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Factors influencing surface runoff generation from two agricultural hillslopes in central Pennsylvania‡

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Abstract:

The variable source area (VSA) concept provides the underlying paradigm for managing phosphorus losses in runoff in the north-eastern USA. This study sought to elucidate factors controlling runoff along two hillslopes with contrasting soils, including characterizing runoff generation mechanisms and hydrological connectivity. Runoff monitoring plots (2 m × 1 m) were established in various landscape positions. Footslope positions were characterized by the presence of a fragipan that contributed to seasonally perched water tables. In upslope positions without a fragipan, runoff was generated primarily via the infiltration-excess (IE) mechanism (96% of events) and was largely disconnected from downslope runoff. Roughly 80% of total runoff originated from the north footslope landscape position via saturation-excess (SE) (46% of events; 62% of runoff) and IE (54% of events; 38% of runoff) mechanisms. Runoff from the north hillslope was substantially greater than the south hillslope despite their proximity, and apparently was a function of the extent of fragipan representation. Results demonstrate the influence of subsurface soil properties (e.g. fragipan) on surface runoff generation in variable source area hydrology settings, which could be useful for improving the accuracy of existing runoff prediction tools. Published in 2009 by John Wiley & Sons, Ltd.

KEY WORDS hillslope hydrology; surface runoff generation; variable source area; landscape position; fragipan; agriculture

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INTRODUCTION

Management of nutrient losses from agricultural landscapes, particularly phosphorus, is tied to current concepts of surface runoff generation (Sharpley *et al.*, 1994; Gburek and Sharpley *et al.*, 1998; Sharpley *et al.*, 2001). The prevailing approach to controlling phosphorus losses from agriculture has been to target remedial practices to critical source areas of phosphorus export, where high concentrations of phosphorus coincide with a high potential for surface runoff to occur (Sharpley *et al.*, 1994). The variable source area (VSA) concept (Hewlett and Hibbert, 1967; Dunne and Black, 1970a; Ward, 1984) provides the underlying paradigm for identifying areas of high runoff potential, assuming that a small portion of the landscape produces the majority of runoff (Gburek *et al.*, 2002). For instance, the Phosphorus Index (Gburek *et al.*, 2000; Czymmek *et al.*, 2003), a tool used to guide field management of agricultural phosphorus, has been adopted by some states to predict runoff potential from two variables meant to represent VSA controls: e.g. distance from a stream and soil hydrologic drainage class. From a hydrological perspective, continued testing of such assumptions is needed to ensure accurate prediction of surface runoff potential.

Understanding the basis of VSA hydrology requires the distinction of saturation-excess (SE) and infiltration-excess (IE) runoff generation mechanisms. IE surface runoff occurs when rainfall intensity exceeds the infiltration capacity of a soil (Horton, 1933). SE surface runoff occurs when soils become waterlogged and no longer possess storage for additional rainfall (Dunne and Black, 1970b; Dunne, 1983). In the north-eastern USA, infiltration capacities of soils tend to be high in relation to typical rainfall intensities (Steenhuis and Muck, 1988; Walter *et al.*, 2003), but a predominance of shallow soils supports seasonally perched water tables, particularly in lower landscape positions where shallow lateral flow accumulates (Gburek *et al.*, 2006). Thus, SE runoff generation is typically tied to VSA hydrology (Ward, 1984).

The link between VSA hydrology and runoff generation mechanisms has been established via a variety of studies in the north-eastern USA. Studies by Srinivasan *et al.* (2002), Walter *et al.* (2003) and Needelman *et al.* (2004) concluded that the primary runoff generation mechanism in select New York and Pennsylvania landscapes was by SE produced by the intersection of perched water tables with the soil surface. The widespread distribution of fragipans and other soil discontinuities that impede vertical infiltration of water has been implicated in the perching of water tables, particularly in near-stream

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zones where shallow lateral flow accumulates (Walter *et al.*, 2000; Gburek *et al.*, 2006). Whereas fragipans are ubiquitous in glaciated regions (e.g. northern Allegheny Plateau of New York), they are primarily associated with colluvial materials in unglaciated regions (e.g. Valley and Ridge of Pennsylvania) and therefore coincide with lower landscape positions (Ciolkosz *et al.*, 1995). Thus, Walter *et al.* (2003) concluded that runoff generation in a New York watershed with extensive fragipans was almost entirely by the SE mechanism, while Needelman *et al.* (2004) observed SE runoff occur primarily on soils containing fragipans within a colluvial footslope.

Even in landscapes prone to VSA hydrology, climatic variables play a key role in determining the extent and nature of surface runoff. Factors such as rainfall duration, rainfall amount, and rainfall intensity all will affect the frequency, occurrence, and predominant runoff generation mechanisms observed during particular events (Ward and Elliot, 1995). For example, Srinivasan *et al.* (2000) studied runoff generation in a small agricultural watershed in central Pennsylvania and found that SE surface runoff was typically produced by frequent, low-intensity spring storms whereas IE surface runoff was favoured by infrequent, high-intensity summer thunderstorms. Similarly, Walter *et al.* (2003) evaluated the prevalence of IE surface runoff in the Catskills region of south-central New York and reported that although IE runoff was rare, it would most likely occur during the summer months (June–September) when high-intensity storms were most common. In addition, Dunne and Black (1971) and Dunne (1983) emphasized the importance of snowmelt runoff events during winter, which can be produced by SE mechanisms when melting snow raises the shallow water table to the surface or IE mechanisms if significant soil frost impedes infiltrating water.

An extension of the VSA paradigm to agricultural management is that runoff generated by the SE mechanism tends to be hydrologically connected to stream flow, whereas IE runoff may not (Srinivasan *et al.*, 2002). Hydrological connectivity (Bracken and Croke, 2007) refers to the passage of water from one part of the landscape to another. Based on VSA hydrology, one would expect that surface hydrologic connection would depend on the connection between saturated areas in the landscape (Bracken and Croke, 2007), which in turn would be affected by the distribution of soil properties supporting the formation of perched water tables. If areas down slope of a zone of runoff generation are not saturated, then there exists a possibility that runoff will infiltrate in such areas, expunging its potential to transport sediment and reactive contaminants such as phosphorus to the stream. Therefore, events that produce larger areas of saturation that are hydrologically connected to a stream pose a greater risk to watershed nutrient losses than events that only saturate limited areas. In fact, Srinivasan *et al.* (2002) observed that runoff generated by IE mechanisms tended to be hydrologically disconnected whereas runoff by SE mechanisms was hydrologically connected.

This study sought to assess factors related to surface runoff generation along a hillslope containing contrasting soils. The overall goal of this study was to compare surface runoff occurrence and frequency and identify principal surface runoff generation mechanisms at three different landscape positions on an agricultural hillslope. The importance of flow pathways and the scales of runoff production also were explored using open and closed runoff plots. The results of this study have potential implications for commonly used metrics that assess the risk of surface nutrient transport in agricultural landscapes (e.g. the Phosphorus Index).

MATERIALS AND METHODS

Study area

The study was conducted within the Mattern watershed (11 ha) located in the Ridge and Valley physiographic province of east-central Pennsylvania. The Mattern watershed is situated within the larger WE-38 experimental watershed (726 ha) (see Pionke *et al.*, 2000 and references therein for more details on WE-38), and is a tributary to the Chesapeake Bay estuary (Figure 1). The climate is temperate and humid, with average annual precipitation of approximately 1060 mm based upon 35 years of data (1968–2002) collected near Klingerstown, PA. Average annual streamflow draining the Mattern watershed was about 10 cm for the period 2003–2006. Elevations in the watershed range from about 265 m to 288 m above mean sea level.

Soils found in the Mattern watershed were formed in shale, siltstone, and sandstone residuum and colluvium. A somewhat poorly drained colluvial Albrights soil (fine-loamy, mixed, semiactive, mesic Aquic Fragiudalf) was located at the base of the hillslopes nearest the stream channel. The Albrights soil formed in colluvial materials and contained a fragipan as well as a high clay-content argillic horizon (Needelman, 2002). Prior to the initiation of the study, we observed prolonged surface saturation of portions of the Albrights soil during periods of extensive precipitation. In contrast, a well-drained residual Berks soil (loamy-skeletal, mixed, active, mesic Typic Dystrudept) was found in residual materials at the middle and upper portions of the hillslopes (Figure 1).

Land use within the Mattern watershed is dominated by agriculture (83%), with small patches of forest land (17%) confined to the top of the north hillslope and the mouth of the watershed. During the course of the study (2002–2004), the watershed was contour-cropped and divided into conventionally tilled fields that were rotated between corn (*Zea mays* L.), soybean (*Glycine max* L.), and alfalfa. The lower portion of the north hillslope typically was too wet for heavy equipment access (corresponded to location of the Albrights soil), and therefore this area was not actively farmed.

