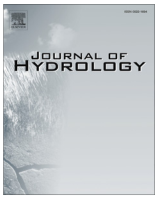
Journal of Hydrology 493 (2013) 1–15

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



Laboratory and numerical investigations of hillslope soil saturation development and runoff generation over rainfall events

Son Phi [a], William Clarke [b], Ling Li [a,c,*]

[a] *National Centre for Groundwater Research and Training, School of Civil Engineering, The University of Queensland, Brisbane 4072, Australia*
[b] *Schools of Civil and Chemical Engineering, The University of Queensland, Brisbane 4072, Australia*
[c] *State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, China*

ARTICLE INFO

Article history:
Received 22 January 2013
Received in revised form 31 March 2013
Accepted 5 April 2013
Available online 16 April 2013
This manuscript was handled by Corrado Corradini, Editor-in-Chief

Keywords:
Wetting front
Saturated zone
Surface and subsurface flow coupling
Soil pressure head response
MODHMS

SUMMARY

Runoff is a key process that controls the behaviour of a hillslope hydrological system. The study presented here aims to examine the mechanisms of runoff generation due to saturation excess by investigating the development of the subsurface saturated zone. Experiments were conducted on a hillslope system with a uniform slope (0.2) and a relatively homogeneous and highly permeable medium ($K_s = 1.28$ cm/min), subjected to high and constant surface recharges (0.51–0.69 cm/min). Two initial conditions prior to the rainfall events were set up in the experiments to represent relatively dry and wet antecedent soil conditions, respectively. Measurements showed that during vertical infiltration, local pressure head and soil moisture remained constant for a certain period, showing a 'waiting' behaviour. The saturated area formed initially at the slope toe, quickly rose to the surface and subsequently expanded to the upslope. When propagating in the upslope direction, the wetting front caused the pore-water flow to deflect in areas above the wetting front and at the slope base. With a wetter initial condition, the soil responded to the rainfall more quickly. The initial moisture conditions also altered the relation between the subsurface discharge and pressure head. Under the applied rainfall rates, the system reached a fully saturated condition and produced surface runoff. The rainfall intensity was found to affect the temporal variations and magnitude of surface runoff characteristics; however it did not seem to impose any significant effect on the maximum subsurface discharge rate. These results provide insight into the behaviour of the hillslope system in response to rainfall.

1. Introduction

Overland flow (surface runoff) is an important part of storm runoff, which occurs on the ground surface. The mechanisms of overland flow generation are generally classified as being due to infiltration excess or saturation excess (Smith and Goodrich, 2005). According to Freeze (1972), infiltration excess overland flow is the "overland flow due to saturation from above", whereas saturation excess overland flow is the "overland flow due to surface saturation from below".

Within the saturation excess runoff generation concept, understanding the dynamics of soil moisture and pore-water pressure is important to explain water runoff that occurs both on the surface and in the soil, as well as associated processes. The saturation excess mechanism provides the principle underlying the variable source area theory for runoff generation (Bernier, 1985; Dunne and Black, 1970; Dunne et al., 1975). Dunne and Black (1970) observed that stream water was recharged mostly from nearby saturated areas. Later studies have shown that the area producing runoff is not limited to the vicinity of the stream, but dynamically expands during rainfall events (Bernier, 1985). Whether the saturated area expands from a perennial stream or a local ephemeral channel somewhere upslope, it is of interest to understand the process of such expansion.

Many studies have been carried out to investigate the response of the soil moisture and pore-water pressure within hillslope systems during either natural rainfall events or experiments with artificial rainfalls produced by sprinklers (e.g., Nieber and Walter, 1981; Tani, 1997; Torres et al., 1998; Uchida et al., 2004; Melone et al., 2006; Essig et al., 2009). Based on their experimental data, Melone et al. (2006) analysed the infiltration excess overland flow process. Essig et al. (2009) conducted experiments with varied slopes and examined the role of slope in controlling overland flow production. These studies have provided evidence and shed light on the mechanisms of runoff generation.

Overland flow due to saturation excess is frequently observed in the low relief environment, which tends to experience a large fluc-

---

[*] Corresponding author at: National Centre for Groundwater Research and Training, School of Civil Engineering, The University of Queensland, Brisbane 4072, Australia. Tel.: +61 7 33653911.

E-mail address: l.li@uq.edu.au (L. Li).

0022-1694/$ - see front matter Crown Copyright © 2013 Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.04.009

tuation in the water table height (Elsenbeer, 2001). Abdul and Gillham (1989) applied artificial rainfalls to a mild slope (4°–9°), V-shape catchment. The water table was initially set to be shallow and relative flat. During rainfall, the water table was found to rise to the ground surface on both stream banks, but there was no significant water ponding on the stream bed (i.e., no stream stage rising). The results suggested that the groundwater discharge to the stream was less than the infiltration, leading to formation of water-saturated areas near the stream. When the water table rose near the stream, two slopes on the water table developed with one towards the stream and the other outwards from the stream. Using Br as a tracer to separate rain water and groundwater components, Abdul and Gillham (1989) found that on the saturated area, there was a small contribution of the groundwater in the overland flow. This is in contrast with infiltration excess runoff, which is fully sourced from the rain water in the overland flow. In a small pasture catchment of gentle slope gradients (less than 10%) of Eastern Amazonia, de Moraes et al. (2006) observed that the perched water table level, monitored by shallow wells, varied by 10–60 cm over rainfall events. In this area, the storm runoff generated by the saturation excess mechanism accounted for 60% of the total runoff events. The results showed the effect of the shallow water table on the formation of the subsurface saturated area in relation to the generation of saturation excess overland flow. It should be noted that both studies were conducted in gently sloping catchments, where the hydraulic head gradients driving water flow to the stream are generally small.

