: 25 mm, intensity of application: 8.3 mm/h. The arrows A, B and C mark the most prominent patterns observed during this simulated rainfall event. The time scale of this plot has a length of one day.
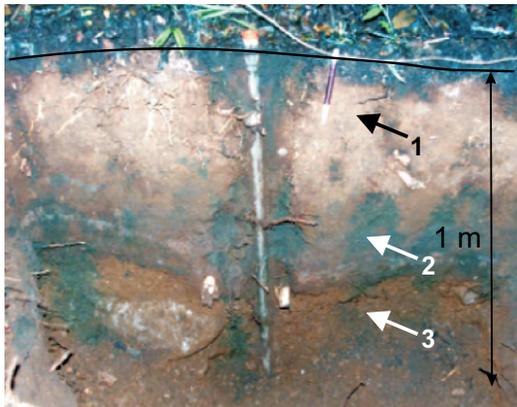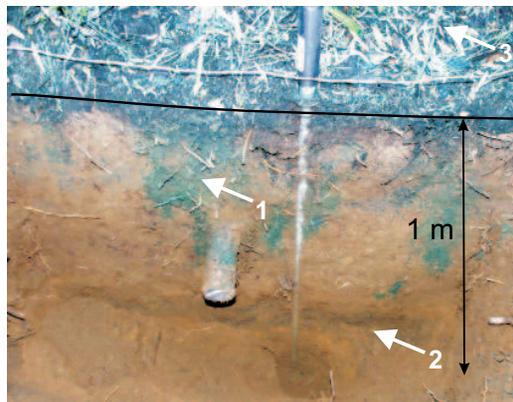
(a) Flow paths at profile probe 1
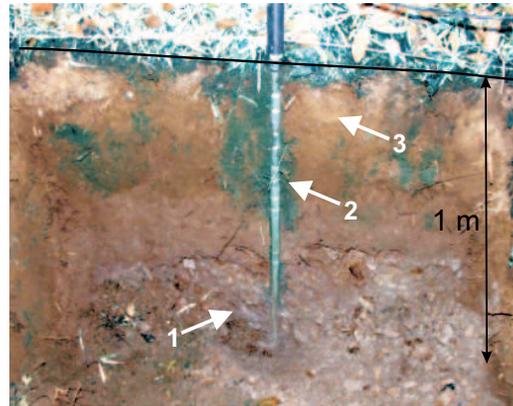
(b) Flow paths at profile probe 2

(c) Flow paths at profile probe 3

Fig. 4. Flow path visualization at the locations of the three continuously logging profile probes. The probes have a length of 1.2 m. The black line indicates the soil surface and the arrows the most important features in each photo. They are numbered for easier reference.
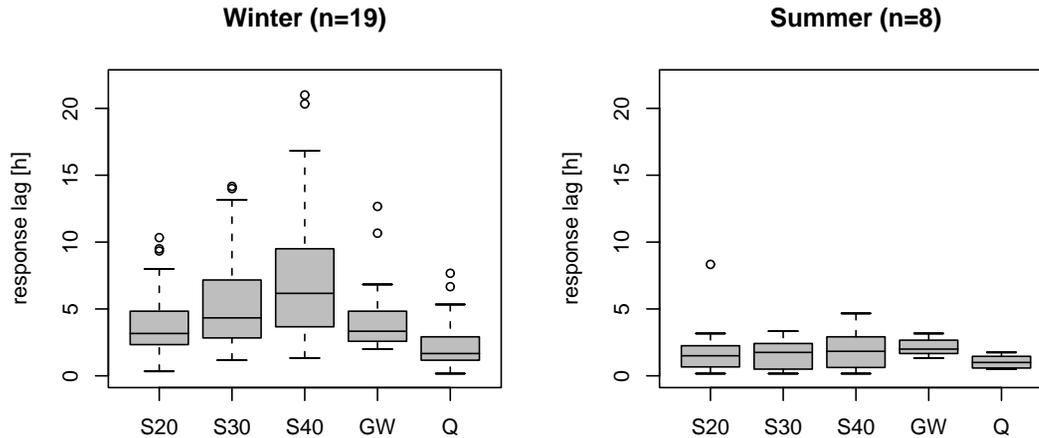
Fig. 5. Lag times of response in soil moisture, discharge (Q) and groundwater levels (GW) for 19 events in winter and 8 events in summer. Soil moisture response times are shown for 20, 30 and 40 cm depth (S20, S30, S40).
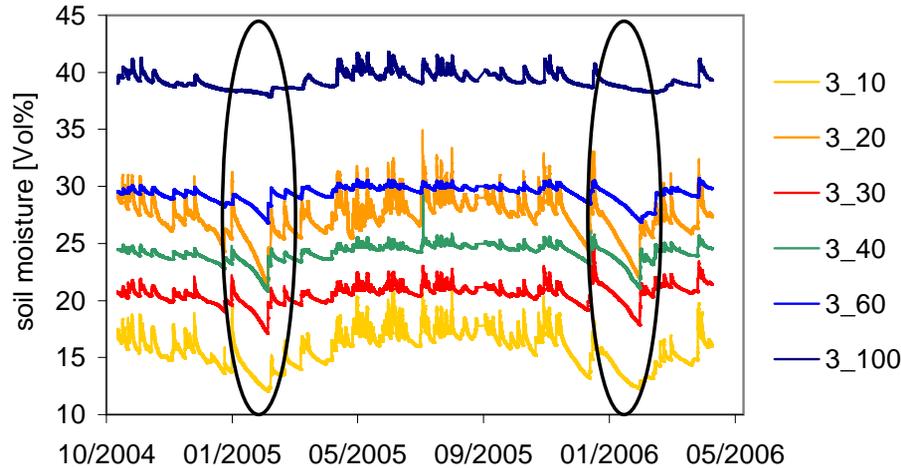
Fig. 6. Time series of soil moisture dynamics of probe 3. The short summer drying period is circled.
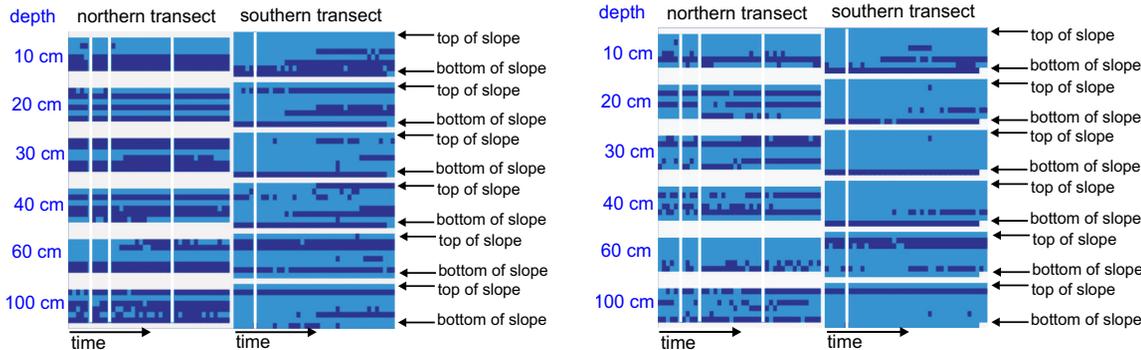
(a) Soil moisture pattern with threshold = median