Site instrumentation and runoff monitoring

Surface runoff monitoring plots were installed at three landscape positions (Conacher and Dalrymple, 1977) on

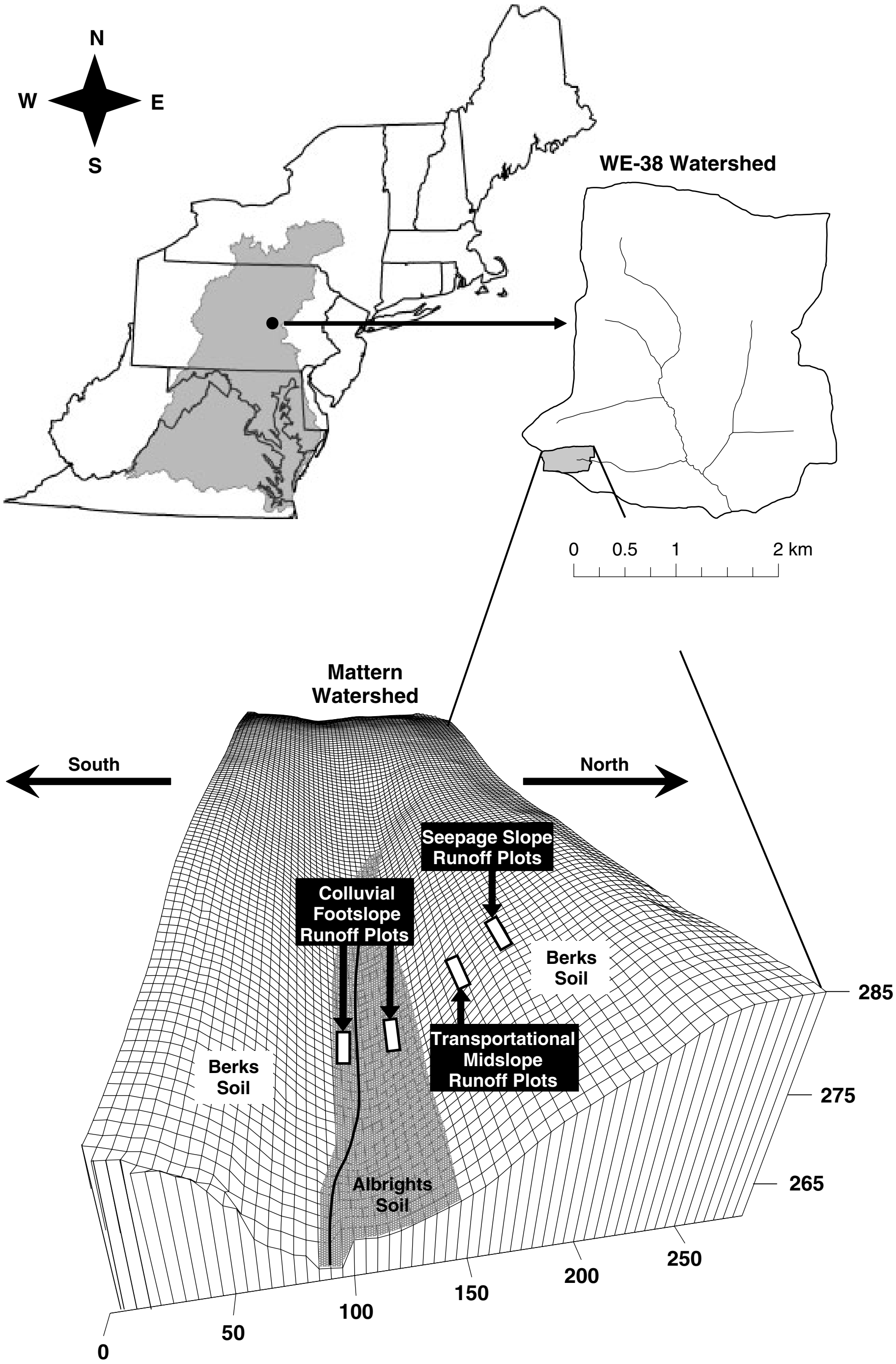

Figure 1. Map showing the location of the Mattern Watershed within the Chesapeake Bay (grey-shaded region in upper-left panel) and the WE-38 Experimental Watershed (upper-right panel). The map also shows the location of experimental runoff plots at different landscape positions along the north and south hillslopes (lower panel). On the lower map panel, units for horizontal distances are given in meters whereas units for vertical distances are given in meters above mean sea level

the north hillslope and at one landscape position on the south hillslope (Figure 1). The runoff study sites were selected to compare the effects of soil, slope, and landscape position on runoff hydrology. The three positions on the north hillslope included the seepage slope (Berks soil, 12% slope), the transportational midslope (Berks soil, 32% slope), and the colluvial footslope (Albrights soil, 18% slope). On the south hillslope, plots were established only at the colluvial footslope position (Albrights soil, 10% slope).

At each landscape position, four pairs of 1 m wide by 2 m long runoff plots were installed along a single elevation line (Figure 2). Each pair consisted of a closed and an open plot (Figure 2), which were designed to assess the importance of flow pathways and hydrologic connectivity during precipitation events of varying amounts, durations, and intensities. Closed plots were isolated on the top three sides by steel frames, which permitted runoff collection only from within the plot itself. The steel frames were 10 cm high, with the first 5 cm of the frame

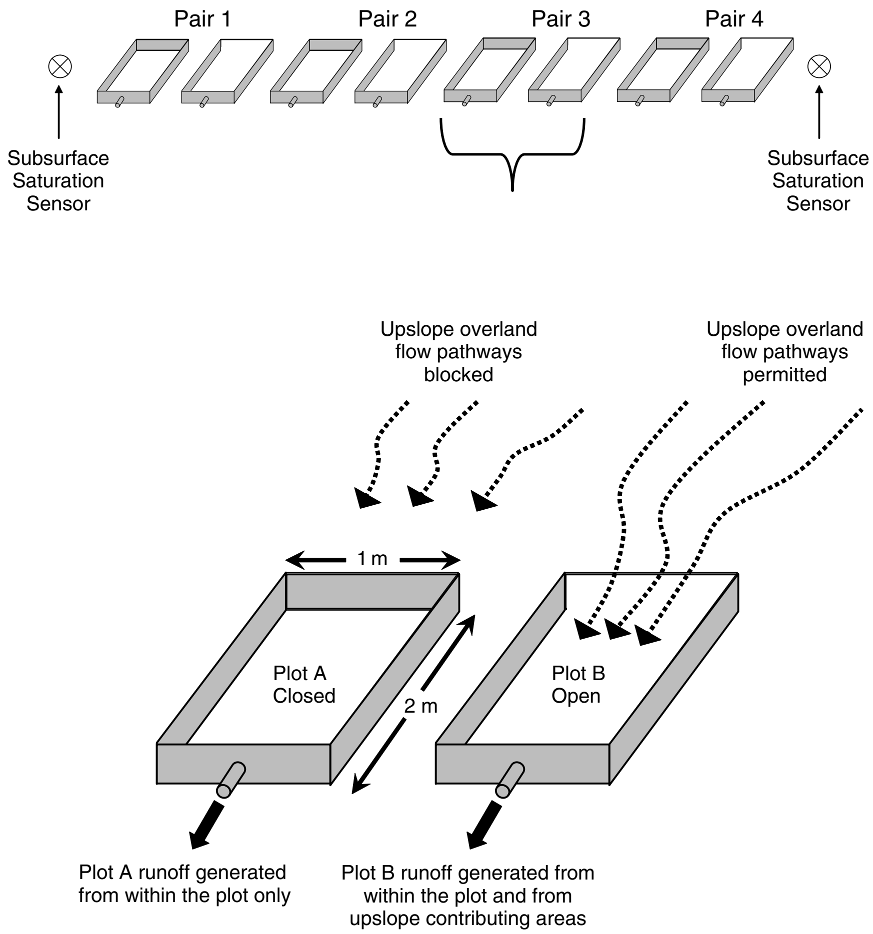

Figure 2. Layout and design of paired open and closed runoff plots

driven into the soil and the remaining 5 cm extended above the ground surface. Open plots did not have the solid steel frame on the upper 1 m wide side, and therefore runoff could be collected from within the plot itself and from flow pathways that originated upslope of the plot (Figure 2). Gutters were inserted 5 cm into the soil at the lower end of each plot.

Depth to the shallow water table was measured using subsurface saturation sensors designed by Srinivasan *et al*. (2000). Each subsurface saturation sensor was a 2 mm thick printed circuit board with six sensor pins used to detect the water table depth at 1 (soil surface), 5, 10, 20, 30, and 45 cm depths at 5 min intervals (see Srinivasan *et al*., 2000 and 2002 for more details on sensor design, operation, and installation). Two subsurface saturation sensors were installed at each landscape position, one at each end of the four pairs of runoff plots (Figure 2).

Once all instrumentation was completed, surface runoff monitoring was begun in July of 2002 and continued to December of 2004. A total of 93 surface runoff producing events were sampled during the 2·5-year study period including rainfall, rain-on-snow, and snowmelt runoff events (Table I). Total rainfall was monitored at 5 min intervals using a tipping bucket rain gauge installed at the seepage slope landscape position (Figure 1), and this permitted the characterization of each event in terms of duration, rainfall amount, and rainfall intensity (Table I). Surface runoff was collected in 10·5 L containers located at the base of each plot, and the total volume of runoff was measured at the end of each event.

During the course of the study, it was recognized that the total surface runoff volume from larger events occasionally exceeded the 10·5 L capacity of the collection

Table I. Frequency of rain, rain-on-snow, and snowmelt runoff events sampled during the study period

Year	Season	Types of runoff events		
		Rain	Rain-on-snow	Snowmelt
2002	Winter	—	—	—
	Spring	—	—	—
	Summer	9	0	0
	Fall	12	1	0
2003	Winter	3	4	4
	Spring	9	0	0
	Summer	20	0	0
	Fall	9	0	0
2004	Winter	3	0	1
	Spring	8	0	0
	Summer	8	0	0
	Fall	2	0	0

containers, especially in the footslope landscape positions. As a result, flow splitters were installed in each of the plots in July 2004. The flow splitters diverted a small fraction of the total runoff to an automated tipping bucket rain gauge so that runoff volumes from large events could be measured more accurately.

Data interpretation and analysis

At each landscape position, surface runoff generation mechanisms were interpreted from data obtained from the runoff plots and two subsurface saturation sensors, one on each end of the four pairs of plots (Figure 2). We averaged the data between the two subsurface saturation sensors at each landscape position and the maximum of that average was recorded for each runoff event. Measured runoff was considered SE surface runoff when the maximum average water table was at or near the surface (<5 cm) (Needelman *et al*., 2004). Surface runoff that occurred when the maximum average water table depth remained greater than 5 cm below the soil surface for the entire event was considered IE surface runoff.

