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Hillslope experiment demonstrates role of convergence during two-step saturation

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Abstract

A continuous and intense rainfall experiment on an artificial hillslope at the Landscape Evolution Observatory in Biosphere 2 resulted in saturation excess overland flow and gully erosion in the convergent hillslope area. An array of 496 soil moisture sensors revealed a two-step saturation process. First, the downward movement of the wetting front brought soils to a relatively constant but still unsaturated moisture content. Second, soils were brought to saturated conditions from below in response to rising water tables. Convergent areas responded faster than upslope areas, due to contributions from lateral subsurface flow. This led to the formation of a groundwater ridge in the convergent area, triggering saturation excess runoff generation. This unique experiment demonstrates, at very high spatial and temporal resolution, the role of convergence on subsurface storage and flow dynamics. The results bring into question the representation of saturation excess overland flow in conceptual rainfall-runoff models and land-surface models, since flow is gravity-driven in many of these models and upper layers cannot become saturated from below.

1 Introduction

Understanding hillslope runoff response to intense rainfall is an important topic in hydrology, and key to correct prediction of extreme streamflow, erosion and/or landslides. In humid regions, saturation excess is one of the dominant mechanisms of overland flow generation (Ward, 1984). Saturation excess occurs when the amount of incoming water exceeds the soil storage capacity at a certain location. Water can enter the soil reservoir through vertical infiltration or lateral subsurface flow (Freeze, 1972; Fiori et al., 2007). The development of saturated areas in catchments is central to the variable source area concept which states that the bulk of runoff is generated from a relatively small fraction of the total catchment area (Dunne and Black, 1970; Freeze, 1974). This source area is generally concentrated around a stream bed and

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can expand upslope into dry channels and laterally up hillslopes. The source areas expand and contract with the seasons (Dunne and Black, 1970) as well as during and after an intense rainfall event (Dunne et al., 1975; Bernier, 1985).

Many factors can influence the development of variable source areas. Firstly, soil hydraulic characteristics play an important role (Dunne and Black, 1970). For example, studies have shown that the presence of a capillary fringe, the zone of the soil profile above the groundwater table that is saturated at negative soil pressures (Abdul and Gillham, 1984), is critical in the formation of variable source areas (Abdul and Gillham, 1984, 1989). Other important factors include antecedent moisture conditions (Beven, 1977; Phi et al., 2013), rainfall characteristics (Dunne and Black, 1970) and catchment geomorphology (Beven and Kirkby, 1979). Analytical studies into the effect of slope shape on saturated areas showed that convergence of subsurface flow generates more saturated areas than planar or divergent alternatives (O'Loughlin, 1981; Troch et al., 2003). In field studies, however, the lack of a sufficiently dense array of subsurface sensors, and unknown variability of soil properties and initial/boundary conditions complicate the study of the role of convergence during saturation excess runoff generation.

Data from the hillslopes at the Landscape Evolution Observatory at Biosphere 2 in Arizona provide an opportunity to study hillslope hydrological processes under controlled conditions. A dense sensor network in the hillslope offers the potential to observe the hydrological response at a high spatial and temporal resolution. The hillslopes have been designed to improve understanding of the evolution of landscapes by studying the interactions between hydrology, ecology and soil science through years of experiments (Hopp et al., 2009). In the first years of the project, the hillslope will remain devoid of vegetation to limit the relevant processes, but vegetation will be added once the initial set of experiments is completed. The unique experimental setup permits constant rainfall rates and known initial and boundary conditions at hillslope scale. The first experiment consisted of a single intense rainfall event that that saturated part of the hillslope and led to unintended gully erosion. Previously, Niu et al. (2013) analyzed

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the hydrological response of this experiment using a physically based model. Here, we analyze sensor data collected within the hillslope, focusing on soil moisture data. In Sect. 2, we will describe the instrumentation of the hillslope and the characteristics of the rainfall event. The results of the data analysis with special attention for the effect of convergence during the formation of saturation excess runoff are presented in Sect. 3 and discussed in Sect. 4. In Sect. 5, we will conclude with a short summary.

