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Soil moisture and rainfall intensity thresholds for runoff generation in southwestern Wisconsin agricultural watersheds

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Abstract:

The goal of this study was to improve understanding of the factors that influence runoff generation during non-frozen ground periods in small agricultural watersheds in southwestern Wisconsin where the landscapes are controlled by dolostone bedrock in order to provide agricultural producers with a manure management tool. Six small watersheds (ranging from 6 to 17 ha) within two southwestern Wisconsin farm sites (Discovery Farms Program (DFP) and Pioneer Farm (PF)) were instrumented, and surface runoff was continuously monitored from 2004 to 2007. The soils in all watersheds were formed in deep (~1 m) loessial sites. A direct-plant management strategy and corn-soybean crop rotation were utilized within watersheds at DFP. A conventional tillage system (chisel plow in the fall followed by soil finisher in the spring) and a corn-oat-alfalfa crop rotation were utilized within watersheds at PF. At PF, the amount of precipitation leaving the landscape as surface runoff (1.8%) was two times greater compared to DFP (0.9%), indicating that the direct-plant management system was better at retaining precipitation than the chisel plow/soil finisher system. Using breakpoint regression analysis, a non-linear response in runoff generation with antecedent soil moisture (ASM) was observed with a threshold ASM of 0.39 cm^3cm^{-3} (approximately 80% of total porosity) for all six watersheds. Below this threshold, runoff coefficients were near zero. Above this threshold, runoff coefficients increased with ASM. A non-linear response in runoff generation with maximum 30 min rainfall intensity (I30) was also observed, and threshold I30 values increased as ASM decreased and as crop cover increased. Copyright © 2012 John Wiley & Sons, Ltd.

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INTRODUCTION

Application of manure on agricultural fields provides nutrients important for crop growth and beneficially alters soil properties (Brady and Weil, 2000). However, when application of manure is improperly managed, it can pose significant risk to water resources (Iserman, 1990; Withers and Lord, 2002). Currently, 39% of monitored rivers and 45% of monitored lakes in the United States are classified as impaired by the United States Environmental Protection Agency (EPA); agricultural non-point source pollution is considered to be the major source of these impairments (EPA, 2000).

In Wisconsin, many agricultural best management practices have been implemented to prevent harmful contaminants from entering surface waters. However, contamination of receiving waters as a result of agricultural non-point sources still occurs. During a 1 year time period (1 July, 2004 to 30 June, 2005), the Wisconsin Department of Natural Resources documented 52 manure runoff events throughout the state, some of which resulted in contaminated wells and fish kills (WDNR, 2006). Proper timing and rates of manure application are imperative for protecting water resources.

Through quantitative risk assessment (Cohrssen and Covello, 1989), the potential for surface water quality impairment due to land application of manure can be evaluated as a function of the magnitude of potential loss (i.e. surface runoff contaminant load) and the probability of occurrence (i.e. probability of surface runoff occurring). The contaminant load of surface runoff originating from manured land depends on manure application rate, method, and timing (Sharpley *et al.*, 1998; Withers and Jarvis, 1998). For agricultural producers who have predetermined rates and methods of manure application, timing of manure application is critical for mitigating surface runoff contaminant loads from manured land. Surface runoff generation depends on rainfall characteristics (e.g. intensity and duration) and landscape characteristics (e.g. vegetation, land use, soil type, topography, and antecedent soil moisture (ASM) conditions). Surface runoff in agricultural watersheds during non-frozen ground periods arises from overland flow in the form of infiltration excess (rainfall intensity exceeding infiltration capacity of the soil; Horton, 1933) or saturation excess runoff (precipitation on a saturated soil surface; Hewlett and Hibbert, 1967; Dunne and Black, 1970; Dunne *et al.*, 1975). Both types of runoff can occur throughout the year within an agricultural watershed (Kwaad, 1991; Ritsema *et al.*, 1996). Landscape

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characteristics alter precipitation interception, surface storage, and infiltration rates, thereby influencing the rainfall–runoff response of watersheds.

ASM is a key factor in partitioning rainfall into infiltration or runoff and has a large influence on the rainfall–runoff response of agricultural watersheds (Aubert *et al*., 2003; Brocca *et al*., 2008). Castillo *et al*. (2003) studied the relation of runoff and ASM of semi-arid watersheds in Southeast Spain and found that ASM was an important factor controlling runoff during low and medium intensity storms. On a pastured New Zealand hillslope, Müller *et al.* (2006) observed different rainfall–runoff responses for storms with similar rainfall intensities and depths but different antecedent moisture conditions and concluded that ASM had a significant impact on the runoff volumes produced. Wei *et al.* (2007) found runoff coefficients for storm events with high ASM were significantly higher than for storm events with low ASM. While not directly correlated to soil moisture, antecedent precipitation is often used as a surrogate for ASM and Istok and Boersma (1986) reported that the 12 and 120 h antecedent rainfalls were the most significant factors influencing runoff generation for low intensity storms in Oregon.

The ability to identify hydrologic and watershed conditions that lead to an elevated risk of surface runoff is critical so that proper management decisions can be made regarding appropriate timing and rates of manure application. Currently, many manure management decisions are made without sufficient understanding of key parameters controlling surface runoff or influencing the likelihood of runoff generation. Identifying storm and landscape parameters that play a key role in surface runoff generation will assist producers in making more informed manure management decisions.

Several previous studies have identified a non-linear 'threshold' response in runoff generation with antecedent moisture conditions (Western and Grayson, 1998; Brocca *et al.*, 2005; James and Roulet, 2007; Detty and McGuire, 2010; Zehe *et al.*, 2010; Penna *et al.*, 2011). These studies cover a range of topographic, climatic, and land use characteristics, however, agricultural watersheds were not considered. Additionally, Tromp-van Meerveld and McDonnell (2005, 2006) found that rainfall needed to exceed a threshold value for significant subsurface stormflow to occur and that subsurface stormflow was related to both antecedent moisture and total precipitation. Detty and McGuire (2010) suggest a need to identify non-linear relationships between runoff and ASM storage at the scale of a small catchment.

The goal of this research was to improve our understanding of the factors that influence runoff generation in small agricultural watersheds in southwestern Wisconsin where the landscapes are controlled by dolostone bedrock. Specifically, the objective was to determine critical soil moisture and rainfall intensity thresholds for surface runoff generation for six agricultural watersheds in southwestern Wisconsin in order to provide producers with a management tool to assist their decision making on the land application of animal manure.

METHODS AND MATERIALS

Site locations

Two sites in the southwestern non-glaciated region of Wisconsin were instrumented to monitor surface water runoff originating from multiple agricultural watersheds. Both sites are located in Lafayette County in the upper portion of the Apple-Plum watershed and separated by approximately 10 km. This part of the non-glaciated region is characterized by broad, rolling ridges and narrow valleys cut by one of the region's numerous rivers and streams. Soils consist of deep loess deposits overlying the clay-rich Rountree Formation that in turn, overlies dolostone bedrock; some soil series are separated based on differing thicknesses of loess over Rountree materials (Clayton and Attig, 1990). A large percentage of this region is farmland due to the productive agricultural soils. Mean daily temperatures are $-6.7\,^{\circ}$C and $20.6\,^{\circ}$C for the winter and summer months, respectively. Average annual precipitation is approximately 840 mm, most of which occurs during the growing season, and average annual snowfall is 990 mm (1971–2000 historical climate data; Wisconsin State Climatology Office, 2007). Depth to groundwater at one of the study sites was measured at 14 – 18 m. The monitored watershed drainage systems are ephemeral and go dry between runoff events. Flows measured for this study were overland flows only.

The first study site is located on a privately owned farming operation that is part of the University of Wisconsin – Discovery Farms Program (DFP). The DFP conducts environmental research on privately owned farms throughout the state of Wisconsin (http://uwdiscoveryfarms.org). Three watersheds at this site (DF1, DF2, and DF3; Figure 1a) were instrumented. Direct-plant management was implemented in all fields within the three watersheds; crops were directly planted into the previous year's residue using a one pass system. Ground residue ranged between 50% and 65% depending on the previously harvested crop. Crops were grown in a 3 year rotation of corn for grain, corn for silage, and soybean. Grass waterways and broad-based cropped terraces were employed as conservation practices in all monitored watersheds. The dominant soil in all three watersheds is the Tama soil series, classified as a fine-silty, mixed, superactive, mesic Typic Argiudoll. The Tama series is a well-drained, very deep, and dark-colored silt loam soil found on upland ridges. Tama soils have high available water contents and natural fertility, making them highly productive for agricultural crops (Watson, 1966).