Bonell and Gilmour (1978) pointed out that on steep slopes perched water tables intensify the saturation overland flow. Their experimental sites were characterized by large slopes (45–62%) and a relatively low saturated hydraulic conductivity at a depth of 20 cm compared to that at the surface. The soil above the 20 cm depth was quickly saturated during the storm events. When the perched water table emerged to the ground surface, it produced exfiltration which combined with the overland flow associated with the rainfall that fell on the (saturated) area. More recently, Tani (1997) and Uchida et al. (2004) provided more details of the formation of the subsurface saturated area with the data of soil water pressure. Tani (1997) showed that the saturated area extended quickly upslope as indicated by the near bedrock tensiometric measurement along the slope. This behaviour was attributed to the spatially varying soil hydraulic conductivity and possibly the macro-pore flow (Tani, 1997). The data of the present study using a homogeneous porous medium showed a significant lag in response of upslope tensiometers. It appeared that the top soil became saturated well before the soil near the bed rock. This led to the progression of saturation conditions downwards from the soil surface. It has been found that in some cases soil saturation developed from the bottom to the top soil layers (Chow et al., 1988; Abdul and Gillham, 1989; de Moraes et al., 2006). This observation seems to be counter-intuitive as infiltration of rainwater would be expected to wet the top soil first. Uchida et al. (2004) found a correlation between the hillslope discharge and the upslope soil pore water pressure and the area of saturation. This correlation was particularly profound during the period of high discharge and in highly permeable soils. In their experiments, the saturated area was linked to the existence of positive soil water pressure at the bedrock, as measured by tensiometers along the longitudinal slope transect.

While the works of Tani (1997) and Uchida et al. (2004) were essentially carried out in a relatively shallow hillslope system bounded by impermeable bedrock, a number of studies conducted in more conductive catchments showed different results with regard to the development of the subsurface saturated area. In an intensively instrumented catchment of the Oregon Coast Range, USA, Anderson et al. (1997) and Montgomery and Dietrich (2002) found that the saturated area did not occur along the slope due to high permeable bedrock. The subsurface saturated area formed locally in the soil as a result of rising water table above the underlying bedrock (Anderson et al., 1997) but never emerged to the soil surface (Montgomery and Dietrich, 2002). Therefore, overland flow did not occur under sprinkler experiments or natural rainfall conditions because of the absence of subsurface saturation up to the ground surface in highly conductive soils (Montgomery and Dietrich, 2002).

Nieber and Walter (1981) carried out a sand flume experiment with a no flow boundary at the lower end of the flume. Water accumulated at that boundary and the water table, as a consequence, rose to the sand surface. The water table formed at the upper boundary at a later stage. The flow field was parallel to the flume bed for most of the flume length and diverted upward to the surface due to the blockage by the downstream no flow boundary. The experiment of Nieber and Walter (1981) illustrated the process of saturated area formation and expansion but the water accumulation process was affected by the no flow boundary that blocked the lateral flow. As pointed out by O'Loughlin (1986), the subsurface saturated area under natural conditions occurs locally as a result of inflow exceeding outflow.

To investigate the effect of the capillary fringe on runoff generation, Abdul and Gillham (1984) conducted sand flume experiments with different initial water table levels. Their results showed that when the water table rose to the sand surface, the hydraulic gradient created by the surface slope forced water to seep out from the groundwater to the lower part of the sloping surface. As in Nieber and Walter's experiments (1981), the obstruction of flow by the lower end flume wall played an important role in the formation of the saturated zone and the subsurface flow regime.

For the case with an open ended flume, the saturated area as defined by the water table was found to be controlled by the outflow at the outlet (Hilberts et al., 2005). With two types of slopes in the plane shape (linearly convergent or divergent in the direction to the outlet) and three different flume slopes, Hilberts et al. (2005) showed that the water table height at the steady state was affected by the combination of the slope shape and the slope gradient. For example, the highest water table was found for the convergent and low gradient slope. Since the major aim of Hilberts et al.'s experiments (2005) was to validate the hillslope – storage Boussinesq model (Troch et al., 2003) for the hillslope drainage process, they did not consider the rising phase of water table nor did they discuss in detail the effects of the slope properties on the water table dynamics.

Szilagyi (2007) examined the nonlinear response of hillslope runoff to rainfall using numerical models. The simulation domain consisted of a gentle slope (1%) with the surface and lower boundaries being set as free flow boundaries. The upper slope and bottom boundaries permitted no flow. The subsurface saturated area given by the water table showed a ridge near the stream. Szilagyi (2007) attributed the behaviour to the initially wetter condition of the area, which subsequently became saturated more quickly. However, close examination of the water table profile presented on Szilagyi's paper revealed that at the outlet boundary, the top part of the soil remained unsaturated. Further investigation on the effect of the boundary condition is still needed.

In the hillslope model of Ogden and Watts (2000), the lower slope section was controlled by a constant head boundary condition. Analyses based on the simulation results were conducted to examine the position of the intersection between the water table and slope surface at steady state under constant rainfall. This was repeated for a range of rainfall intensities, slopes, soil thicknesses, slope lengths and saturated hydraulic conductivities. Assuming that all the rainwater falling on the upper slope unsaturated area infiltrated the soil, Ogden and Watts (2000) derived an