2 Experimental setup

The hillslope at Biosphere 2 is 11 m × 30 m and has an overall slope of 10°. The slope has a convergent shape with a central trough running from the toe of the slope to 18 m upslope (see Fig. 1). The overall slope between the central trough and the far sides of the hillslope is 7°. The upslope, bottom and side boundaries are impermeable. At the toe of the slope a 0.5 m wide gravel section and a perforated plate followed by an open trough provide seepage face boundary flow conditions. The hillslope has been filled to a constant depth of 1 m using a granular basalt material ground to the texture of loamy sand. Laboratory testing determined that the material has a porosity of 0.39, a bulk density of 1.59 $\mathrm{g\,cm^{-3}}$ and a capillary fringe of approximately 30 cm. The corresponding Van Genuchten curve can be found in Fig. 3. Based on laboratory measurements, the saturated hydraulic conductivity of the material is estimated to be 0.67 $\mathrm{m\,d^{-1}}$ ($7.8 \times 10^{-6}\,\mathrm{m\,s^{-1}}$), however, later model calibration suggested that the effective saturated conductivity at hillslope scale is closer to 12.10 $\mathrm{m\,d^{-1}}$ ($1.4 \times 10^{-4}\,\mathrm{m\,s^{-1}}$) (Niu et al., 2013).

Subsurface flow was collected along the lower end of the hillslope, which is divided into six sections. From each section, the flow is routed to an electromagnetic flow meter and a tipping bucket, installed in series. A composite of measurements from these instruments gives accurate estimates of flow ($R^2 = 0.99$) when compared to known flow rates. Though instrumentation to measure overland flow was absent, estimates were made by two different methods. Before the rainfall was turned off, estimates were based

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on water balance analysis using measured precipitation, storage and subsurface flow data. The evaporation term was neglected because this period was during the night. After the rainfall was turned off, overland flow was collected every half hour and the flow rate was calculated based on the time that was needed to fill a fixed volume.

Within the hillslope, an array of 496 5TM Decagon (Pullman, WA, USA) soil moisture sensors recorded volumetric water content (VWC). These are located on a regular grid of 154 vertical transects (see Fig. 2). At each transect, sensors are placed at 3 or 4 depths between 5 and 85 cm below the soil surface. In addition, the groundwater table was measured by 34 vibrating wire piezometers (GeoInstruments, San Francisco, CA, USA) installed at the bottom of the soil profile. These are placed along the central trough and along several cross-sections of the hillslope (see Fig. 2). Also, ten load cells measure the total system mass, which can detect mass change equivalent to less than 1 cm of water.

Rainfall was applied to the hillslope by means of a sprinkler network and was measured by an electromagnetic flow meter in the irrigation line. The experiment consisted of a single continuous rainfall event with a constant intensity of 12 mm h^{-1} for a duration of 22 h. At this time, gully formation was observed and rainfall was stopped to prevent further unplanned changes to the topography of the hillslope. The total rainfall depth in this experiment is similar to events that can trigger discharge extremes and/or landslides in natural environments (Turner et al., 2010; Brauer et al., 2011; Nguyen et al., 2013). Initial conditions were relatively dry, with volumetric water content of 8–11 % in most of the hillslope, except for the bottom of soil near the central trough where conditions were wetter due to testing several weeks before (Fig. 4a). Data was collected from all instruments every 15 min.