Additional interpretation of runoff generation mechanisms was aided by creating maps of surface soil saturation regions during the course of the study. Surface saturated areas were mapped once or twice per month by walking the perimeter of wet soil areas using a hand-held global positioning system (GPS). These areas were readily delineated by naked eye.

A total of 93 events were sampled during the study, but not every event produced runoff at each sampling location, which resulted in non-normally distributed data that were positively skewed. As a result, nonparametric statistics were used to conduct the statistical analysis. Differences in runoff volume between open and closed plots were analysed using Wilcoxon's signed rank test (analogous to paired t-test). Differences in runoff volume between landscape positions were analysed using the Kruskal–Wallis test (nonparametric ANOVA). Treatment differences discussed in the text were significant at $\alpha = 0{\cdot}05$. All statistical analyses were conducted in SAS (SAS, 2004).

RESULTS AND DISCUSSION

Climatic trends

The 2·5 year study period within the Mattern watershed was wetter than the long-term average recorded at the primary rain gauge within the WE-38 experimental watershed. Annual precipitation amounts within the Mattern watershed were 1265 mm and 1224 mm for 2003 and 2004, respectively (Table II). In comparison, long-term (1968–2004) mean annual precipitation recorded within the WE-38 experimental watershed was 1056 mm.

On a seasonal basis, the majority of rainfall that fell within the Mattern watershed in 2003 and 2004 occurred during the summer months, which were wetter than the long-term summertime mean recorded at WE-38 (Table II). The fall and spring months represented the next two most important periods for rainfall accumulation in the Mattern watershed. The winter months were the driest periods of 2003 and 2004, and most of this precipitation fell as rain. A few significant snowfalls did occur during the study period including the President's Day snowstorm on 17 February 2003, which deposited about 430 mm (17 in) of snow. While infrequent in nature, these snow events did create opportunities for surface runoff due to snowmelt and rain-on-snow (Table I).

The majority of monitored rain storms ($\sim$99%) had return periods less than 2 years based on the methods of Aron *et al*. (1987), which take into account storms of varying duration (Table II). Overall, the largest 1 h and 24 h rainfall amounts occurred during the summer months, which was in part due to the occurrence of short-duration thunderstorms with high intensity rainfall (Figure 3a). While thunderstorms were most common during the summer, storms during the winter, spring, and fall typically included short-duration events with small rainfall amounts (Figure 3b) and longer duration events that produced moderate rainfall amounts (Figure 3c). The largest single event was a long-duration storm that occurred late in the summer of 2004 (17–18 September 2004) and was caused by the remnants of Hurricane Ivan. This event produced the greatest 1-hr rainfall intensity (29 mm h^{-1}) and the largest 24-hr rainfall amount (86 mm) (Table II, Figure 3d). Rainfall from the storm, which lasted 27 h, totaled 147 mm, ranking it as a 10 year return-period storm and the most unique event that occurred during the study.

Observed trends in runoff

Surface runoff was measured in both open and closed runoff plots in order to assess whether there were any differences due to overland flow pathways. Preliminary analyses using Wilcoxon's signed rank test did not show any significant ($P < 0{\cdot}05$) differences between open and closed plots on surface runoff volumes at a given landscape position. As a result, the majority of the results and discussion section focuses on results obtained from the open runoff plots unless otherwise noted.

Substantial differences were observed in the frequency, occurrence, and amount of runoff produced at the four landscape positions monitored in the study. The north footslope plots located in somewhat poorly drained Albrights soil produced measurable runoff ($>0{\cdot}01$ L) during 81 out of 93 monitored runoff events. This rate of runoff production was 1·3 times more frequent than the transportational midslope plots (63 events) and 2·8 times more frequent than the seepage slope plots (29 events), both of which were located farther up the north hillslope in well-drained Berks soil (Figure 1 for plot locations). In addition to running off more frequently, the north footslope landscape position produced six times more total runoff (555·9 L) than the transportational midslope position (90·5 L) and 12 times more total runoff than the seepage slope position (46·3 L). It should be mentioned that surface runoff from north

Table II. Comparison of annual rainfall (mm), maximum 1-hour rainfall, and maximum 24-hr rainfall observed during the Mattern study (2002–2004) to long-term climate data recorded within the WE-38 experimental watershed. Return periods (years) are listed in parentheses to the right of Peak 1-Hr and Peak 24-Hr rainfall values

Location	Time Period	Season	Rainfall Amount (mm)[†]	Peak 1-Hr Rainfall (mm)[†,‡]	Peak 24-Hr Rainfall (mm)[†,‡]
Mattern Watershed	**2002**	Winter			
		Spring			
		Summer	202	16 (<1)	42 (<1)
		Fall	334	7 (<1)	39 (<1)
		Annual	**–**	**16 (<1)**	**42 (<1)**
	2003	Winter	221	5 (<1)	33 (<1)
		Spring	247	8 (<1)	38 (<1)
		Summer	466	24 (<1)	47 (<1)
		Fall	330	14 (<1)	40 (<1)
		Annual	**1265**	**24 (<1)**	**47 (<1)**
	2004	Winter	188	6 (<1)	27 (<1)
		Spring	364	22 (<1)	36 (<1)
		Summer	424	29 (1)	86 (2)
		Fall	249	13 (<1)	32 (<1)
		Annual	**1224**	**29 (1)**	**86 (2)**
WE-38 Watershed	**Mean***	Winter	211	07 (<1)	35 (<1)
		Spring	315	16 (<1)	52 (<1)
		Summer	292	11 (<1)	50 (<1)
		Fall	239	10 (<1)	40 (<1)
		Annual	**1056**	**11 (<1)**	**44 (<1)**
	Min*	Winter	91	3 (<1)	16 (<1)
		Spring	165	3 (<1)	23 (<1)
		Summer	119	5 (<1)	20 (<1)
		Fall	119	3 (<1)	20 (<1)
		Annual	**716**	**3 (<1)**	**16 (<1)**
	Max*	Winter	358	30 (1)	86 (2)
		Spring	557	86 (>100)	152 (25)
		Summer	493	25 (<1)	102 (5)
		Fall	458	51 (10)	124 (10)
		Annual	**1401**	**86 (>100)**	**152 (25)**

[†] Long-term statistics on annual rainfall amounts and 24-hour rainfall amounts were calculated using data from 1968–2004. Long-term statistics on 1-hr rainfall amounts were calculated using data from 1968–1993.
[‡] Return intervals for 1-hr and 24-hr storm events were estimated using methods developed by Aron *et al*. (1987)

footslope plots was affected by the 10·5 L maximum sampling capacity, therefore differences may be greater than what is reported. On an event basis, median runoff production at the north footslope plots (8·1 L per event) was significantly ($P < 0{\cdot}05$) greater than median runoff production at the remaining three landscape positions (Figure 4). Overall, the 555·9 L of runoff from the footslope position accounted for 80% of the total runoff (692·7 L) produced from the north hillslope during the study. These results support the findings of earlier studies using natural (Needelman *et al*., 2004) and simulated (Kleinman *et al*., 2006) rainfall events demonstrating that colluvial soils (Albrights) produced significantly greater runoff volumes than residual soils (Berks).

Trends in runoff from the north and south footslope positions offer compelling insight into the role of landscape processes on runoff generation. Although both sets of plots were established in the same soil map unit, the slopes differed in the extent of the fragipan-containing Albrights soil (Figure 1). On the north hillslope, the Albrights soil extended about 20 m upslope of the runoff plots. On the south hillslope, the Albrights soil extended only 5 m upslope of the runoff plots before immediately transitioning to well-drained Berks soil. Over the course of the study, the footslope plots on the north hillslope ran off 1·7 times more frequently (81 events vs 49 events) and produced five times more runoff (555·9 L vs. 114·5 L) than the footslope plots on the south hillslope. Again, the effects of using 10·5 L containers may actually underestimate the magnitude of this difference. This is consistent with a larger VSA zone on the northern hillslope in association with the broader distribution of the Albrights.

Seasonal differences in runoff frequency and volumes were apparent during the course of the study at all four monitoring sites. In 2003, runoff tended to occur most frequently at all landscape positions during the summer months (July, August, September), which most likely was due to significantly higher rainfall amounts observed during that particular season (Table II). In 2004, the spring months (April, May, June) resulted in the most frequent