The second study site is within the University of Wisconsin – Platteville Pioneer Farm (PF), a research farm operated by the University of Wisconsin – Platteville (http://www.uwplatt.edu/pioneerfarm). Three watersheds at this site (PF3, PF5, and PF7; Figure 1b) were instrumented. Fields at PF were operated on a 7 year crop rotation consisting of 3 years corn, 1 year oat-alfalfa, and 3 years alfalfa. Tillage in this farming system consisted of chisel plowing in the fall followed by a soil finisher in the spring to prepare the seedbed. Ground residue after planting ranged between 15% and 30%. Conservation practices included

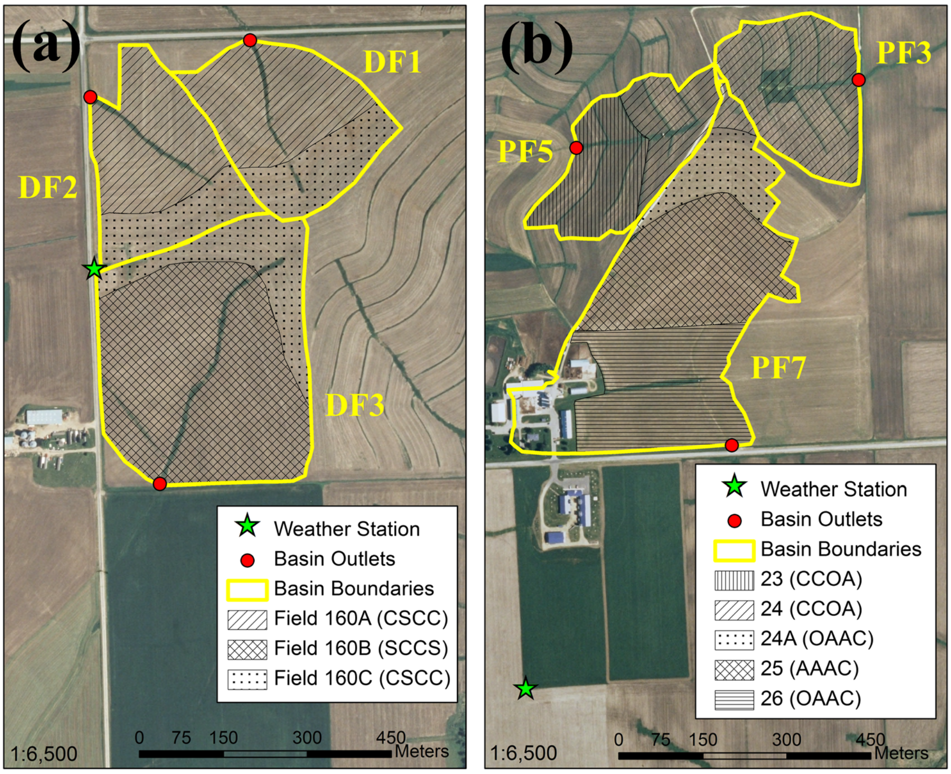

Figure 1. Watershed boundaries, instrumentation locations, and fields located at the: (a) Discovery Farm and (b) Platteville Pioneer Farm (note: 2004 – 2007 field crop rotations listed in parentheses; C = corn, S = soybean, O = oat/alfalfa, and A = alfalfa)

narrow-based terraces and grass waterways at PF3 and PF5 and broad-based cropped terraces and grass waterways at PF7. Watershed PF7 includes approximately 2 ha of farmstead (mostly impervious surfaces including buildings, pavement, compacted surfaces, and feedlots). The Tama soil series is the dominant soil in watershed PF7. The dominant soil in watersheds PF3 and PF5 is the Ashdale silt loam, classified as fine-silty, mixed, superactive, mesic Typic Argiudoll. The Ashdale soil is a well-drained, deep, and darkly colored silt loam found in upland ridges; it is also a productive agricultural soil (Watson, 1966). The main difference between the two soil series is the thickness of the silt caps; Tama soils are found in more than 122 cm of silt while the silt covering on Ashdale soils ranges from 92–115 cm. Watershed characteristics including area, average slope, dominant soil series, and crop rotation are summarized in Table I. Surface runoff monitoring at the outlet of each watershed (edge-of-field) was conducted by the U.S. Geological Survey from 2004 to 2007.

In October 2004, two small tiled infiltration basins (total area of 0.3 ha) were installed in series within PF3 to promote infiltration of precipitation and slow the flow of water during surface runoff events (Mentz *et al*., 2007). The installed tile system within the infiltration basins did not provide subsurface drainage. Surface inlets to the tile system were installed at the lowest point in each infiltration basin. The outlet of the upslope basin daylighted into the downslope basin. The outlet of the downslope basin daylighted approximately 10 m down slope of the infiltration basins and discharged flow within PF3.

Instrumentation

Surface runoff was measured continuously during runoff events at the outlet of each watershed with an H-flume (Tracom, Inc., Alpharetta, GA). All H-flumes were 0.8 m except at the outlet of PF5 where a 0.6 m H-flume was installed. Stage in each H-flume was measured with a dry gas nitrogen bubbler system (Rickly Hydrological Company, Columbus, OH) and a Sutron Accubar 5600-0125 pressure transducer (Sutron Corporation, Sterling, VA). During runoff events stage was recorded every minute.

Table I. Watershed characteristics

Watershed	Area (ha)	Mean slope (%)	Dominant soil	Cropping summary 2004	2005	2006	2007
DF1	6.8	5	Tama soil series	Corn	Soybean	Corn	Corn
DF2	7.0	5	Tama soil series	Corn	Soybean	Corn	Corn
DF3	16.0	5	Tama soil series	Soybean	Corn	Corn	Soybean
PF3	5.7	7	Ashdale soil series	Corn	Corn	Oat-Alfalfa	Alfalfa
PF5	5.8	7	Ashdale soil series	Corn	Corn	Oat-Alfalfa	Alfalfa
PF7	16.9	5	Tama soil series	Alfalfa	Alfalfa	Alfalfa	Corn

Rainfall was recorded every minute at each farm's weather station with a H340SDI tipping-bucket rain gage (Design Analysis Associates, Logan, UT). Soil moisture was recorded every 15 min at each farm's weather station with a CS616 probe (Campbell Scientific, Inc., Logan, UT). The probes were inserted vertically into the soil profile and measured volumetric soil moisture integrated over the top 30 cm of soil. Additional details on instrumentation can be found in Stuntebeck *et al.* (2008).

Additional soil moisture measurements were made throughout each watershed during October 2007 and between April 2008 and August 2008 at both sites to assess spatial variability of soil moisture throughout the watersheds, to calibrate the weather station's installed soil moisture probe, and to assess whether the soil moisture measured at the weather station was representative of mean watershed soil moisture. Watershed soil moisture measurements were made with a 1502B Metallic TDR Cable Tester (Tektronix, Richardson, TX) and CS605 soil moisture probe (Campbell Scientific, Inc., Logan, UT). The soil moisture probe was inserted vertically into the soil profile and measured volumetric soil moisture integrated over the top 30 cm of soil. Watershed soil moisture measurement locations were arranged in a grid within each watershed. The grid size was approximately 60 m^2 for the smaller watersheds (DF1, DF2, PF3, and PF5) and 75 m^2 for the larger watersheds (DF3 and PF7), resulting in 70–71 measurement locations for each study site. A GeoExplorer CE Series (Trimble, Sunyvale, CA) global positioning system was used to locate the sampling points and to ensure that soil moisture was consistently measured at the same location. During soil moisture sampling events, soil moisture was also measured at each farm's weather station near the location of the installed CS616 soil moisture probe. All soil moisture measurements were completed in a single day at each farm, and 17 sampling events were conducted in order to capture a range of soil moisture conditions.

Storm event data

Data analyzed in this study corresponded to non-frozen ground precipitation events from March 2004 through September 2007. Non-frozen ground periods were defined as periods when soil temperatures recorded at each weather station at 2, 5, 10, 20, 40, and 80 cm depths were above 0 °C. Annual start dates corresponded to the last week of March for all years and annual end dates were between mid-November to mid-December, except in 2007 when data collection ended at the end of September. Individual storm events were determined based on a criterion of at least 120 min without precipitation before or after the event. All storms with precipitation depth greater than or equal to 2.5 mm were included in the analysis (hereafter referred to as 'storm events'). Storm event data and landscape characteristics included runoff depth, antecedent volumetric soil moisture (ASM), precipitation depth, maximum 30 min precipitation intensity (I30), average precipitation intensity, and crop cover (CC). ASM was not recorded at PF between 1 June and 31 August, 2006 because the soil moisture probe was damaged.

Soil moisture instrumentation calibration

The in-watershed soil moisture measurement system (TDR cable tester and CS605 soil moisture probe) was calibrated in the laboratory using silt loam soil obtained from the University of Wisconsin - Madison West Madison Agricultural Research Station. The soil was dried at 105 °C for 24 h. Water was mixed with pre-weighed dry soil to obtain 10% volumetric water content, and the wet soil was packed to a bulk density of 1.3 g cm^{-3} into a 15 cm diameter by 91.5 cm long PVC pipe. Ashdale and Tama soils have moist bulk densities ranging from 1.25 to 1.60 g cm^{-3} (Watson, 1966). The soil moisture probe was inserted vertically into the soil to measure the soil moisture content integrated over the top 30 cm. After measurement, the soil–water mixture was unpacked, and additional water was added to and mixed with the soil to obtain a higher water content. The soil–water mixture was repacked to the same bulk density (1.3 g cm^{-3}) into the PVC pipe and soil moisture content measured. This procedure was repeated for eight soil moisture contents ranging from 0.10 to 0.33 cm^3cm^{-3}.