3 Results

The rainfall event unexpectedly saturated part of the hillslope to the surface in and close to the central trough. Soil moisture time series show that the saturation process

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can be described by a step-wise rather than a gradual process at all depths: three relatively stable phases (1–3) are separated by two rather abrupt steps (see example in Fig. 5a). The results show volumetric water contents exceeding the maximum porosity determined in the laboratory. This was not observed during sensor calibration in which sensors in the same soil material were exposed to typical soil moisture values. Testing showed that the sensors read values exceeding the porosity of the soil when influenced by a capillary fringe or groundwater table. Therefore, saturation is assumed when measured volumetric water contents exceed the porosity determined in the laboratory. This assumption is further justified by comparing storage estimates based on spatial averaging of soil moisture data and load cell measurements. Spatial averaging of raw soil moisture data shows significant overestimation of storage compared to the change in system mass measured by the load cells. When a maximum moisture content of 39 % is used, however, estimates compare well to estimates based on load cell data (see Fig. 5b). Unfortunately, the piezometer data showed sensitivity to ambient temperature fluctuations, but could still be used for qualitative assessment of groundwater table dynamics.

The first step in the saturation process marks a sudden increase from initially dry conditions in the first phase to wetter, but still unsaturated conditions in the second phase (Fig. 5a) corresponding to the arrival of the infiltration front. After the passage of the infiltration front, the soil moisture content stays steady in time but decreases with depth (see Figs. 5a and 4b). The mean and median moisture contents at each depth in phase 2 are significantly different ($p < 0.01$). The second step marks a transition from unsaturated conditions in the second phase to saturated conditions in the third phase marking the arrival of the saturation front.

Phase 2 is observed first at shallower sensors hours after the start of the rainfall event ($T = 5.5$ h) and propagates downwards to the bottom of the soil profile, as shown for cross-sections A and B in Fig. 6. The third phase is observed first at the lower sensor depths and moves to the surface. While the propagation of the second phase is relatively even across the hillslope, that of the third phase is not. The third phase

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reaches the soil surface in and near the central trough (T = 16.5–22 h), while at the far sides and top of the hillslope it does not reach above 50 cm depth. This difference in expansion forms a groundwater ridge (see Fig. 6b). The development of the three saturation phases at hillslope scale is shown in Animation A1.

Subsurface flow at the bottom of the hillslope starts after 13 h of rainfall. Although instrumentation to directly measure overland flow was absent, estimates indicate that overland flow starts after a similar 14 h of rainfall and shows a sharp increase after about 20 h (see Fig. 7a). According to soil moisture data, saturation first reaches the surface after 18–19 h (Fig. 7b). Once the groundwater ridge reaches the surface, it expands along the side slopes of the central trough (see Fig. 6). The ridge creates a slightly reversed hydraulic gradient from the ridge in the direction of the side slopes. This gradient is strongest when the ridge has just reached the surface and slightly decreases in time. Longitudinal cross-sections shown in Fig. 6a reveal increasing saturation in the downslope direction. Saturation at the surface occurs along the lowest 20 m.

The hillslope is divided into a convergent and upslope part to compare the timing and speed of the saturation and subsequent drying processes (Fig. 2). The timing of step 1 is the time at which the soil moisture starts to increase and marks the transition from phase 1 into phase 2. In the same way, the timing of step 2 marks the transition from phase 2 to phase 3. The relationship between sensor depth and timing of step 1 is approximately linear for both parts (see Fig. 7b). The speed of the infiltration front based on this relationship is similar with 7.8 $cm\,h^{-1}$ in the convergent area and 6.7 $cm\,h^{-1}$ in the upslope area. However, the difference in timing is not significant based on the bootstrap confidence interval ($p = 0.15$).

Once the infiltration front reaches the bottom of the soil profile, a water column quickly forms and rises upwards (Fig. 7b). In contrast to the infiltration front, the development of saturation in the soil profile is significantly different between the two areas. First, at each soil depth saturation is observed significantly sooner in the convergent area than in the upslope area. In addition, step 2 is not observed near the

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surface in the upslope area, meaning that these areas do not reach phase 3. However, once a groundwater table develops, the speed of the rise is similar in the convergent and upslope areas, at 15.5 and 15.0 $cm\,h^{-1}$ respectively, or about two times faster than the infiltration front.

