

A MECHANISM FOR STORM RUNOFF GENERATION DURING LARGE RAINFALL EVENTS

R.J. McKinnon¹, J.F. Dowd¹, D.M. Endale²

AUTHORS: ¹ Department of Geology, The University of Georgia, Athens, Georgia 30602. ² U. S. Department of Agriculture, Agricultural Research Service, J. Phil Campbell Sr. Natural Resource Conservation Center, 1420 Experiment Station Road, Watkinsville, Georgia 30677
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Abstract. Flowpaths of stormwater from upland areas have long been the subject of major debate. A series of subsurface gutter experiments, situated on the mid-slope of a Piedmont catchment, were conducted to investigate a potential mechanism for the rapid mobilization of storm runoff from the unsaturated zone. Gutters were 1.45 m long and installed approximately 10 cm below the ground surface. Direct surface runoff was excluded from entering the gutters. Nearly a year of natural rainfall monitoring data showed a close relationship between rainfall intensity and the resulting runoff in the subsurface gutters. The gutter response closely followed the onset of intense rainfall and likewise “switched off” with the cessation of storm events. This behavior is not indicative of a saturated subsurface flow mechanism. Stable isotope analysis of runoff samples demonstrated that stormflow was comprised primarily of “old water,” which is water that was in the soil before the initiation of rainfall. Thus, the traditional explanations, macropore flow and overland flow, could not have been the dominant processes because they produce mainly “new water”. The data suggest that runoff from large storm events occurs when high intensity rainfall generates pressure waves that rapidly travel through the soil and induce pre-event water. Some hydrologists refer to this as a kinematic process. Research on this process at the field level will lead to understanding of stormflow pathways and the associated potential for transport of pollutants at the landscape scale.

INTRODUCTION

Large rainfall events cause large runoff events and a rapid mobilization of water in the shallow subsurface. During these events, there are many flow paths that can link hillslopes to headwater streams. Although there is considerable literature regarding flow paths, there is little understanding of what drives runoff delivery to the rapid flow paths during large precipitation events.

Isotopic studies have shown that new rain water is not a substantial contributor to the discharge appearing in headwater streams (McDonnell *et al.*, 1991; Collins *et al.*, 2000; Shanley *et al.*, 2002). Environmental tracers have

demonstrated that storm runoff is dominated by pre-rainfall event water that is stored in the subsurface. The mechanism by which pre-event water is quickly introduced into ephemeral rapid flow path networks during large precipitation events has not been clearly defined. Understanding the runoff generation mechanism will enable researchers to identify the areas of the watershed and conditions that cause runoff.

A field study monitoring rainfall and runoff on a hillslope was conducted to demonstrate a potential mechanism: pressure wave generated runoff under natural field conditions. Subsurface gutter collection systems were installed on a hillslope in a small, humid, vegetated catchment to collect stormflow. The timing, intensity, and volume of rainfall and runoff for the site were analyzed. Isotopic composition was analyzed to establish residence times and origins of storm runoff.

Previous Work. Small storms, as described by Anderson and Kneale (1982), do not generally result in large runoff events and the variable source area concept explains observed discharge (Beldring *et al.*, 2000). During large storm events, however, there is a rapid, high-volume response where the contributing watershed source area can exceed sixty-five percent (for example, Meyles *et al.*, 2003), far in excess of the variable source area.

Residence times of catchment soil water are important in inferring storm runoff during large storm events. Accumulating evidence from environmental tracer studies is causing a re-examination of the subsurface transmission of water from the hillslope to the stream (Shanley *et al.*, 2002). Kirchner (2003) details a “double paradox” that exists within catchment hydrology. Water in small, humid, vegetated catchments is quickly translated to the stream network during large runoff events, however, the water is not “new.” Stable isotopic analyses of stream water samples indicate storm runoff discharge into stream is largely “old” water - water that has been residing in a watershed prior to a rainfall event.

The mobilization of old water during storm flow events suggests the hypothesis that most runoff is quick subsurface flow (Hursh, 1944). However, this mechanism

does not explain the size and timing of most storm hydrographs.

Rasmussen *et al.* (2000) discusses a laboratory soil core tracer experiment that implies a kinematic flow process. The experiment utilized three intact saprolite columns that were irrigated by misting 0.3 mm of water, calcium chloride tracer, and flush water at various intervals in a repeating cycle. The cores were held at near-saturation and were outfitted with micro-tensiometers at various depths to measure soil tension at one minute intervals. The tracer velocity through the saprolite cores was consistent with preferential flow and took approximately two days for the chloride peak to appear in the uppermost lysimeter. Within minutes of mist application, however, some water was ejected from the core bottom. Rasmussen *et al.* (2000) found that the pressure wave celerity was approximately 1000 times faster than the chloride tracer velocity.