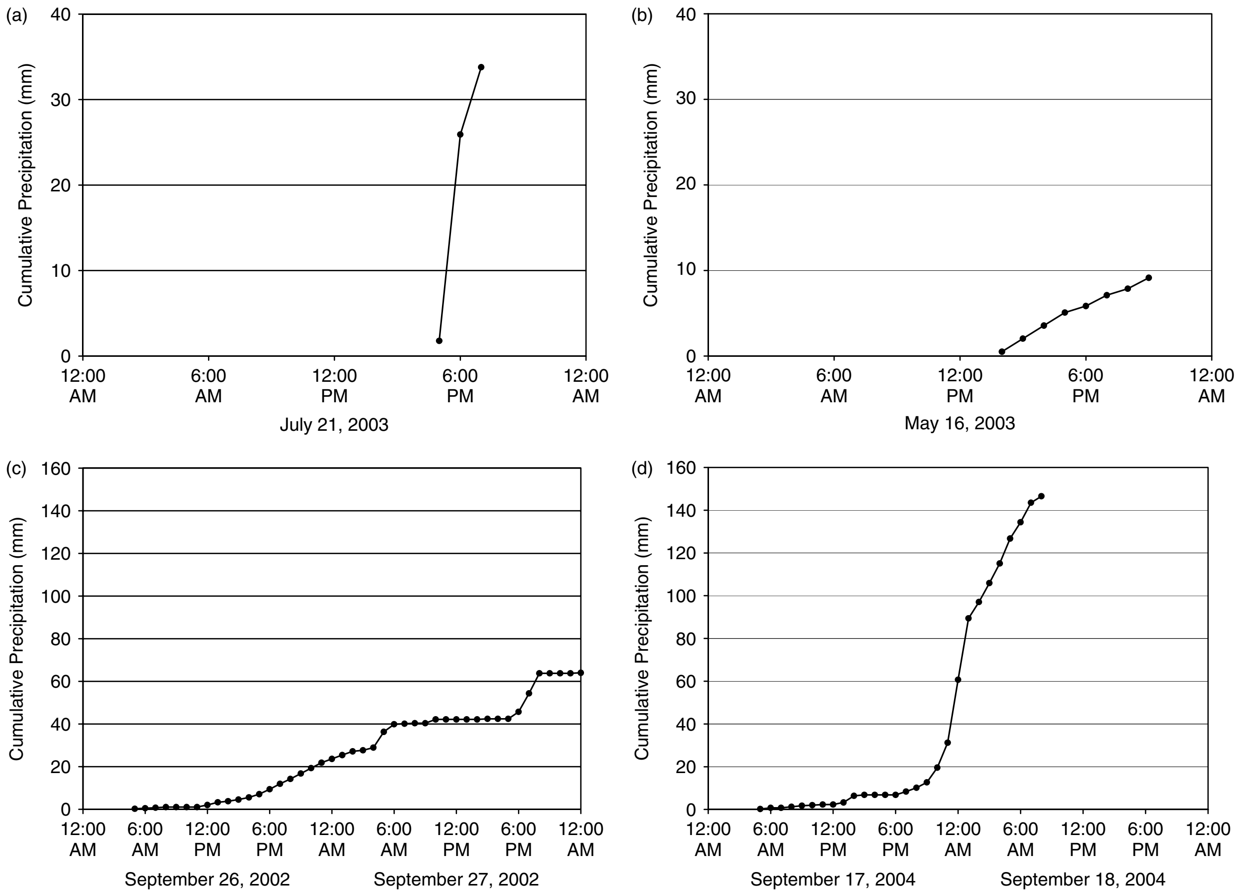

Figure 3. Cumulative precipitation amounts (mm) for representative storm events that occurred during the Mattern study period (2002–2004): (a) short-duration, high-intensity thunderstorm during summer; (b) short-duration storm during late spring; (c) long-duration storm during early fall; (d) remnants of Hurricane Ivan—long-duration event that produced the highest single-storm rainfall amount during the study period (147 mm)

runoff at every landscape position but the seepage slope, where winter runoff was most frequent (Table III). With regard to seasonal runoff volumes, the footslope position on the north hillslope yielded the highest total (Table III) and event-based (Figure 4) runoff during the spring, summer, and fall months of 2003 and 2004. During the winters of 2003 and 2004, the significance of runoff production at the other three landscape positions increased relative to the footslope position on the north hillslope (Table III, Figure 4) due to the occurrence of a few large snowmelt runoff events following the snowstorm on 17 February 2003 and a large winter rainstorm in January of 2004 (42·8 mm). In fact, at the seepage slope and transportational midslope positions, winter runoff volumes in 2003 and 2004 accounted for 71% to 96% of the total annual runoff for those years and in 2004 actually exceeded the winter runoff volumes observed at the footslope position on the north hillslope (Table III). This showed that hydrologic conditions during winter (e.g. snowmelt and rain-on-snow events) can be important for generating significant runoff volumes at landscape positions that are located in well-drained residual soils upslope and away from the stream channel.

Runoff generation mechanisms

Surface runoff from plots and shallow groundwater levels obtained from subsurface saturation sensors at each landscape position were used to categorize runoff generation as IE or SE following the approach of Needelman *et al.* (2004). While we cite Needelman *et al.* (2004) to define SE runoff (i.e. groundwater within 5 cm of soil surface), others have found deeper critical water table depths at which SE runoff may be defined. The importance of these different approaches with respect to our study is discussed in greater detail below.

October 2003 and 23 July 2002 runoff events. Data from two storms are first used to illustrate the typical runoff responses to precipitation during the study period. The first storm, which occurred on 14 October 2003, illustrates the differences in runoff generation mechanisms between upslope and lower landscape positions due to a significant rainfall on saturated soils (Figure 5). A total of 36 mm of rainfall fell between 6 : 00 PM on 14 October 2003 and 12 : 00 AM on 15 October 2003. During the course of the storm, shallow water table levels responded only very weakly at the seepage slope and transportational midslope positions, remaining well below 40 cm depth (Figure 5). As a result, small amounts of IE surface runoff were produced (<1 L) at the seepage slope position (one out of eight plots) and the transportational midslope position (six out of eight plots). These small volumes of runoff probably flowed for a short distance before re-infiltrating the soil (Srinivasan *et al.*, 2002).

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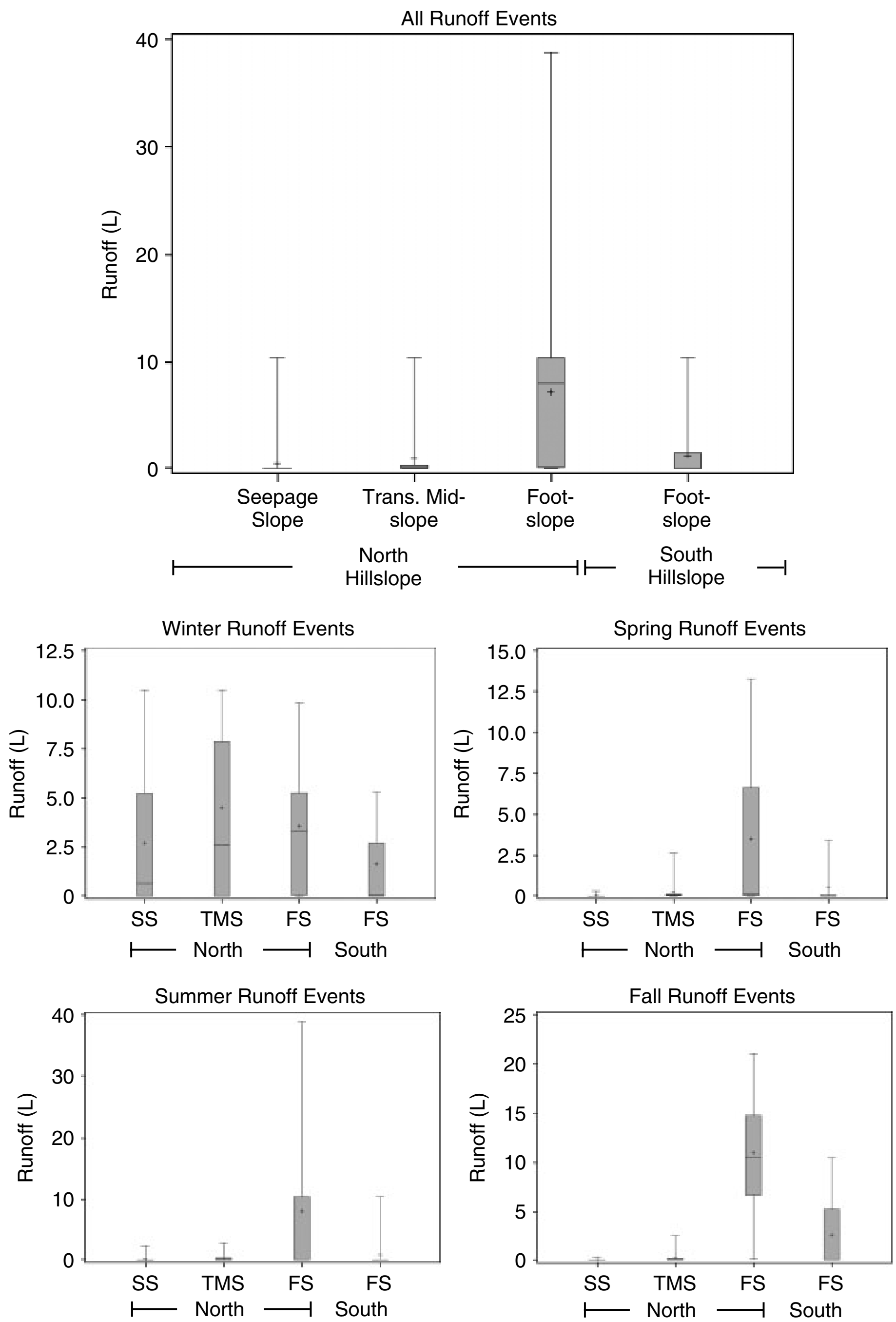

Figure 4. Box plots showing the distribution of sampled runoff (L) for all events during the 2·5-year sampling period as well during winter (Jan—Mar), spring (Apr—Jun), summer (Jul—Sep), and fall (Oct—Dec). Differences in surface runoff volume between the north footslope and remaining landscape positions may be greater than what is depicted due to the use of 10·5 L sampling containers

In contrast, shallow water table levels at both footslope positions showed an immediate response to precipitation, rising to within 1 cm of the surface at the north footslope and to within 20 cm of the surface at the south footslope. The large rise in shallow water table depths at the north footslope position resulted in SE surface runoff, which produced greater than 10 L of runoff at all eight plots. This demonstrated how a fragipan in colluvial soils (Albrights) can enhance runoff generation in footslope positions due to the rise of perched water tables in response to infiltrating precipitation and subsurface lateral contributions from upslope sources (Needelman *et al.*, 2004). Across the stream channel at the south footslope position, the spatial extent of Albrights soil was much less than the north footslope position. As a result the shallow water table remained below the surface during the entire event and therefore resulted in smaller volumes (~0·1 L) of IE surface runoff at only two of the eight plots.