The difference between the convergent and upslope areas is also evident during the subsequent drying phase. The recession start time is defined as the time at which the soil moisture in a saturated location first drops below the maximum porosity. This phase is slower than the wetting phase and starts in relatively shallow or upslope locations before moving on to deeper locations and the convergent area (see Fig. 7b). Subsurface flow at the toe of the slope peaks just after the end of the rainfall event and shows a long recession tail (see Fig. 7a). Overland flow peaks at the time rainfall is turned off, though the size of this peak is very uncertain. Runoff over the surface then continues for more than 24 h after the sprinklers were turned off, causing erosion in the central trough. This erosion formed a gully extending 18 m upslope and changed the topography of the hillslope.

4 Discussion

The results show that the hillslope saturated by a stepwise process, as has been previously observed in small-scale experiments on slopes with planar geometry (Phi et al., 2013). Identification of the steps and phases is aided by the experimental setup with constant rainfall rates but is likely more challenging in natural catchments due to the rare nature of intense storms and the fact that soil moisture signals will also reflect the effect of varying rain rates. The steps are very consistent throughout the hillslope, though there are individual locations that seem to show different behavior. One of these is at the bottom of the soil profile at the toe of the slope, where sensors appear to stay in phases 1 and 2 and therefore these sensors do not reach saturation (Fig. 6). However, in these select locations the soil moisture content reaches over 38.5 %, or very close to the maximum slope porosity, suggesting that the sensors could in fact be in phase 3.

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The two-step process supports existing theories of water movement in hillslopes in which water first moves downwards through the unsaturated zone, then contributes to the formation of a groundwater table and subsequently moves downslope. This concept is an important assumption in previous physically based modeling studies (e.g. Robinson and Sivapalan, 1996). Yet, many conceptual hydrological models allow for only one-way interaction between reservoirs and do not allow for lateral redistribution of water (e.g. van Esse et al., 2013), which were crucial mechanisms of overland flow generation in this experiment due to the relatively shallow soil.

Field studies on saturation and overland flow generation have shown similar development of saturated areas in hillslopes (Dunne and Black, 1970; Wilson and Dietrich, 1987). One study focusing on the role of topography in throughflow generation on a hillslope with similar characteristics to the artificial hillslope in this study also suggested the importance of convergent soil water flow in the formation of the saturated wedge (Anderson and Burt, 1978). However, the resolution of data collected during field studies is often limited (Dunne and Black, 1970; Anderson and Burt, 1978) and results are affected by environmental factors, such as varying rainfall rates (Anderson and Burt, 1978) or bedrock permeability (Wilson and Dietrich, 1987). The present study of the saturation process uniquely combines high resolution data and controlled conditions with near-field scales.

The constant timing of the infiltration front across the hillslope supports the fact that absence of vegetation and other disturbances excludes the formation of instabilities which can have a large influence on flow paths, such as finger flow or macropore flow (e.g. Beven and Germann, 2013). In the case of a constant infiltration rate and a homogeneous soil, one would expect the equilibrium moisture content of phase 2 to be similar at all depths based on Richards' equation. Instead, our data show a significant decrease in soil moisture content with depth in the second phase in both convergent and upslope areas at hillslope scale (see Fig. 4b). The explanation for these observations cannot be determined based on the collected data and requires further research into the role of vertical heterogeneity in soil hydraulic properties.

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Another interesting observation is that the infiltration front speed is more than five times faster than the rainfall rate. The fact that the moisture content is relatively stable in time after the passage of the wetting front suggests that the specific flux is constant with depth. At the same time, this flux must be equal to the rainfall rate at the surface. This suggests that a limited portion of the available pore space in the soil is used in water transport. The saturation front has a higher speed than the infiltration rate, which can be linked to the smaller specific yield between the second and third phases than between the first and second phases. We would expect the rise of the saturation front to accelerate as the groundwater table due to decreasing available pore space (Fig. 4b), but we do not observe this at hillslope scale. In addition, we would expect the speed of the saturation front to be higher in the convergent zone than in the upslope area in the presence of flow convergence. Instead, the speeds in both areas are very similar at hillslope scale (Fig. 7b).