During calibration, the in-watershed soil moisture measurement system consistently measured approximately 0.02 cm^3cm^{-3} higher than the actual water content (Actual water content = 1.0*Measured water content – 0.02; $R^2 = 0.99$). This difference may be attributed to the void space created around the probe during insertion into the soil or the visual interpretation of the TDR wave. The same insertion technique and visual interpretation of the TDR wave used in calibration were used for all watershed measurements and, therefore, watershed soil moisture measurements were adjusted by subtracting 0.02 cm^3cm^{-3}.

The relationships between soil moisture measured using both the DFP and PF weather station soil moisture probes and the calibrated in-watershed soil moisture measurement system was approximately 1:1 (DFP best fit slope = 1.04 ($p << 0.001$); PF best fit slope = 1.01 ($p << 0.001$). However, the soil moisture probe at the PF weather station read approximately 0.05 cm^3cm^{-3} higher than the in-watershed probe. In order to be consistent with watershed-wide measurements, soil moisture measurements previously collected between 2004 and 2007 at the PF weather station were corrected by subtracting 0.05 cm^3cm^{-3}. Soil moisture measurements at the DFP weather station were not corrected. Figure 2 displays the time series of soil moisture at the DFP and PF weather stations.

Average watershed soil moisture contents were compared to the corrected weather station soil moisture contents (Figures 3 and 4) to assess differences as a result of vegetation and landscape position. During the time period in which watershed wide soil moisture measurements were made (October 2007 and April through August 2008), annual crops were grown in DF1 and DF2 (soybean) and in DF3 and PF7 (corn); alfalfa, a perennial crop, was grown in PF3 and PF5; and grass was the primary vegetation at both weather stations. When soil moisture content was at or above 0.30 cm^3cm^{-3}, average watershed soil moisture within all DFP watersheds and PF7 were in close agreement with weather station measurements (DFP best fit slopes

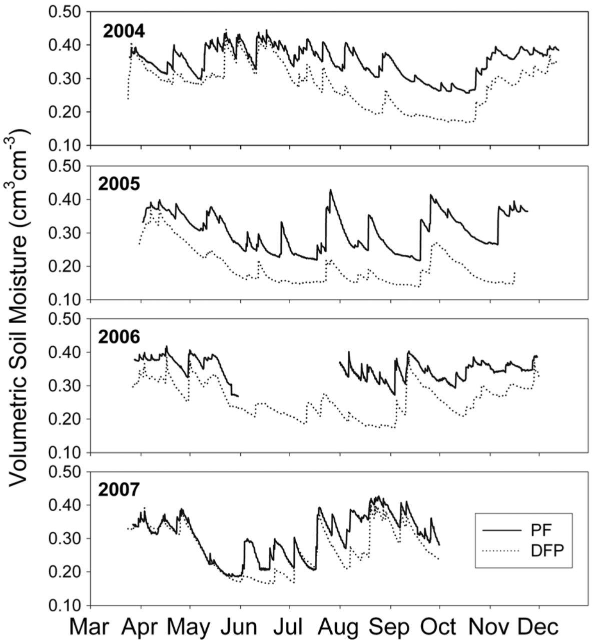

Figure 2. Time series of soil moisture at the DFP and PF weather stations

ranged from 0.98–1.02 ($p < 0.001$) and intercepts ranged from 0.01–0.02; PF7 best fit slope = 0.85 ($p < 0.001$) and intercept = 0.05). Below this moisture content, differences between average watershed soil moisture and weather station measurements were more pronounced and attributed to temporal vegetation differences between the watersheds and weather station. During dry conditions in the fall after harvest (13 October, 2007) and spring before significant crop growth (22 May, 2008 and 23 June, 2008), grass at the weather station continued to transpire and remove water from the soil profile. Transpiration within the watersheds during these periods was low due to limited or no vegetation. During dry conditions with significant crop growth (9 July, 2008, 7 August, 2008, and 27 August, 2008), water use by grasses at the weather station and by crops within the watersheds was likely similar; differences between average watershed soil moisture and weather station soil moisture were $\leq 0.02\,\mathrm{cm^3cm^{-3}}$ on 9 July, 7 August, and 27 August, 2008.

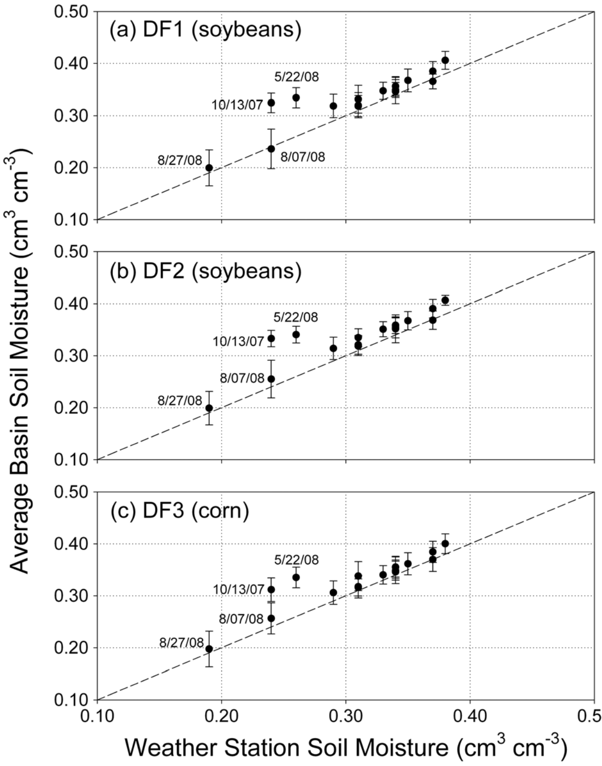

Figure 3. Comparison of weather station installed soil moisture probe and average watershed soil moisture for: (a) DF1, (b) DF2, and (c) DF3 (note: 1:1 lines plotted, error bars represent standard deviation, and dates noted are in mm/dd/yy format)

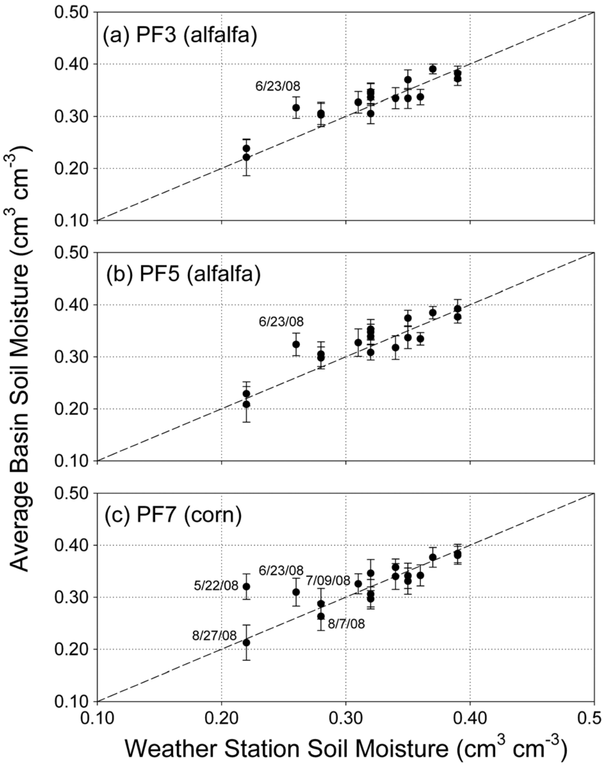

Figure 4. Comparison of weather station installed soil moisture probe and average watershed soil moisture for: (a) PF3, (b) PF5, and (c) PF7 (note: 1:1 lines plotted, error bars represent standard deviation, and dates noted are in mm/dd/yy format)

Average watershed soil moisture within PF3 and PF5 were in close agreement with weather station measurements across all sampling dates. Vegetative cover within PF3 and PF5 (alfalfa) was similar to that at the weather station (grass). The greatest difference observed between PF3 and PF5 average watershed soil moisture and soil moisture at the weather station ($0.06\,\mathrm{cm^3cm^{-3}}$) was on 23 June, 2008; the remaining differences did not vary by more than $\pm 0.03\,\mathrm{cm^3cm^{-3}}$. Alfalfa was harvested six days before the in-watershed measurements on 23 June, 2008. During the dry period after harvest, soil moisture at the weather station fell below 0.30 $\mathrm{cm^3cm^{-3}}$ and water use by the alfalfa decreased due to the removal of vegetative biomass.