In contrast to this storm, a short-duration thunderstorm on 23 July 2002 illustrates the response of all four landscape positions to intense precipitation during very dry antecedent conditions (Figure 6). A total of 12 mm of rainfall fell between 1:00 PM and 2:00 PM on 23

Table III. Frequency (annual and seasonal) of surface runoff (L) from different landscape positions along the north and south hillslopes

Year	Season	North hillslope						South hillslope	
		Seepage slope		Transportational midslope		Footslope		Footslope	
		Runoff		Runoff		Runoff		Runoff	
		Events (n)	Volume (L)	Events (n)	Volume (L)	Events (n)	Volume (L)	Events (n)	Volume (L)
2002	Winter	—	—	—	—	—	—	—	—
	Spring	—	—	—	—	—	—	—	—
	Summer	5	1·1	7	5·3	3	10·5	4	0·9
	Fall	0	0·0	6	1·7	13	121·3	5	13·2
Total		5	1·1	13	7·0	16	131·9	9	14·1
2003	Winter	5	27·2	9	55·6	10	42·7	7	21·2
	Spring	2	0·3	8	3·5	5	19·1	3	2·7
	Summer	6	0·3	11	4·3	19	216·0	9	21·1
	Fall	5	0·6	8	4·3	9	121·3	7	39·6
Total		18	28·4	36	67·8	43	399·0	26	84·6
2004	Winter	3	13·8	2	12·4	4	11·4	3	4·2
	Spring	1	0·3	8	1·2	8	40·5	7	6·4
	Summer[a]	2	2·7	4	3·8	8	73·5	2	7·9
	Fall	0	0·0	0	0·0	2	21·0	2	10·5
Total		6	16·8	14	17·4	22	146·3	14	29·0
Study total	Winter	8	41·0	11	68·0	14	54·0	10	25·4
	Spring	3	0·6	16	4·7	13	59·5	10	9·1
	Summer	13	3·0	22	8·1	30	289·5	15	28·9
	Fall	5	1·7	14	9·6	24	152·8	14	51·1
Grand total		29	46·3	63	90·5	81	555·9	49	114·5

[a] Runoff splitters installed at all plot locations.

July 2002. During the course of the storm, shallow water table depths remained well below the surface (>40 cm depth) at all landscape positions (Figure 6). As a result, IE runoff was generated from all eight plots at the seepage slope (0·6 to 1·8 L) and transportational midslope (2·0 to 4·7 L) positions. IE runoff also occurred at both footslope positions, but only two of eight plots generated runoff at the north footslope position (<1 L) and four of eight plots generated runoff at the south footslope position (~0·1 L).

Saturation-excess versus infiltration-excess runoff over all events. The results for the entire study reflect the contrasting runoff responses represented by these two storm events. Infiltration-excess surface runoff occurred almost exclusively at the seepage slope (22 out of 25 events) and transportational midslope (54 out of 54 events) landscape positions. These landscape positions were located in well-drained Berks soil and typically were not saturated at the surface during the study period. At the transportational midslope position, a significant ($p < 0{\cdot}05$) positive relationship between the number of plots generating runoff and rainfall intensity (Figure 7a) was consistent with the importance of rainfall intensity in generating IE surface runoff as described by Horton (1933). The IE runoff generation mechanism produced 13·5 L of total runoff at the seepage slope position and 65·9 L of total runoff at the transportational midslope position for the entire study (Table IV).

While IE surface runoff was the predominant runoff generation mechanism at the upper landscape positions, SE surface runoff was noted during the winter of 2003. Snowmelt following the snowstorm on 17 February resulted in three SE surface runoff events at the seepage slope position, which generated more runoff (18·6 L) than the total runoff from 22 IE events (13·5 L) during the entire study period (Table IV). This demonstrates the importance of snowmelt in the development of localized saturation conditions, which can result in significant runoff generation during winter periods.

The two footslope landscape positions offered an interesting contrast in runoff generation during the study period. Saturation-excess (33 events) and IE (34 events) surface runoff were equally important runoff generation mechanisms on the north footslope. While the SE mechanism (369·5 L) produced 1·6 times more runoff than the IE mechanism (225·6 L), it was interesting to note the importance of IE surface runoff at the north footslope position. This landscape position was located in the somewhat poorly drained Albrights soil, which had a fragipan and a seasonal perched water table. The importance of the perched water table in generating runoff was evidenced by the fact that rising water table depths were significantly ($P < 0{\cdot}05$) and positively ($R^2 = 0{\cdot}79$) related to the number of plots generating runoff (Figure 7b). As a

Table IV. Frequency (annual and seasonal) of SE and IE surface runoff from different landscape positions along the north and south hillslopes

Year	Season	North hillslope												South hillslope			
		Seepage slope				Transportational midslope				Footslope				Footslope			
		IE runoff		SE runoff		IE runoff		SE runoff		IE runoff		SE runoff		IE runoff		SE runoff	
		Events (n)	Vol. (L)	Events (n)	Vol. (L)	Events (n)	Vol. (L)	Events (n)	Vol. (L)	Events (n)	Vol. (L)	Events (n)	Vol. (L)	Events (n)	Vol. (L)	Events (n)	Vol. (L)
2002	Winter	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Spring	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Summer	5	1·1	0	0·0	7	5·3	0	0·0	3	10·5	0	0·0	4	0·9	0	0·0
	Fall	0	0·0	0	0·0	6	1·7	0	0·0	3	19·1	10	102·3	5	13·2	0	0·0
Total		5	1·1	0	0·0	13	7·0	0	0·0	6	29·6	10	102·3	9	14·1	0	0·0
2003	Winter	2	8·5	3	18·6	7	44·8	0	0·0	7	25·7	0	0·0	4	10·7	0	0·0
	Spring	2	0·3	0	0·0	8	3·5	0	0·0	3	0·1	2	18·9	3	2·7	0	0·0
	Summer	6	0·3	0	0·0	11	4·3	0	0·0	6	46·4	13	169·6	8	10·6	1	10·5
	Fall	4	0·3	0	0·0	7	1·8	0	0·0	5	79·3	3	31·5	5	23·7	1	10·5
Total		14	9·5	3	18·6	33	54·3	0	0·0	21	151·5	18	220·0	20	47·7	2	21·0
2004	Winter	0	0·0	0	0·0	0	0·0	0	0·0	0	0·0	0	0·0	0	0·0	0	0·0
	Spring	1	0·3	0	0·0	4	0·8	0	0·0	3	7·8	0	0·0	0	0·0	0	0·0
	Summer[a]	2	2·7	0	0·0	4	3·8	0	0·0	3	26·3	5	47·3	0	0·0	1	7·9
	Fall	0	0·0	0	0·0	0	0·0	0	0·0	1	10·5	0	0·0	1	0·0	0	0·0
Total		3	3·0	0	0·0	8	4·6	0	0·0	7	44·5	5	47·3	1	0·0	1	7·9
Study total	Winter	2	8·5	3	18·6	7	44·8	0	0·0	7	25·7	0	0·0	4	10·7	0	0·0
	Spring	3	0·6	0	0·0	12	4·3	0	0·0	6	7·9	2	18·9	3	2·7	0	0·0
	Summer	13	4·0	0	0·0	22	13·4	0	0·0	12	83·2	18	216·9	12	11·5	2	18·4
	Fall	4	0·3	0	0·0	13	3·4	0	0·0	9	108·8	13	133·8	11	36·9	1	10·5
Grand total		22	13·5	3	18·6	54	65·9	0	0·0	34	225·6	33	369·5	30	61·8	3	28·9

[a] Runoff splitters installed at all plot locations.