The formation of a groundwater ridge has been linked to the presence of a capillary fringe by several studies (Abdul and Gillham, 1984, 1989). Theory predicts that when rainfall is added to a soil whose capillary fringe reaches the land surface the groundwater table rises rapidly and a groundwater ridge is formed. The occurrence of groundwater ridging in the field is influenced by the amount of rainfall in an event, the number of days since the previous rainfall event and the depth of the initial groundwater table (Waswa et al., 2013). In previous studies, initial groundwater tables were closer to the surface than in upslope areas (Abdul and Gillham, 1984, 1989). As a consequence, the capillary fringe reached the surface for a limited distance from the stream. This condition can influence groundwater ridge formation because the addition of a small amount of rainfall saturates these areas quickly, while the upslope areas respond more slowly. In the present study, there was no initial groundwater table and the soil depth is uniform. This suggests that the formation of the groundwater ridge in the trough is not only affected by the presence of a capillary fringe, but also by subsurface flow from the side slopes and the upslope area due to the convergent topography. However,

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groundwater ridge formation at the toe of the slope is also influenced by wetter initial conditions.

The continuation of overland flow for a long period after rainfall had stopped indicates that lateral subsurface flow was a major contributor to overland flow generation in this experiment, signaling a persistent hydrologic connectivity between upslope and convergent areas. Previously, Sklash and Farvolden (1979) demonstrated that runoff in their study area could be dominated by either event or pre-event water depending on initial conditions. Under wetter conditions, such as was the case at the onset of runoff in the present study, overland flow and streamflow hydrographs were dominated by groundwater (Sklash and Farvolden, 1979). Initially, the subsurface component of overland flow in the present experiment was caused by the groundwater ridge alone. However, gully formation and expansion influenced flow paths in the hillslope. The erosion gully formed by the overland flow was limited to the central trough in the hillslope. A study of rill formation in the artificial Chicken Creek catchment showed a larger network of rills, but the longer and deeper main rill was similarly located along the convergent axis of the catchment (Hofer et al., 2012). It is expected that the steep sides of the gully in the present study increased local hydraulic gradients, increasing runoff generation and the related erosion while groundwater levels remained high on either side of the gully. In this way, the subsurface component of overland flow was enhanced by morphologic changes caused by erosion.

5 Conclusions and outlook

An experiment on a large experimental hillslope that resulted in overland flow and soil erosion provided a unique opportunity to study the importance of convergence on the development of saturation. Data collected from an array of 496 soil moisture sensors at a high temporal resolution show a two-step saturation process: a first step related to the downward propagation of the infiltration front and a second step characterized by saturation of the soil from below in response to rising water tables. Soil profiles in

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convergent areas responded sooner than soil profiles in upslope areas. In addition, soil profiles in the convergent area saturated completely, while the soil surface in the upslope area remained unsaturated. This difference created a groundwater ridge. Due to the uniform soil depth and lack of soil heterogeneity, the difference between the two areas can be attributed solely to lateral subsurface flow in the saturated zone of the soil profiles.

Our experimental data demonstrate the importance of convergence on subsurface flow and storage dynamics at the hillslope scale. Though the main concept supports existing theory in hillslope hydrology, several observations at the hillslope scale are not easily explained. One important question is how to explain the observed decreasing moisture content with depth despite constant infiltration rates and a homogeneous soil. Further research into vertical heterogeneity and small-scale processes is needed to explain the mechanisms behind these observations. Insight in these mechanisms is an important step to improve understanding of saturation excess overland flow generation and related natural hazards such as flash floods and landslides, and their representation in land surface models, many of which currently do not allow for lateral and/or upward movement of water.

Supplementary material related to this article is available online at http://www.hydrol-earth-syst-sci-discuss.net/11/2211/2014/hessd-11-2211-2014-supplement.zip.