Soil moisture patterns were less spatially variable (decreasing variance and coefficient of variation) as mean soil moisture increased (Figure 5); however, wet areas were not consistently along drainage lines, and dry areas were not consistently along hilltops. The absence of an impeding layer in the soil profile and the lack of long time periods with

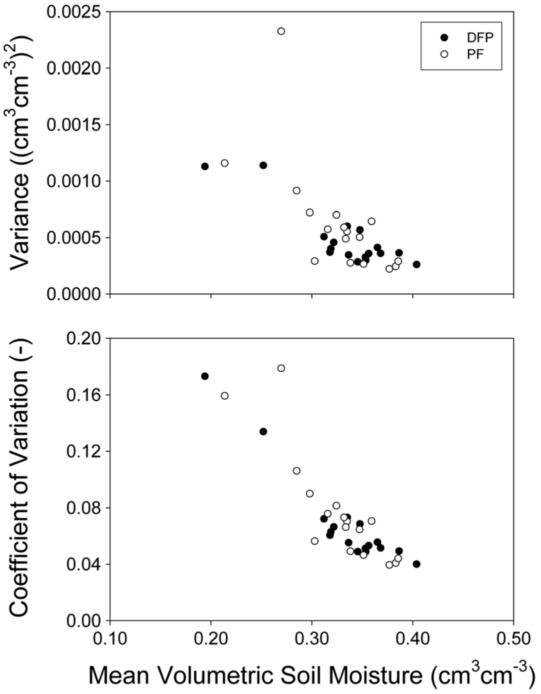

Figure 5. Variance and coefficient of variation of soil moisture at DFP and PF (each circle represents a discrete sampling date)

sufficiently high moisture content during data collection are likely the reasons that topographic influences of soil moisture patterns were not observed. Weak correlation between spatial pattern in shallow soil moisture and topographic position are attributed to dominance of vertical fluxes (James and Roulet, 2007).

Overall, soil moisture measured at the weather station was representative of average watershed soil moisture, particularly at water contents greater than 0.30 cm^{3}cm^{-3}. Below 0.30 cm^{3}cm^{-3}, average soil moisture in watersheds with perennial crops differed from soil moisture at the weather station shortly after harvest events. Average soil moisture in watersheds with annual crops differed from soil moisture at the weather station after harvest in the fall and before significant vegetation growth in the spring. Sufficient data were not collected to assess a correction factor for these specific conditions. Therefore, the assumption was made that soil moisture data collected throughout the study period at the weather station were representative of average soil moisture for all watersheds.

Crop growth modeling

Crop growth was modeled throughout the study period with DSSAT (Hoogenboom *et al*., 2004) and ALFALFA V.1.4 (Denison and Loomis, 1989) in order to estimate daily crop canopy cover within DFP and PF watersheds. Individual weather station data, including solar radiation, temperature, and precipitation, were required as input for each model. Corn and soybean growth were simulated directly with DSSAT, while oat growth was simulated with DSSAT using the barley crop growth parameters. Annual recorded planting and harvesting dates were used as simulation start and end dates for corn, soybean, and oat. Daily output from DSSAT simulations was plant biomass (kg ha^{-1}, dry weight) which was converted to crop canopy cover for corn, soybean, and oat using the following equation (Arnold *et al*., 1995):

$$\mathrm{CC} = 1 - e^{-\beta_c \beta_m} \tag{1}$$

where CC is canopy cover (0–1), β_c is a crop specific parameter (3.6, 14.0, and 5.2 for corn, soybean, and oat, respectively), and β_m is the plant biomass (kg m^{-2}, dry weight).

Alfalfa growth was modeled with ALFALFA V.1.4. In the PF crop rotation, alfalfa and oat (cover crop while alfalfa was establishing) were planted simultaneously. Oat growth was used to estimate crop canopy cover for the period of planting oat and alfalfa to harvesting oat. After oat harvest, alfalfa growth was used to estimate crop canopy cover. In order to establish an appropriate alfalfa plant population at the time of oat harvest, alfalfa growth simulations were also initiated with planting of oat and alfalfa. For continual yearly alfalfa growth, simulations were suspended at the onset of frozen ground conditions in the fall and resumed at spring thaw. Recorded tillage dates were used to specify the end of alfalfa growth simulations. Canopy cover (0–1) was output directly from ALFALFA V.1.4.

Watersheds at DFP contained three separate crop fields and PF watersheds contained five separate crop fields (Figures 1a and 1b). Crop growth and canopy cover were simulated for each field. In watersheds with more than one field, watershed canopy cover was determined by an area weighted average of the field canopy cover within the watershed (Table II).

Statistical analysis

A breakpoint regression analysis was conducted using R 2.5.0 (R Development Core Team, 2007) to determine threshold levels of ASM and I30 for surface runoff generation. For each watershed, storm event runoff coefficients (runoff depth divided by precipitation depth) were plotted *versus* ASM, and two linear regressions were fit to the data; one regression through all data below a specified ASM (i.e. breakpoint) and a second regression through all data above the specified ASM. The breakpoint was adjusted until the lowest combined standard error for the two regressions was achieved. If the slope of the regression above this breakpoint was significantly greater than zero or significantly greater than the slope of the regression below the breakpoint ($\alpha = 0.05$), a threshold ASM was defined at the breakpoint value. A minimum of three degrees of freedom were needed above and below the breakpoint to conduct the analysis.

Storm events were divided into groups based on ASM (<0.35, 0.35 to 0.40, and ≥0.40 cm^{3}cm^{-3}) and CC (<50% and ≥50%). Within each group, runoff coefficients were plotted *versus* I30 and a breakpoint regression analysis as previously described for ASM was repeated in order to identify threshold I30 values for each combination of ASM and CC group.

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Table II. Field areas within DFP and PF watersheds

		DFP Field area (ha)			PF Field area (ha)				
		160A	160B	160C	23	24	24A	25	26
Watershed	Farmed area (ha)	(CSCC)*	(SCCS)*	(CSCC)*	(CCOA)*	(CCOA)*	(OAAC)*	(AAAC)*	(OAAC)*
DF1	6.8	4.5	0	2.3	-	-	-	-	-
DF2	7.0	5.5	0	1.5	-	-	-	-	-
DF3	16.0	0	12.3	3.7	-	-	-	-	-
PF3	5.7	-	-	-	0	5.7	0	0	0
PF5	5.8	-	-	-	3.3	2.5	0	0	0
PF7	14.9	-	-	-	0	0.3	2.3	6.4	5.9

*crop rotations 2004 – 2007; C = corn, S = soybean, O = oat/alfalfa, A = alfalfa

RESULTS AND DISCUSSION

Precipitation characteristics

Study period. Similar precipitation characteristics were observed at DFP and PF (Figures 6 and 7) because of the close proximity of the two sites (10 km). Total non-frozen ground precipitation during the study period was 2530 mm and 2630 mm at DFP and PF, respectively. During the study period, there were a total of 195 storm events at DFP and 201 storm events at PF. Quantile–quantile plots (Figure 8) were used to compare DFP and PF precipitation characteristics, including storm event precipitation depth, maximum 30 min-intensity (I30), and average intensity. Below the 95% quantile, precipitation characteristics for DFP and PF were similar. Fifty percent of the storm events at DFP and PF had precipitation depths less than 8.5 mm, I30 less than 6.5 mm h^{-1}, and average intensity less than 3.0 mm h^{-1}. Small to medium storm events (depth $<$ 40 mm; I30 $<$ 35 mm h^{-1}; average intensity $<$ 30 mm h^{-1}) at DFP and PF were comparable. For large storm events, higher I30s were observed at DFP, and higher average intensities were observed at PF. At DFP, there were eight storm events that equaled or exceeded the 1 year return period (1.0 – 1.9 year) and one event that exceeded the 10 year return period (14 year). At PF, there were six storm events that exceeded the 1 year return period (1.2 – 1.7 year) and two storms that exceeded the 2 year return period (2.8 and 4.2 year).

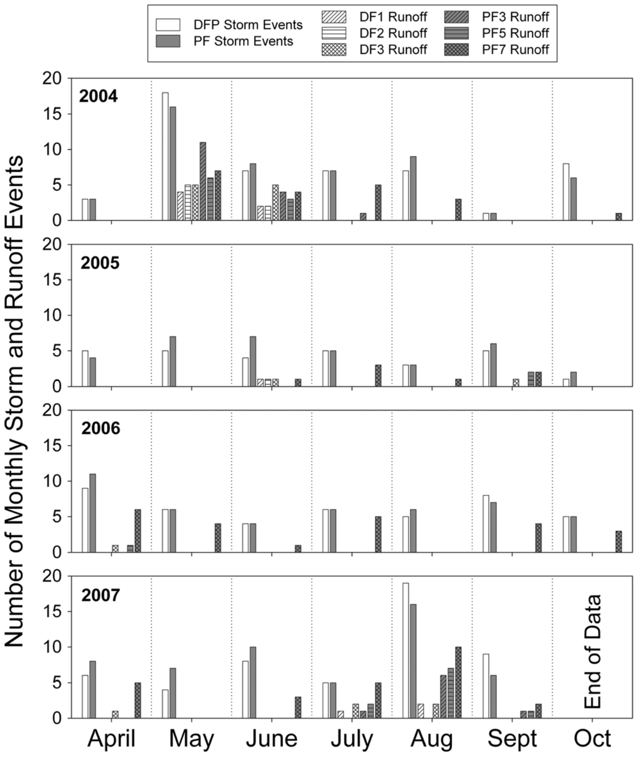

Figure 6. Monthly number of storm and runoff events at DFP and PF

Annual. April through October precipitation was close to historic area averages for all study years except 2005, when precipitation at DFP and PF was roughly 225 mm below average (Figure 7). The largest difference in April through October precipitation between the two sites was recorded in 2007, when PF received 45 mm of precipitation more than DFP.