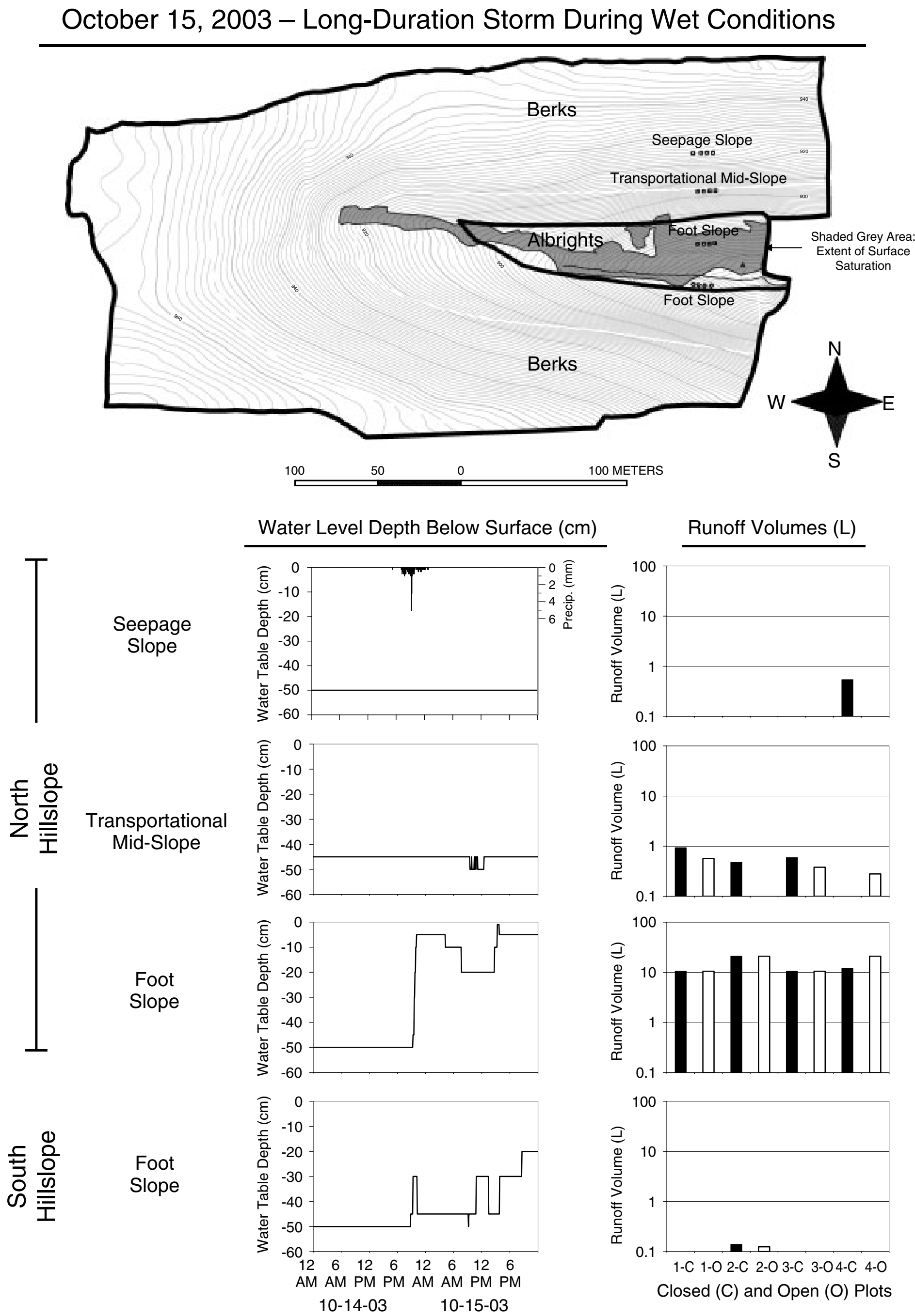

Figure 5. Runoff and shallow water table response to a moderate-intensity storm during wet antecedent conditions at different landscape positions along the north and south hillslopes in the Mattern watershed. Incremental precipitation amounts (mm) are shown in the seepage slope shallow water table plot. The shallow water table response plots show the mean of two subsurface saturation sensors installed at each landscape position (see Figure 2)

result, one would expect that the presence of a fragipan would result in mostly SE surface runoff. In actuality, IE surface runoff was almost as important as SE surface runoff, which contrasts the basic findings of recent studies by Srinivasan *et al.* (2002), Needelman *et al.* (2004), and Gburek *et al.* (2006).

At the south footslope landscape position, the IE mechanism (30 events) clearly was more important than the SE mechanism (three events) in generating surface runoff. While IE surface runoff generated 61·8 L of total runoff, 3 SE runoff events generated 28·9 L of runoff, which accounted for almost one-third of the total runoff for the study period at this location. Evidence for its importance is shown by the fact that a greater number of plots produced runoff when shallow water tables reached the surface (Figure 7b). Even though the SE mechanism was relatively infrequent at the south footslope position, it still was capable of generating significant volumes of runoff when it occurred. Nonetheless, it appears that the limited extent of the fragipan on the south footslope did not result in frequent perched water tables, and therefore, played a smaller role in

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generating SE surface runoff at this landscape position.

Overall, the SE surface runoff mechanism generated larger volumes of runoff than the IE mechanism, accounting for 53% of the total runoff observed from all landscape positions during the study. On an event-basis, this contribution could significantly be underestimated due to the fact that volume estimates for runoff were capped at 10·5 L. The installation of splitters in July 2004 permitted a more accurate estimate of the runoff production potential at all sites for a few storm events that occurred near the end of the study period. The remnants of Hurricane Ivan, which deposited 147 mm of rainfall on 17–18 September 2004, help to illustrate the significance of SE runoff generation compared with IE runoff on the north hillslope. While the antecedent conditions were relatively dry prior to the storm (Figure 8), the substantial rainfall resulted in widespread runoff at all landscape positions. Infiltration-excess surface runoff occurred at the seepage slope and transportational midslope positions and produced upwards of 10 L of runoff. Saturation-excess surface runoff at the north footslope position generated anywhere from 800 to 4000 L of runoff, which was more than 1–2 orders of magnitude greater than the upslope landscape positions. This demonstrated that during large storm events, the colluvial soils could potentially produce upwards of 99% of the total runoff from the hillslope.

Selection of threshold water table depth to define saturation-excess events. The prevalence of SE runoff reported above may, in part, be influenced by one's selection of a threshold for the water table depth that produces SE runoff. In this study, we assumed that SE runoff occurred when the average water table measurement from two sensors at a particular landscape position was within 5 cm of the soil surface at any point during a runoff event. Selection of a 5 cm shallow water table depth to define SE runoff is consistent with several previous studies of runoff generation (Evans *et al.*, 1999; Srinivasan *et al.*, 2002; Needelman *et al.*, 2004). However, a recent study by Lyon *et al.* (2006) suggests that that SE runoff may occur when the water table is approximately 10 cm below the surface.

In order to test the importance of this definition, we compared the number of events and volumes of runoff attributed to SE and IE mechanisms at all four landscape positions. Increasing the shallow water table depth at which SE runoff is presumed from a depth of 5 cm to a depth of 10 cm had no effect on the prevalence of IE and SE runoff events at the transportational midslope and the south footslope (Table V); however, the proportion of SE to IE events increased from 0·14 to 0·25 at the seepage slope and from 0·97 to 1·79 at the north footslope. These events accounted for an additional 44·6 L of flow, equivalent to an increase in SE attributed runoff of 134% from the seepage slope and 32% from the north footslope. While not inconsequential, the change in selection of a threshold water table depth did not substantially modify conclusions regarding runoff generation mechanisms, landscape position or flow.

Importance of flow pathways

The importance of flow pathways on runoff generation was assessed using paired open and closed runoff plots at each landscape position. Results from the seepage slope and transportational midslope landscape positions showed that there was no significant difference between runoff from open and closed plots (Figure 9). This suggested that runoff generation at these landscape positions was not significantly influenced by contributions from upslope surface flow pathways. For most events, runoff probably was generated by local IE mechanisms and flowed for a short distance before re-infiltrating into the soil, which would have minimal impacts on downslope water quality.

The two footslope landscape positions provided a nice contrast in hillslope responses to runoff. At the north footslope landscape position, median runoff from open plots was much greater (8·1 L) than runoff from closed plots (3·2 L) (Figure 9). The difference (5·7 L) was associated with a P-value of 0·07. This high P-value may have been due to the fact that total event runoff volumes were capped at 10·5 L. Data from the final four runoff events using flow splitters suggested that a much greater difference existed between open and closed plots at the north footslope position (open = 3986 L; closed = 2331; difference = 1655 L). As a result, larger flows may have entered the open runoff plots during the course of the study indicating the possibility of a hillslope-scale response to runoff with significant contributions of surface water from upslope landscape positions. At

Table V. Frequency of IE and SE runoff and associated runoff volumes at threshold water table depths of 5 cm and 10 cm for landscape positions on the north and south hillslopes

Shallow water table depth (cm)		North hillslope						South hillslope	
		Seepage slope		Transportational midslope		North footslope		South footslope	
		Number	Volume (L)	Number	Volume (L)	Number	Volume (L)	Number	Volume (L)
5	IE runoff	22	13·5	54	65·9	34	225·6	30	61·8
	SE runoff	3	18·6	0	0	33	369·5	2	28·9
10	IE runoff	20	7·5	54	65·9	24	187·0	30	61·8
	SE runoff	5	24·6	0	0	43	408·1	2	28·9

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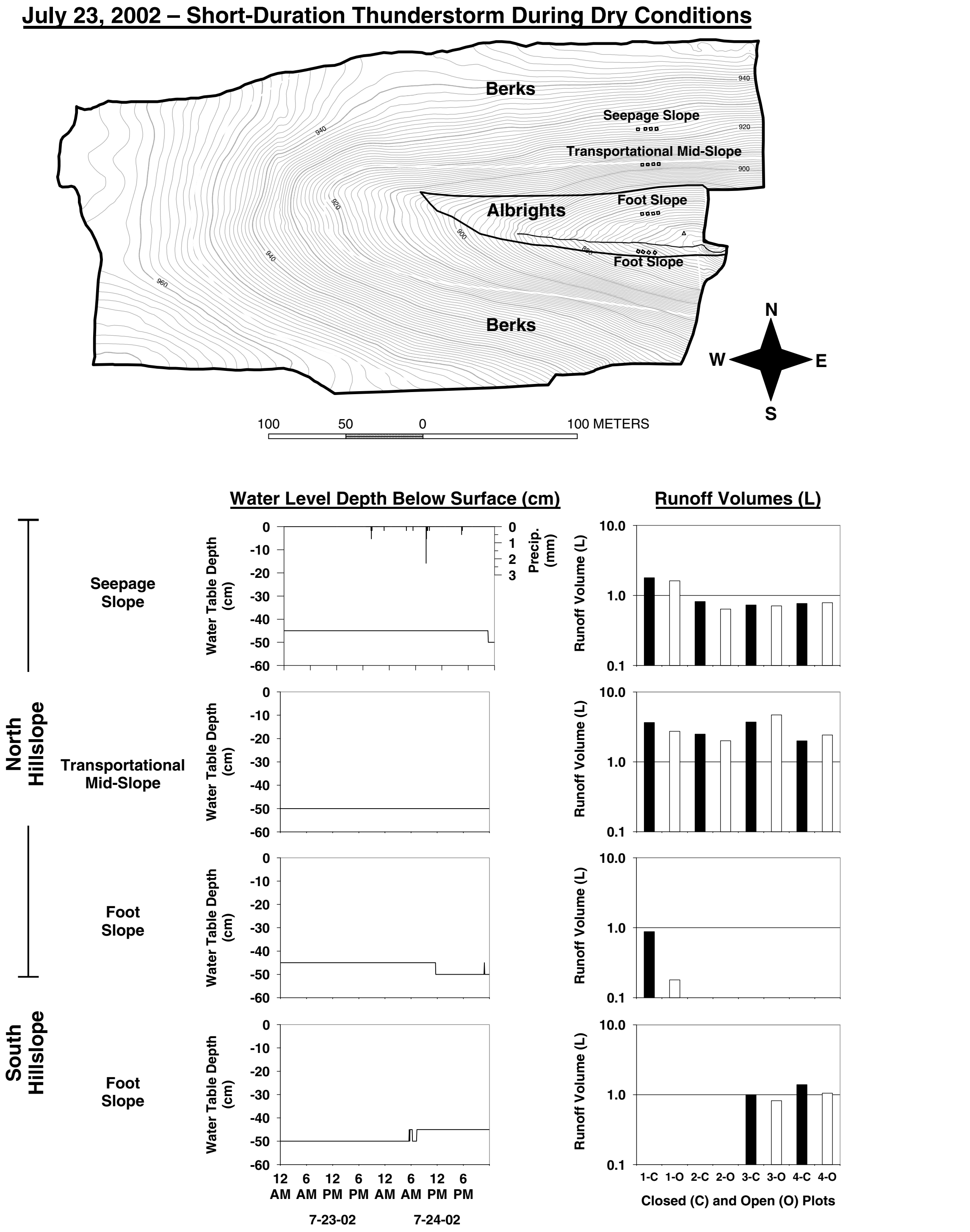