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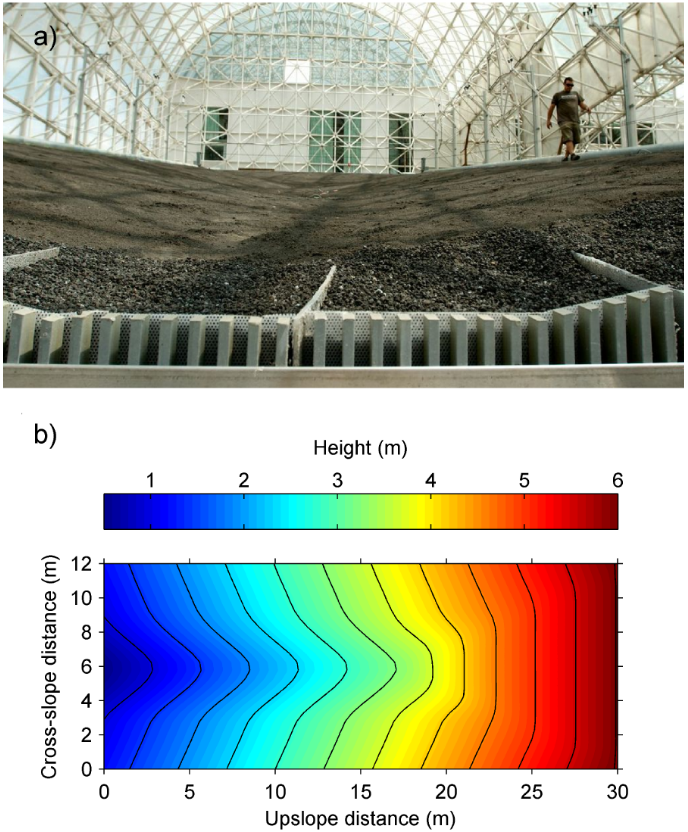

Fig. 1. Hillslope design. **(a)** Photo of one of the Biosphere 2 hillslopes. **(b)** Topographic map of the hillslope with contours (solid lines) drawn every 0.5 m. Note the convergent trough in the center. The soil has a constant depth of 1 m.

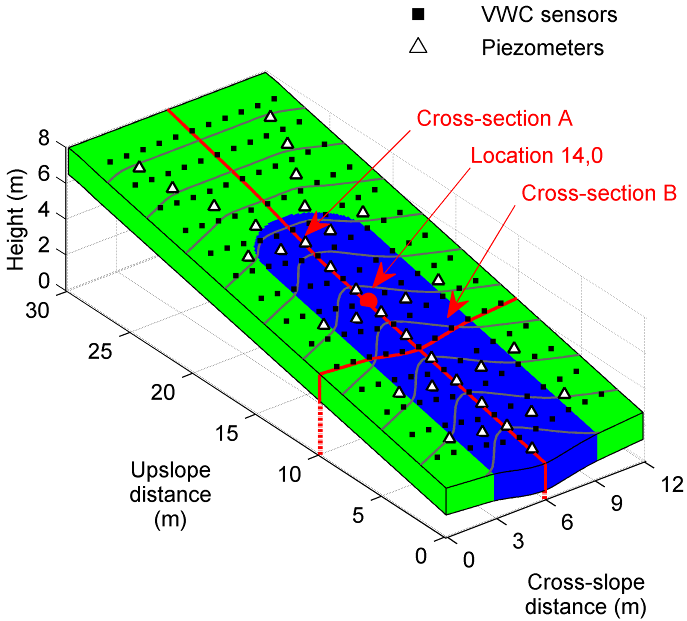

Fig. 2. Schematization of the instrumentation of the hillslope with a vertical exaggeration factor of 1.5. The figure shows contour lines (grey), locations of soil moisture sensors, piezometers, and cross-sections used for analysis. The convergent zone of the slope, defined as all locations within 3 m of the central trough, is shown in blue and the upslope area in green.