Monthly. Monthly precipitation depths were similar for DFP and PF throughout the study period (Figure 7). Differences between monthly totals for the two sites were all less than 30 mm, except for July 2005 and August 2007. During each of these months, PF received approximately 50 mm of additional precipitation compared to DFP. Precipitation at DFP and PF exceeded historical area averages by an average of 130 mm in May 2004 and 125 mm in August 2007.

Surface runoff characteristics

Study period. During the study period, there were more non-frozen ground runoff events and greater depth of runoff (defined as runoff volume measured at the watershed outlet divided by the corresponding watershed area) at PF than at DFP. Of the 201 storm events that occurred at PF, 12% (24 events) produced runoff at PF3, 11% (22 events) produced runoff at PF5, and 40% (80 events) produced runoff at PF7. Of the 195 storm events that occurred at DFP, 5% (ten events) produced runoff at DF1, 4% (eight events) produced runoff at DF2, and 9% (18 events) produced runoff at DF3. Of the total non-frozen ground precipitation during the study period, 0.9% (24 mm) was measured as surface runoff at DFP, and 1.8% (49 mm) was measured as surface runoff at PF. Mean runoff coefficients were also greater at PF than at DFP.

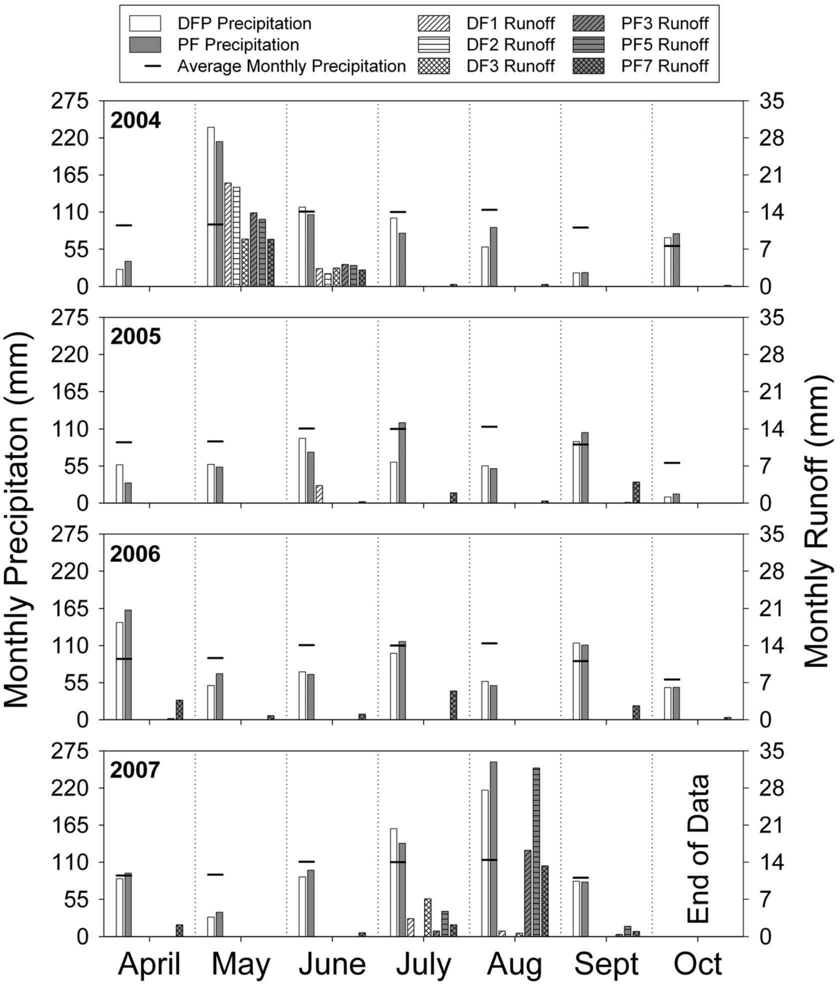

Figure 7. Monthly precipitation and runoff depth at DFP and PF (data shown includes precipitation events < 2.5 mm). Average monthly precipitation is for the period of 1971–2000 (Wisconsin State Climatology Office, 2007)

Differences were observed when all non-zero runoff depths at DFP were compared to PF (Figure 9). Watershed DF1 had the highest median runoff depth among the DFP watersheds. Watersheds DF1 and DF2 had similar inter-quartile ranges (IQR; 25th percentile to 75th percentile). When compared with PF5 runoff depths, PF3 displayed smaller median, 75th and 90th percentiles and IQR, indicating the effectiveness of the tiled infiltration basin located within PF3. The IQR range of PF7 was much smaller compared to both PF3 or PF5. Also, the 90th percentile runoff depth at PF7 was less than the 75th percentile runoff depths of both PF3 and PF5, indicating the occurrence of many small runoff events at PF7, most likely generated from the small impervious area within PF7.

Storm and landscape characteristics were similar at DFP and PF (Figure 8 and Table I); however, crop rotations and tillage strategies differed. Throughout the study period, the crop rotation at PF (corn-oat-alfalfa) provided more vegetative cover than the crop rotation at DFP (corn-soybean; Figure 10). Although increased vegetative cover provides more precipitation interception and soil protection, generally resulting in lower runoff depths (Linsley *et al*., 1982), more runoff events and greater runoff depths were observed at PF compared to DFP.

Different tillage strategies utilized at DFP (direct-plant) and PF (chisel plow/soil finisher) may explain some of the observed differences in runoff. Tillage can alter soil physical properties, such as infiltration rates and hydraulic conductivities, which influence surface runoff generation. Results from studies comparing physical soil properties of direct-plant cropping systems and conventional cropping systems that utilize various tillage practices (hereafter referred to as ‘conventional tillage’) have varied. Long term direct-plant systems improve soil quality by increasing organic carbon content and improving soil structure (Gajri *et al*., 2002). Numerous studies have reported that direct-plant cropping systems have higher infiltration rates and saturated hydraulic conductivities than conventional tillage systems (Dick *et al*., 1989; Chang and Lindwall, 1990; Sauer *et al*., 1990; Packer *et al*., 1992; Benjamin, 1993; Dao, 1993; Mahboubi *et al*., 1993; Azooz and Arshad, 1996; Arshad *et al*., 1999; Elliott and Efetha, 1999). Conversely, Ross and Hughes (1985) and Lipiec *et al*. (2006) reported lower infiltration rates for direct-plant systems when compared with conventional tillage systems. Horne *et al*. (1992) and Freese *et al*. (1993) reported higher infiltration rates for conventional tillage systems immediately following tillage. However, Freese *et al*. (1993) also reported that infiltration rates before tillage and two weeks after tillage

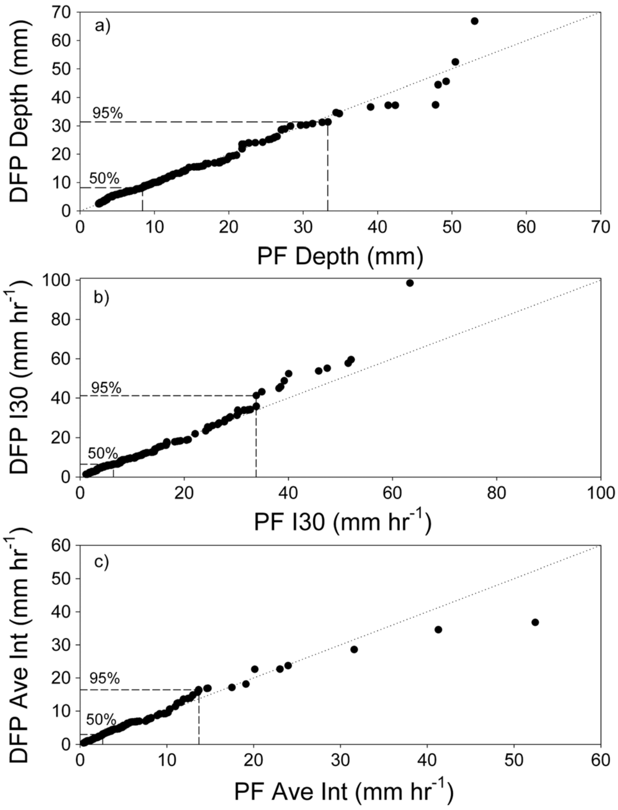

Figure 8. Q-Q plots of storm event: (a) precipitation depth, (b) I30, and (c) average intensity (note: 50% and 95 % quantiles are labeled and dotted lines represent 1:1 relationship)