Torres (2002) discusses a study where tracer data from an irrigation experiment showed no spike increases in fluid pressure throughout the system. Therefore, it is likely that the tension response that indicates pressure wave translatory flow is related primarily to perturbation by rainfall, as demonstrated in Rasmussen *et al.* (2000). There is a pressure gradient between surrounding soils and macropores that keeps water from sitting in the rapid flow routes. A decrease in the pressure to near-zero leads to enhanced drainage and a release of water into the macropores (Torres and Alexander, 2002).

Site Description. The study area, as described by Endale *et al.* (2002), is a humid, vegetated watershed centered in the Southern Piedmont Physiographic Province. The experimental watershed is located at the J. Phil Campbell, Senior, Natural Resource Conservation Center, a part of the Agricultural Research Service agency of the United States Department of Agriculture, in Watkinsville, GA, about 12km south of Athens, GA. The hillslope soil is a sandy loam of the Cecil soil series (fine, kaolinitic, thermic Typic Kanhapludult) (Endale *et al.*, 2002).

Methods. Rainfall/runoff collection systems were installed on a hillslope plot (13 m x 10 m) in the mid-slope region. There were two replications of a subsurface runoff gutter collection systems. Repetition 1 (left) and Repetition 2 (right) are shown in Figure 1.

Rainfall and runoff were monitored for nearly one year. An ONSET tipping bucket rain gauge with a HOBO Event data logger was vertically mounted approximately 0.5 m above ground and used to record rainfall volume at 0.01 in intervals.

Each runoff collection system consisted of two trenches in which 1.25 m long gutters were inserted to collect subsurface stormflow. Steel plates were driven at

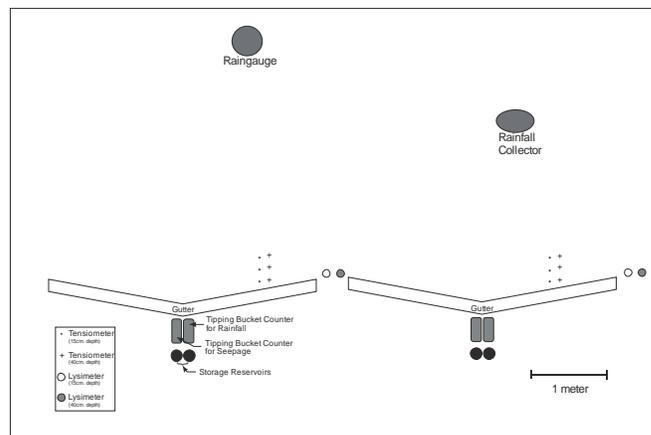


Figure 1. Watkinsville Study Plot--Map View.

an angle into the upslope soil face, approximately 10 cm at depth just above the Bt horizon to facilitate the seepage collection into the gutters. The drip plates induce soil water conditions similar to incipient channels or pipe-flow at a seepage face. A near-saturated wedge collects at the lip and transmits flow across the steel plate, which in turn drips into the gutters (Figure 2). The trenches were covered so that no direct precipitation or saturation overland flow could enter the subsurface gutters. Gutter flow was directed to an ONSET tipping bucket rain gauge that measured the volume and timing of flow.

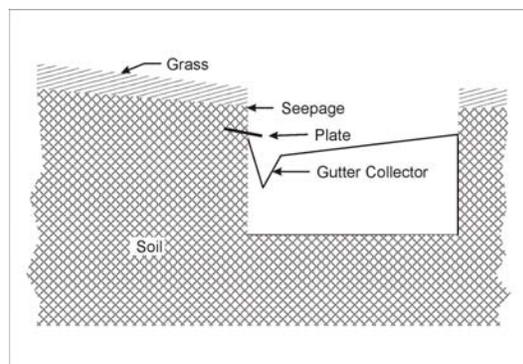


Figure 2. Gutter Design.

Stable isotopic analyses (deuterium) was conducted on the rainfall, runoff, and soil water samples that were collected following runoff generating storm events. Soil water was collected from suction lysimeters.