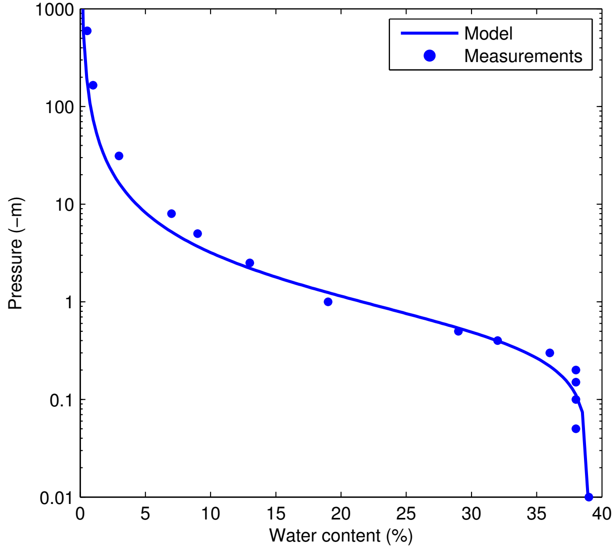

Fig. 3. Laboratory measurements of the water retention curve and the van Genuchten model that best fits the measurements.

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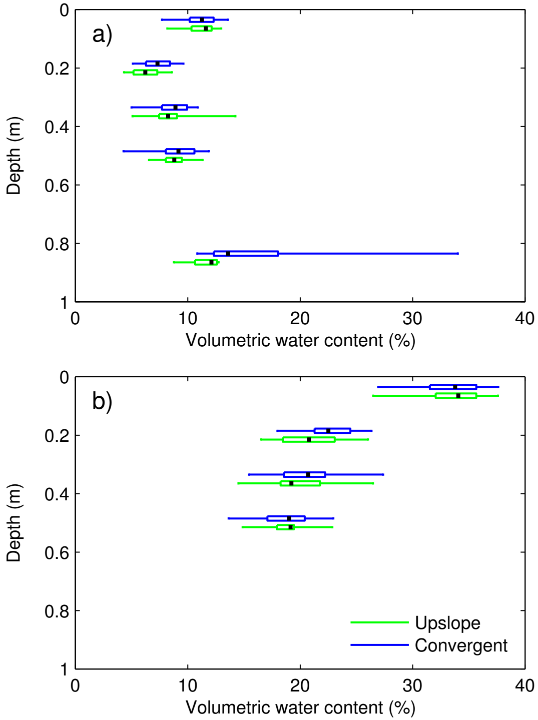

Fig. 4. Box-and-whisker plots show the volumetric water content in phase 1 **(a)** and phase 2 **(b)** for the convergent and upslope areas and for each sensor depth. The whiskers show the 5th and 95th percentiles. Sensor depths are slightly offset to improve visibility of the data.

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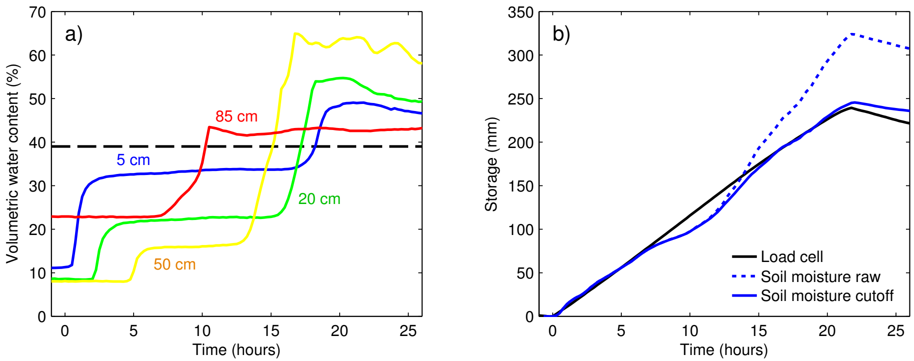

Fig. 5. Volumetric water content **(a)** and storage estimates **(b)** in time relative to the start of the rainfall event. The volumetric water content is shown for four sensors along a vertical transect at location (14, 0) where depths are relative to the surface. A horizontal line indicates the maximum porosity, above which locations are considered to be saturated. Storage estimates **(b)** relative to initial storage are derived from (i) load cell data, (ii) spatial averaging of raw soil moisture data and (iii) spatial averaging of soil moisture data with a cutoff of 39 %.