Figure 6. Runoff and shallow water table response to a high-intensity storm during dry antecedent conditions at different landscape positions along the north and south hillslopes in the Mattern watershed. Incremental precipitation amounts (mm) are shown in the seepage slope shallow water table plot. The shallow water table response plots show the mean of two subsurface saturation sensors installed at each landscape position (see Figure 2)

the south footslope position, there was no significant difference between runoff from open and closed plots (Figure 9), and therefore runoff generation at this site was more of a localized response with little surface water contributions from upslope landscape positions.

A closer look at the possibility of upslope runoff contributions to the north footslope reveals that median runoff from the open plots at the transportational midslope only was 207 L, which accounted for at most 8% of the observed differences between open and closed plots at the north footslope. This statement makes the explicit assumption that all runoff from the transportational mid-slope contributed to runoff at the footslope, when in fact there may have been events when this water re-infiltrated into the soil and did not connect with lower landscape positions (thunderstorm on 23 July, Figure 6). Nonetheless, it is clear that considerable volumes of water are generated from open plots at the north footslope that

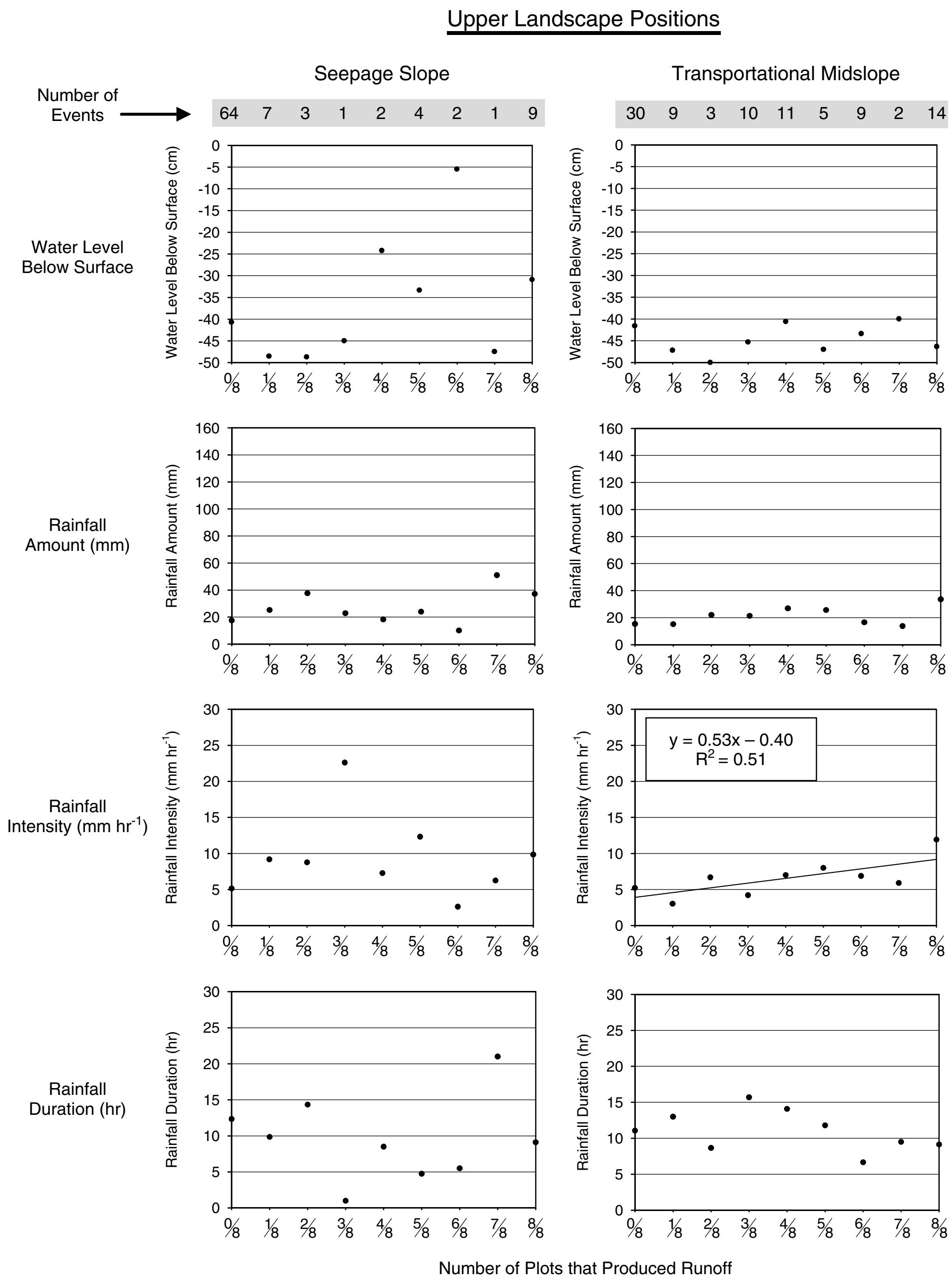

Figure 7a. Upper landscape position scatterplots showing the relationship between mean event characteristics (water level below the surface, rainfall amount, rainfall intensity, rainfall duration) for a particular number of plots producing runoff and the number of plots that produced runoff under the given conditions. The number of events used to calculate the mean is shown along the grey bar at the top of each set of landscape position plots

cannot be accounted for by looking at runoff from upslope landscape positions.

The activation of other flow pathways, especially subsurface flow pathways, is likely to be important at the north footslope landscape position due to the influence of the fragipan (Albrights soil) on shallow water table depths and runoff generation (Needelman *et al.*, 2004; Gburek *et al.*, 2006). Previous work in humid watersheds (Weiler *et al.*, 2005 and references therein) has demonstrated the importance of subsurface flow pathways in runoff generation. While the monitoring employed in this study targeted only surface runoff flow pathways, results obtained from the comparison of open and closed surface runoff plots from the north footslope suggest that subsurface flow pathways may be important. Clearly, future work at this site should monitor surface and subsurface runoff to determine the relative importance of these flow pathways during storm events.

CONCLUSIONS AND IMPLICATIONS

In the current study, surface runoff frequency, occurrence, and principal generation mechanisms differed between landscape position, soils, and north versus south hillslopes in a central Pennsylvania agricultural watershed. On the north hillslope, surface runoff from