Results and Discussion. During the experimental monitoring period, fifty-one storm events were recorded. Although each event entails a unique combination of rain-

fall/runoff responses, deuterium composition, and antecedent conditions, representative storms will be used to summarize the response. Deuterium analysis of the gutter flow confirmed that runoff was similar to the lysimeter soil water isotopic value, thus old water dominated the gutter flow.

Figure 3 shows a typical subsurface gutter response to rainfall. After an initial lag the gutter flow mimics the rainfall, starting and stopping abruptly with rainfall. The initial lag is due to wetting of the hillslope, the amount required is dependent on antecedent conditions. Gutter flow only occurred when the hillslope was reasonably wet. Once the hillslope is “primed”, the gutter flow consistently responds within minutes to the onset of rain. Similarly, within a few minutes after rainfall stops, the gutter stops.

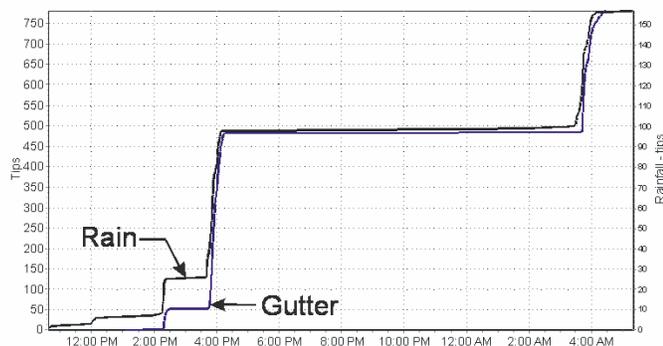


Figure 3. Rainfall and Gutter Response.

The largest storm on record (3.91 in) took place on October 6-7, 2005, as shown in Figure 4. This storm exhibited a rapid initiation of gutter flow and the abrupt on/off periods that mirrored the rainfall. Both gutter collection systems typically displayed similar results in timing and flow rates.

A storm that took place on April 22-23, 2005, is shown in Figure 5. Although it is a fairly small storm (0.42 in), it had the largest volume relative to rainfall. Early gutter response for this storm shows that gutter flow rate is dependent upon rainfall intensity.

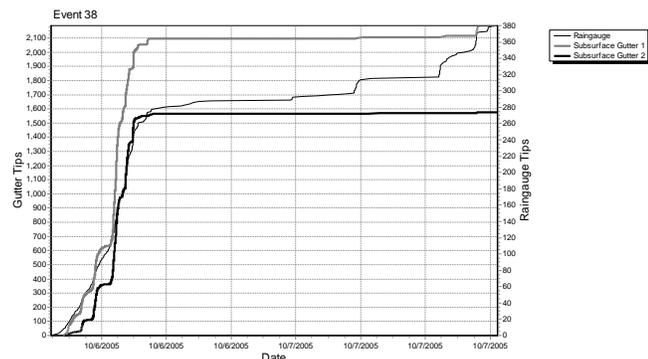


Figure 4. Rainfall/runoff, Oct. 6-7, 2005.

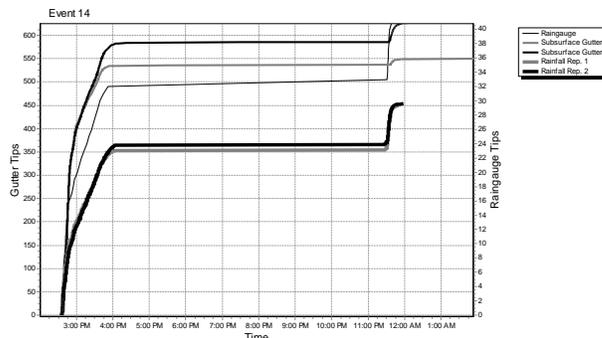


Figure 5. Rainfall/runoff, Apr. 22, 2005.

The behavior of the gutters is inconsistent with either saturated or unsaturated subsurface flow. Flow abruptly commences in the gutters with a constant rate; flow abruptly ceases after rainfall ends. This is not consistent with Darcian flow. The presence of old water in the gutters eliminates the possibility that the site is dominated by traditional macropore flow or Hortonian overland flow. In addition, no water table was observed in the pits. A pressure wave process, however, is consistent with all of the observed behavior.

Conclusions. The gutter experiment was designed to simulate the response in an ephemeral network. The behavior of the gutters demonstrates a pressure wave phenomenon delivering water to the pathway. On a watershed scale, this ephemeral network will grow or shrink during a storm, delivering water to the perennial stream. Future work will be directed towards identifying this network, thus the runoff generating areas of a small watershed.

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