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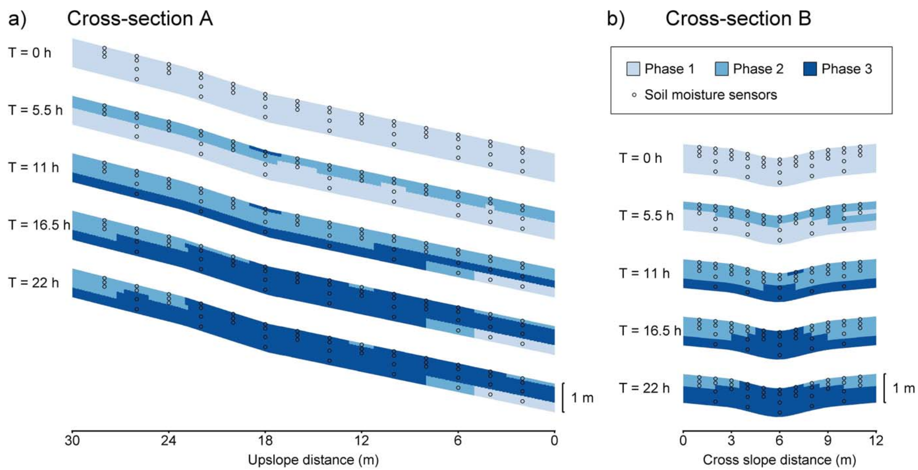

Fig. 6. The development of the two-step saturation between the start ($T = 0$ h) and end ($T = 22$ h) of the rainfall event for cross-sections A **(a)** and B **(b)**. Open circles show soil moisture sensor locations.

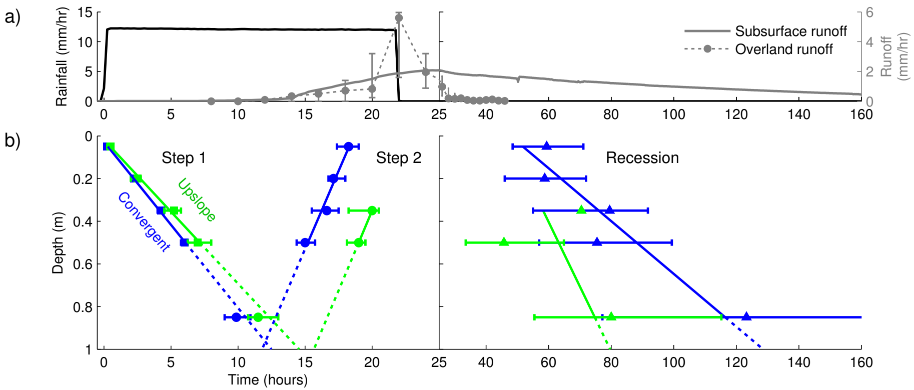

Fig. 7. The rainfall-runoff characteristic **(a)** and the timing of different phases of saturation and recession for the convergent and upslope areas **(b)**. Time is relevant to the start of the rainfall event and depth is relative to the soil surface. Overland flow estimates **(a)** are based on water balance analysis and volumetric measurements, and error bars express operator's uncertainty. In **(b)**, the median timing of each phase is shown with error bars representing the 95 % bootstrapping confidence interval of the median. Lines show best fits through the medians and are solid within the range of fitting and dotted when extrapolated.

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