(b) Soil moisture pattern with threshold = 75% quantile

Fig. 7. Manual soil moisture measurements at irregular intervals at 41 occasions during the field campaigns (December 2003–February 2004, October 2004–December 2004, November 2005–December 2005 and April–May 2006). The northern transect is shown on the left, the southern transect is shown on the right. Each block corresponds to one depth on that particular slope. Sensors are ordered as follows: lowest sensor on the slope is plotted on the lowest line of a single block. On the left transect there are 6 sensors, on the right transect there are 8 sensors. y axis is position on the slope (within bars) and depth (from one bar to the next), x axis is time (i.e. the 41 temporally irregularly spaced data points). Dark blue indicates measurements of soil moisture above the median **(a)** or the 75% quantile **(b)** of that depth, light blue are values below these thresholds. Missing data is indicated with white fields.

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(a) H4

(b) H5
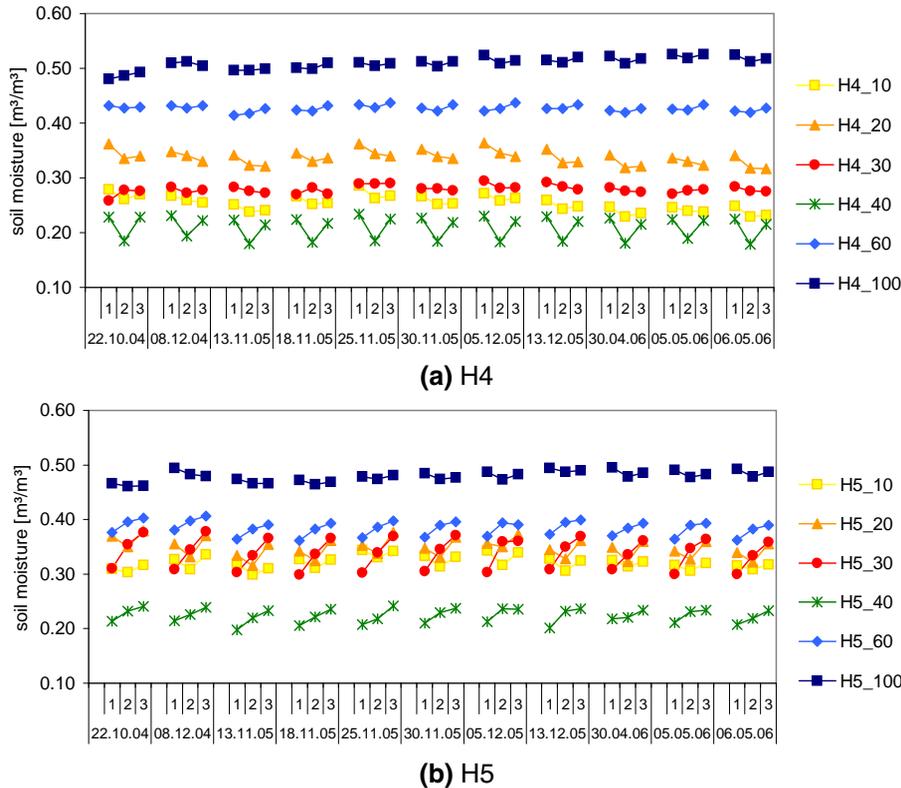
Fig. 8. Directional or small scale variability at manual measurement points H4 and H5. Measurements 1, 2, 3 at each date are repetitions within the same access tube, while rotating the probe by 120°. Note that the measurements are taken at irregular time intervals.

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