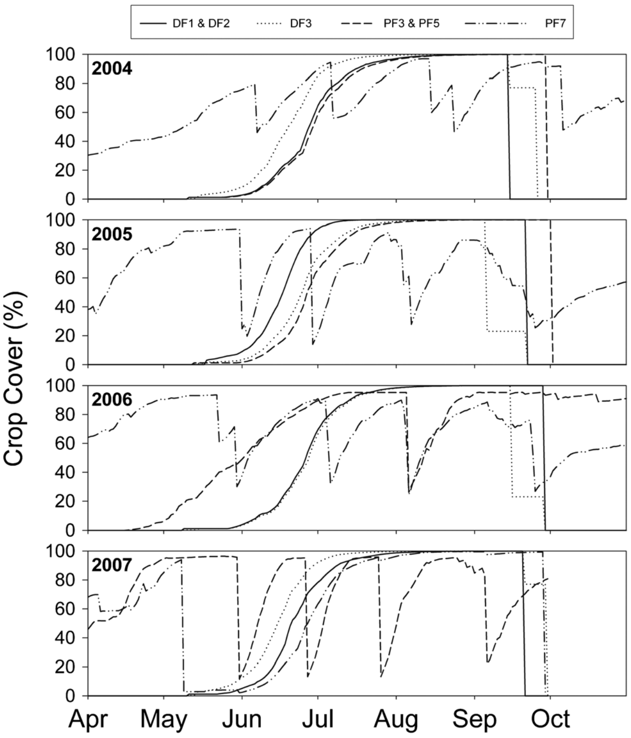

Figure 10. Time series of watershed crop cover

were greater for a direct-plant system. In general, when compared with conventional tillage systems, direct-plant systems tend to increase macropore connectivity which leads to increased infiltration rates and saturated hydraulic conductivities (Strudley *et al.*, 2008).

The direct-plant system at DFP provided more residue cover (55–60%) compared to the chisel plow/soil finisher system at PF (15–30%). Residue cover decreases runoff by intercepting and retaining precipitation and promoting infiltration of precipitation. Dry residue can absorb water two to four times greater than its own mass (Alberts and Neibling, 1994). Residue also promotes infiltration by protecting the soil from rain drop impact and subsequent surface sealing of soils (Alberts and Neibling, 1994). Lang and Mallett (1984) and Baumhardt and Lascano (1996) reported that increased residue cover resulted in increased infiltration. Results from the study presented herein indicate that the direct-plant management system was better at retaining precipitation at the soil surface than the chisel plow/soil finisher system, likely due to a combination of increased infiltration rates and increased residue cover.

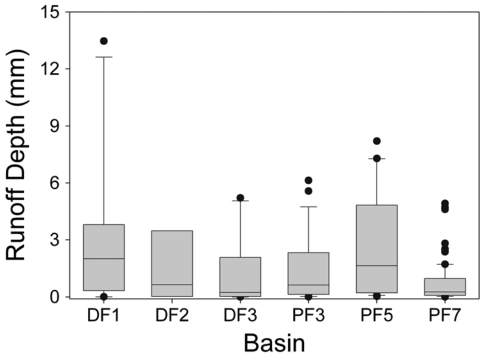

Figure 9. Box plots of runoff depth at each watershed (note: the box indicates the 25th, 50th, and 75th percentiles; the 10th and 90th percentiles are represented by whiskers above and below the box; outlying data points are plotted outside of the whiskers; the limited number of runoff events (8) at DF2 prevented calculation of 10th and 90th percentiles and outlying data points)

Differences in the total number of runoff events and runoff depths observed among the watersheds at PF can be attributed, in part, to structural features within two of the watersheds. Although the total number of runoff events generated at PF3 and PF5 were similar (Figure 6), PF5 produced larger runoff depths (Figure 7). Watersheds PF3 and PF5 are similar in terms of area, slope, soil type, and crop rotation (Table I); however, a tiled infiltration basin that was installed in PF3 at the end of 2004 provided additional storage and infiltration capabilities, decreasing runoff depths (Mentz *et al.*, 2007). Approximately, four times as many runoff events were generated at PF7 (80 events) compared to PF3 (24 events) and PF5 (22 events). However, the total runoff depth at PF7 (55 mm) was the same as the total runoff depth at PF5 (55 mm) and greater than the total runoff depth at PF3 (36 mm). Surface runoff during small precipitation events was likely generated from the impervious area within PF7, thereby increasing the total number of runoff events at PF7. Despite the likely production of runoff from the impervious area during small precipitation events, these runoff depths from PF7 were minimal because the impervious area constitutes only 12% of that watershed's total area.

Annual. Annual non-frozen ground runoff varied at DFP and PF. At both sites, the greatest runoff depths occurred in 2004 and 2007. In 2005 and 2006, runoff depths were minimal for all watersheds except PF7. In 2005, precipitation totals were much lower than historical averages. In 2006, precipitation totals were close to historical averages; however, precipitation events were evenly distributed throughout the non-frozen ground period. The annual runoff responses were similar at PF3, PF5, DF1, DF2, and DF3; nearly all (98%) of the non-frozen ground runoff generated from these watersheds occurred in 2004 and 2007. During these 2 years, 2% and 3% of the total non-frozen ground precipitation ran off the surface at DFP watersheds and PF3/PF5, respectively. In contrast, PF7 generated more consistent runoff depths, with approximately 2% of the annual non-frozen ground precipitation measured as surface runoff each year.

Monthly. Runoff primarily occurred during two main time periods at DFP, PF3, and PF5: May/June 2004 and July/August 2007 (Figures 6 and 7). Of the total 36 runoff events throughout the study period at DFP, 28 (78%) occurred during the months of April, May, and June, with 23 of those 28 runoff events occurring during the May/June 2004 period. Of the total 46 runoff events throughout the study period at PF3 and PF5, 25 (63%) occurred during April, May, and June, with 24 of those 25 runoff events occurring during the May/June 2004 period. Runoff events at PF7 were more evenly distributed throughout the study period, with only 26 of the 80 (33%) runoff events occurring during May/June 2004 and July/August 2007. The months of April, May, and June produced 31 of the 80 (39%) runoff events at PF7.

Thresholds for runoff generation

Soil moisture. Runoff coefficients (depth of runoff divided by depth of precipitation) are a measure of the runoff response of a landscape to rainfall. For DF1, DF2, DF3, PF3, and PF5, runoff coefficients increased significantly above ASM levels in the range of approximately 0.35 to 0.40 cm^3cm^{-3} (Figure 11), indicating a threshold range at which the rainfall–runoff response changes. The few non-zero runoff coefficients at lower ASM levels for DFP watersheds, PF3, and PF5 were due to intense rainfall events (storms with return periods greater than or equal to 1 year). For watershed PF7, a threshold ASM level is not as obvious. Runoff coefficients increase with ASM; however, the differences between runoff coefficients at low and high soil moisture levels are small, likely due to the runoff contributions from the impervious area within PF7.

The breakpoint regression analysis yielded a consistent ASM threshold of 0.39 cm^3cm^{-3} for DFP and PF watersheds, despite differences in tillage and cropping systems. Runoff coefficients were near zero when ASM was below this threshold and increased with ASM above this threshold.

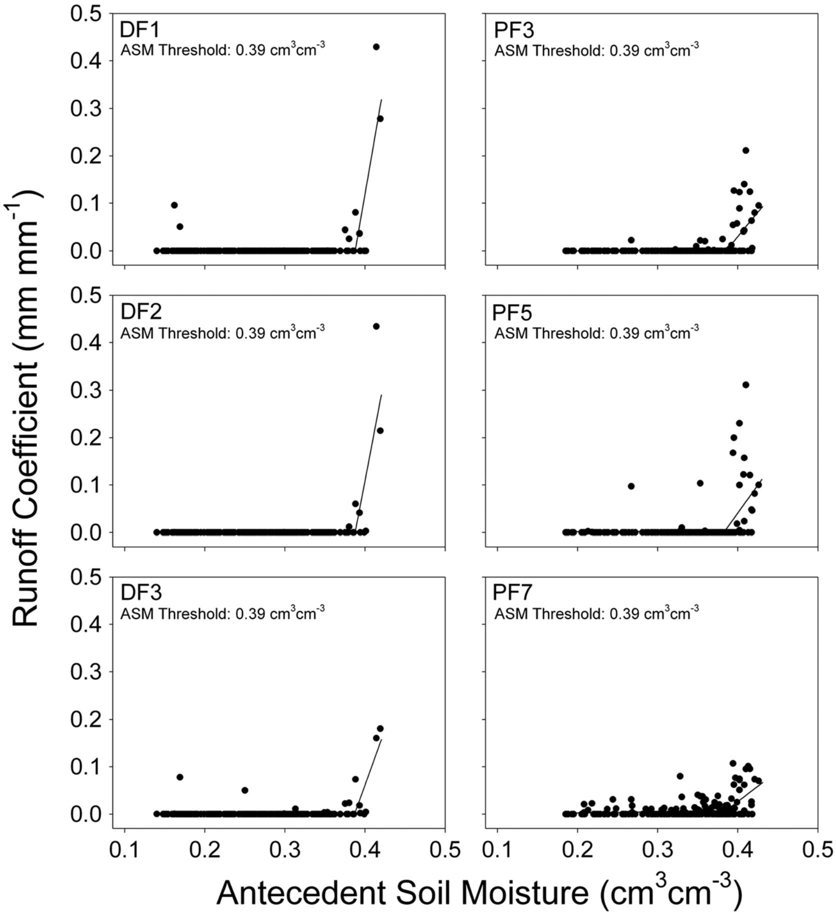

Figure 11. Breakpoint regression analysis of runoff coefficient *versus* antecedent soil moisture for DFP and PF watersheds