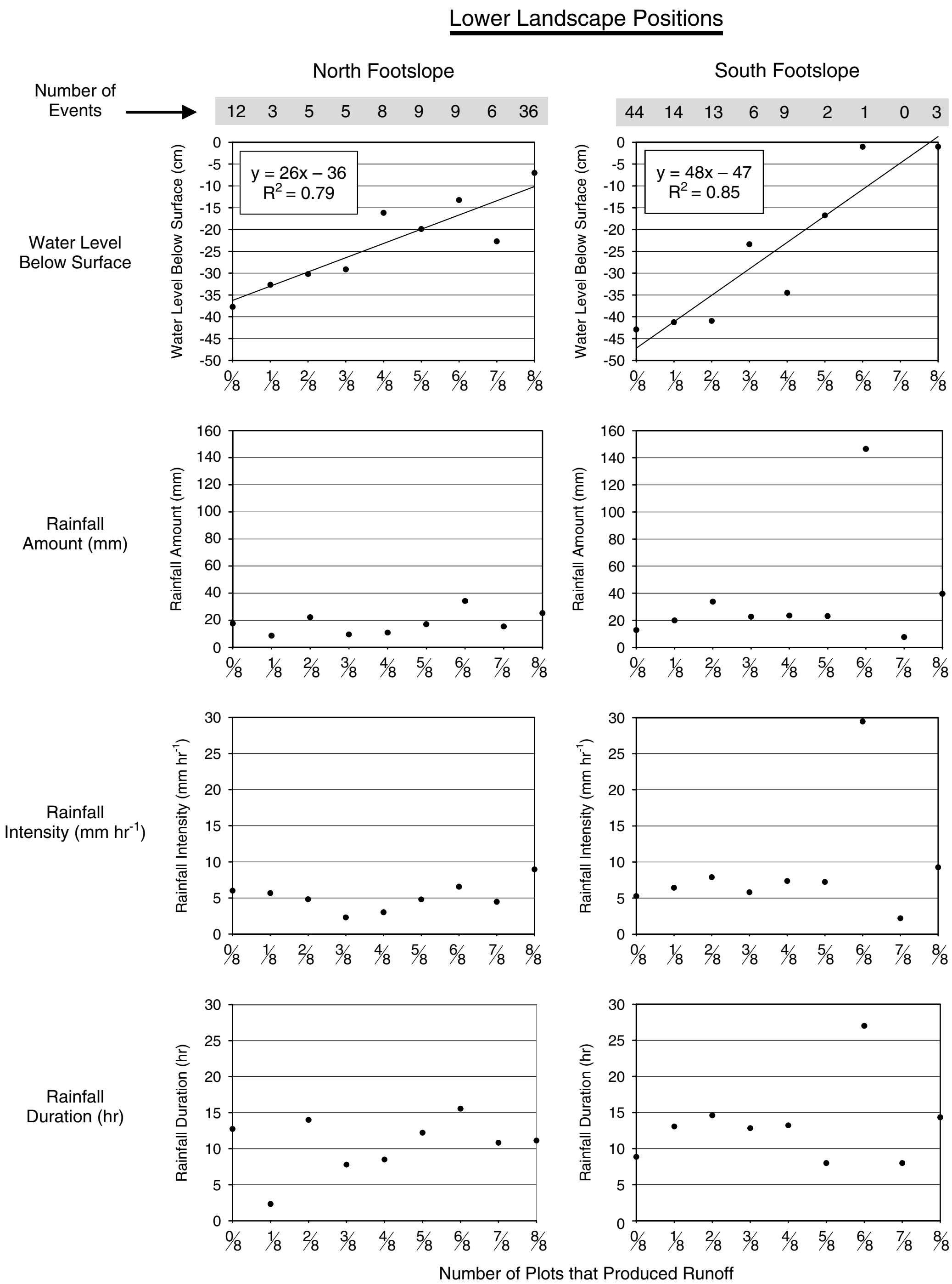

Figure 7b. (*Continued*)

well-drained Berks soil in the upper two landscape positions was generated predominately via the IE mechanism (96% of events generating runoff); however, three snowmelt runoff events in 2003 generated significant SE surface runoff at the seepage slope position. The importance of IE runoff was verified at the transportational midslope position, where increased rainfall intensities enhanced surface runoff production. Similar surface runoff volumes from open and closed runoff plots suggested that runoff at these landscape positions was influenced mostly by local site factors and not upslope overland flow pathways.

At the north footslope, the presence of a fragipan in the somewhat poorly drained Albrights soil resulted in perched water tables, which generated more frequent and larger volumes of runoff than the upper two landscape positions. While IE surface runoff occurred more frequently than anticipated (54% of events generating runoff) at the north footslope, SE surface runoff generated larger volumes (62% of runoff volume) and activated more runoff plots due to the influence of shallow water tables. Furthermore, greater surface runoff volumes in open versus closed runoff plots suggested that upslope flow pathways (surface and

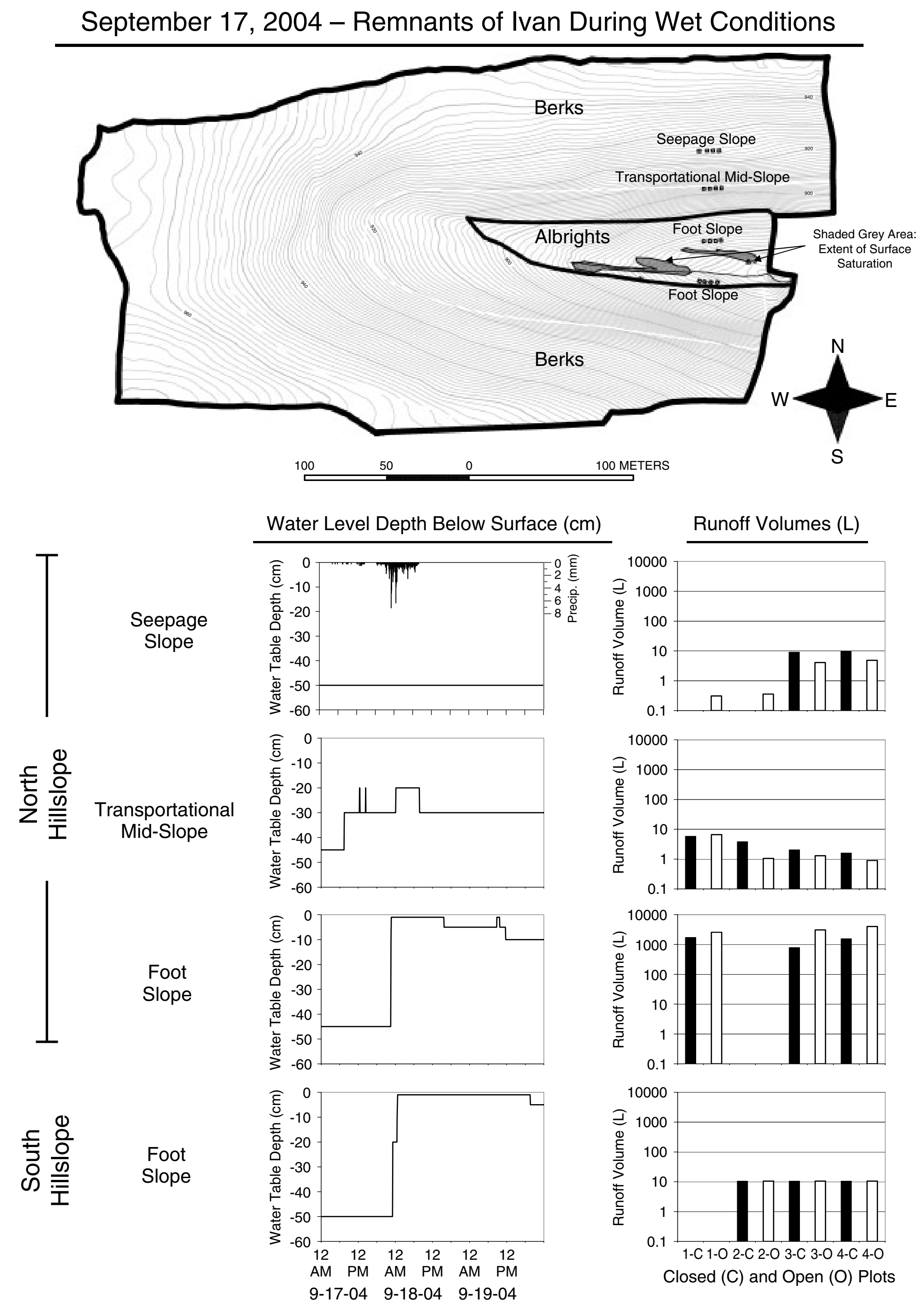

Figure 8. Runoff and shallow water table response to a long-duration storm during slightly wet antecedent conditions at different landscape positions along the north and south hillslopes in the Mattern watershed. Incremental precipitation amounts (mm) are shown in the seepage slope shallow water table plot. The shallow water table response plots show the mean of two subsurface saturation sensors installed at each landscape position (see Figure 2)

subsurface) may be important sources of water during events.

Finally, trends in runoff from the north and south footslope positions offered compelling insight into the role of landscape processes on runoff generation. Although both sets of plots were established in the same soil map unit, the slopes differed in the extent of the fragipan-containing Albrights soil. As a result, the south footslope generated less frequent and smaller volumes of mostly IE surface runoff than the north footslope.

The overall results of the study offer insight into the accuracy of existing runoff prediction tools in variable source area hydrology settings. In the current study, the curve number would suggest similar runoff generation from Berks and Albrights soil. As such, findings from this study suggest a much greater potential for runoff

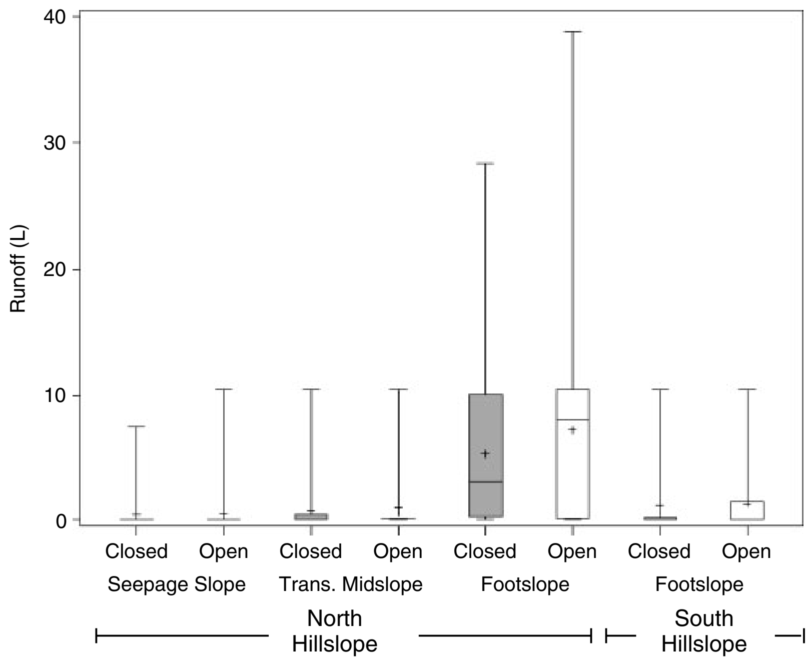

Figure 9. Box plots showing surface runoff (L) distributions for open and closed plots at seepage slope, transportational midslope, and footslope landscape positions along the north and south hillslopes. Mean runoff is denoted by the plus sign (+), whereas median runoff is denoted by the solid line

generation from the north footslope plots, especially during large events. Models could be improved by considering how subsurface soil properties, especially the occurrence and distribution of fragipans, influence surface runoff generation in agricultural watersheds with variable source area hydrology.

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