Approximately, 80% of the total runoff depth at DFP and PF watersheds originated when ASM was above the threshold of 0.39 $\mathrm{cm^3cm^{-3}}$ (Table III). Storms with return periods equaling or exceeding 1 year generated 82% of the total runoff depth below the ASM threshold at DF1, DF2, and DF3; 53% at PF3 and PF5; and 22% at PF7. There were only two extended time periods during which soil moisture levels equaled or exceeded the soil moisture threshold at DFP and PF: May/June 2004 and August 2007. These two time periods produced the greatest amount of runoff during the study period.

Threshold values of ASM for runoff generation have been reported in other studies (Table IV). Western and Grayson (1998) analyzed soil moisture and runoff for a small Australian watershed with silty clay loam soils and smooth undulating hills grazed by cattle. The authors reported that surface runoff was a threshold process controlled by soil moisture and that the soil moisture threshold ranged from 0.41 to 0.46 $\mathrm{cm^3cm^{-3}}$ depending on the depth of the soil moisture measurements. A similar threshold of 0.45 $\mathrm{cm^3cm^{-3}}$ was documented by Penna *et al.* (2011) for a small headwater catchment in the Italian Alps densely vegetated by alpine grasslands. On a small experimental grassland plot with sandy loam soils in Italy, Brocca *et al.* (2005) observed a soil moisture threshold of 0.36 $\mathrm{cm^3cm^{-3}}$ for runoff generation; runoff coefficients above the soil moisture threshold were significantly greater than zero (in Brocca *et al.*, 2008). James and Roulet (2007) report a lower antecedent moisture threshold of 0.23 $\mathrm{cm^3cm^{-3}}$ for a small forested catchment in Quebec, Canada. Although not directly comparable to results obtained from the watersheds with silt loam soils in the present study, Meyles *et al.* (2003) found that the rainfall–runoff response of a small watershed with peat soils in Southwest England changed when soil moisture levels reached 0.60 $\mathrm{cm^3cm^{-3}}$; runoff coefficients above the soil moisture threshold were significantly greater compared to runoff coefficients below the threshold. Detty and McGuire (2010) observed a clear threshold pattern when antecedent moisture and gross precipitation were summed and compared to total stormflow for a watershed in the Hubbard Brook Experimental Forest, New Hampshire. Our study confirms a similar threshold response for a set of agricultural watersheds in southwestern Wisconsin. In different landscape, soil, and climatic settings, both similar and dissimilar ASM thresholds were reported. Soil texture and structure influence the thresholds, and the reported thresholds generally increase with porosity (Table IV).

Rainfall intensity. Threshold maximum 30 min rainfall intensity (I30) was investigated using breakpoint regression analysis for storm event runoff coefficients. Rainfall was measured at each site's weather station. Runoff coefficients for DFP are averages of the three watersheds (DF1, DF2, and DF3) for each event, and runoff coefficients for PF are averages of PF3 and PF5 for each event. Storm event data for DFP and PF were combined for this analysis in order to maintain statistical rigor and since similar surface runoff characteristics were observed for these watersheds in the ASM breakpoint analysis. Storm event runoff coefficients and I30 were sorted into six groups based on ASM and CC: group A – ASM $\geq$0.40 $\mathrm{cm^3cm^{-3}}$ and CC $\geq$50%; group B – ASM $\geq$0.40 $\mathrm{cm^3cm^{-3}}$ and CC <50%; group C – ASM 0.35 to 0.40 $\mathrm{cm^3cm^{-3}}$ and CC $\geq$50%; group D – ASM 0.35 to 0.40 $\mathrm{cm^3cm^{-3}}$ and CC <50%; group E – ASM <0.35 and CC $\geq$50%; group F – ASM <0.35 $\mathrm{cm^3cm^{-3}}$ and CC <50%. Threshold I30 levels were observed after grouping the storm event data by ASM and CC (Figure 12). Watershed PF7 was excluded from this analysis because of the different runoff characteristics observed throughout the study period, most

Table III. Runoff depths for antecedent soil moisture above and below the threshold (0.39 $\mathrm{cm^3cm^{-3}}$)

	Runoff depth (mm)		% Runoff depth	
Watershed	ASM $\geq$ 0.39 $\mathrm{cm^3cm^{-3}}$	ASM <0.39 $\mathrm{cm^3cm^{-3}}$	ASM $\geq$ 0.39 $\mathrm{cm^3cm^{-3}}$	ASM <0.39 $\mathrm{cm^3cm^{-3}}$
DF1	22.4	8.2	73%	27%
DF2	20.8	0.2	99%	1%
DF3	11.6	8.6	57%	43%
PF3	33.1	2.7	93%	7%
PF5	48.2	7.2	87%	13%
PF7	28.2	19.7	59%	41%

Table IV. Comparison of antecedent soil moisture thresholds reported by other studies and observed at DFP and PF

Study	Soil texture	Porosity	Soil moisture threshold	Percentage of porosity
Brocca *et al.* (2005)	sandy loam	43%*	36%	83%
James and Roulet (2007)	sandy loam	47%	23%	49%
This Study	silt loam	49%*	39%	80%
Western and Grayson (1998)	silty clay loam	53%*	41 to 46%	78 to 87%
Penna *et al.* (2011)	clay loam/silty clay loam	53–57%	45%	79 to 85%

*estimated porosity calculated from bulk density; bulk density estimated from soil texture (Saxton *et al.*, 1986)

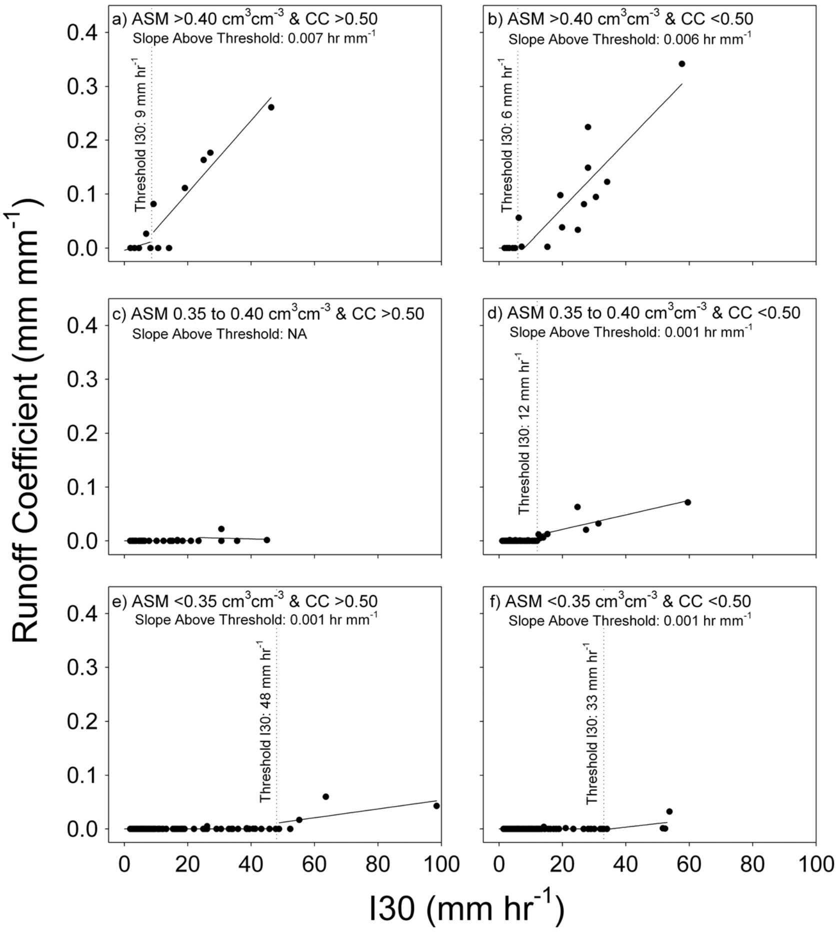

Figure 12. Runoff coefficient *versus* I30 categorized by antecedent soil moisture content and crop cover (ASM = antecedent soil moisture, CC = crop cover, and NA = not applicable)

likely because of the impervious surfaces located within the watershed.

In the highest ASM category ($\geq 0.40\,\mathrm{cm^3cm^{-3}}$), there were a total of 31 storm events at DFP and PF3/PF5 (Figures 12a and 12b); within this soil moisture category (groups A and B), 27 storm events occurred at PF and only four storm events occurred at DFP. Throughout the study period, soil moisture was typically higher at PF compared to DFP (Figure 2). Storm events in groups A and B accounted for 75% of the total runoff depth observed at both PF3/PF5 and DFP watersheds. The greater number of storm events in this soil moisture category at PF contributed to more runoff events and larger runoff depths compared to DFP. Within this soil moisture category, CC had a minor influence on surface runoff; a slightly higher I30 threshold of $9\,\mathrm{mm\ h^{-1}}$ was observed for $\mathrm{CC} \geq 50\%$ compared to $6\,\mathrm{mm\ h^{-1}}$ for $\mathrm{CC} < 50\%$; however, the slopes of the regressions above the threshold were not significantly different from each other ($p = 0.76$). The I30 thresholds for groups A and B were the lowest observed among all six groups. The slopes of the regressions above the I30 thresholds were also significantly greater for groups A and B than for any other ASM/CC group ($p < 0.05$).

In the 0.35 to $0.40\,\mathrm{cm^3cm^{-3}}$ ASM category, there were 103 storm events at DFP and PF3/PF5 (Figures 12c and 12d). Within this soil moisture category (groups C and D), CC had more of an influence on surface runoff. For storm events in group C (ASM 0.35 to $0.40\,\mathrm{cm^3cm^{-3}}$ and $\mathrm{CC} \geq 50\%$), an I30 threshold was not identified because the slope of the regression above the I30 breakpoint of $22\,\mathrm{mm\ h^{-1}}$ was neither significantly greater than zero ($p = 0.83$) nor significantly different from the slope of the regression below the breakpoint ($p = 0.48$). Additional monitoring of storm events in group C, particularly for $\mathrm{I30} > 35\,\mathrm{mm\ h^{-1}}$ may allow determination of an I30 threshold. Based on the small amount of runoff generated over the range of I30s observed and the breakpoint of $22\,\mathrm{mm\ h^{-1}}$ initially identified, this threshold is likely to be greater than the I30 threshold of $12\,\mathrm{mm\ h^{-1}}$ observed for storm events in group D (ASM 0.35 to $0.40\,\mathrm{cm^3cm^{-3}}$ and $\mathrm{CC} < 50\%$). The $12\,\mathrm{mm\ h^{-1}}$ I30 threshold for group D was slightly greater than that of groups A or B; however, the slope of the regression above the I30 threshold in group D was significantly lower than that of groups A or B ($p < 0.01$).

In the $< 0.35\,\mathrm{cm^3cm^{-3}}$ ASM category, there were 251 storm events at DFP and PF3/PF5 (Figures 12e and 12f). A higher I30 threshold was observed for storm events in group E (ASM $<0.35\,\mathrm{cm^3cm^{-3}}$ and CC $\geq 50\%$) compared to storm events in group F (ASM $<0.35\,\mathrm{cm^3cm^{-3}}$ and CC $<50\%$). However, the lack of storm events in Group F with I30 between 35 and $50\,\mathrm{mm\ h^{-1}}$ may have contributed to the lower I30 threshold than that of Group E. Slopes of the regressions above the thresholds in group E and F were not significantly different from each other ($p = 0.89$).

ASM influenced the threshold I30 level for runoff generation as well as the amount of runoff produced above the threshold. Storm event I30 thresholds for runoff generation increased as ASM decreased indicating that higher intensity storms are required to generate runoff when moisture content is low. In the highest soil moisture category ($\geq 0.40\,\mathrm{cm^3cm^{-3}}$), runoff coefficients above the threshold increase with I30 at a significantly higher rate compared to the lower soil moisture categories (0.35 to $40\,\mathrm{cm^3cm^{-3}}$ and $<0.35\,\mathrm{cm^3cm^{-3}}$). The influence of CC on the I30 threshold appears to increase as ASM decreases; however, additional data would help to establish this claim.

CONCLUSIONS

The factors that influence surface runoff generation in small agricultural watersheds in southwestern Wisconsin where the landscapes are controlled by dolostone bedrock were analyzed using a continuous, 4 year U.S. Geological Survey monitoring record of precipitation, runoff, and soil moisture. Six small watersheds within two farms with similar landscape and precipitation characteristics as well as very similar soils but with differing farming systems were studied. The majority of the non-frozen ground runoff occurred in only two months during the 4 year study period. The number of runoff events, depth of runoff, and mean runoff coefficients were greater under a fall chisel-spring finish tillage system than under a direct-plant system. Significant amounts of organic residues in varying states of decomposition that accumulate at the soil surface in the direct-plant farming system likely account for these differences by increasing infiltration and percolation of precipitation.

When the ASM at both sites was at, or above, $0.39\ \mathrm{cm^3cm^{-3}}$ the rainfall–runoff response of the watersheds changed; although storm events that exceeded this threshold accounted for only 16% of the total precipitation, they generated 78% of the total runoff depth during the non-frozen ground study period. A few intense storm events (return periods ≥ 1 year) generated runoff when the soil moisture was below this threshold; however, these runoff contributions were small relative to the total runoff depth. This threshold was the same regardless of farming system and represents approximately 80% of total porosity. The ASM threshold as a percentage of total porosity is similar to many reported in other studies and confirms, for small agricultural watersheds in southwestern Wisconsin, a non-linear response in runoff with ASM. Topography did not appear to have a large influence on the spatial distribution of soil moisture within these watersheds. Spatial soil moisture variability decreased as mean soil moisture increased.

A non-linear response in runoff generation with rainfall intensity was also observed when storm event data were grouped by ASM and CC. I30 thresholds for runoff generation increased as ASM decreased and as CC increased. Storm events in the highest ASM category ($\geq 0.40\,\mathrm{cm^3cm^{-3}}$) generated the majority (75%) of the total runoff at both sites.

High ASM can indicate risk for surface runoff in agricultural watersheds and can also influence the quantity of surface runoff generated during rainfall events. Avoiding manure applications during time periods with a high probability of rainfall when soil moisture is at or near threshold levels decreases the risk of surface water contamination. Agricultural producers can utilize soil moisture measurement to guide the timing and rate of manure application to further reduce environmental risk.

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REFERENCES

Alberts EE, Neibling WH. 1994. Influence of crop residues on water erosion. In *Managing Agricultural Residues*, Unger PW (ed). Lewis Publishers: Boca Raton, FL; 19–39.

Arnold JG, Weltz MA, Alberts EE, Flanagan DC. 1995. Plant Growth Component. In *USDA-Water Erosion Prediction Project Hillslope Profile and Watershed Model Documentation*, Flanagan DC, Nearing MA (eds). USDA-ARS: West Lafayette, Indiana. NSERL Report #10, 1–13. Available at: http://topsoil.nserl.purdue.edu/nserlweb/weppmain/docs/readme.htm, Accessed 19 November 2008.

Arshad MA, Franzluebbers AJ, Azooz RH. 1999. Components of surface soil structure under conventional and no-tillage in northwestern Canada. *Soil & Tillage Research* **53**: 41–47.

Aubert D, Loumagne C, Oudin L. 2003. Sequential assimilation of soil moisture and streamflow data in a conceptual rainfall-runoff model. *Journal of Hydrology* **280**: 145–161.

Azooz RH, Arshad MA. 1996. Soil infiltration and hydraulic conductivity under long-term no-tillage and conventional tillage systems. *Canadian Journal of Soil Science* **76**: 143–152.

Baumhardt RL, Lascano RJ. 1996. Rain infiltration as affected by wheat residue amount and distribution in ridged tillage. *Soil Science Society of America Journal* **60**: 1908–1913.

Benjamin JG. 1993. Tillage effects on near-surface soil hydraulic properties. *Soil & Tillage Research* **26**: 277–288.

Brady NC, Weil RR. 2000. *Elements of the Nature and Properties of Soils*. Prentice-Hall: Upper Saddle River, NJ.

Brocca L, Melone F, Moramarco T. 2005. Empirical and conceptual approaches for soil moisture estimation in view of event-based rainfall-runoff modeling. In *Progress in Surface and Subsurface Water Studies at the Plot and Small Basin Scale*, Maraga F, Arattano M (eds). IHP-VI, Technical Documents in Hydrology No. **77**, UNESCO: Paris; 1–8.

Brocca L, Melone F, Moramarco T. 2008. On the estimation of antecedent wetness conditions in rainfall – runoff modeling. *Hydrological Processes* **22**: 629–642.

Castillo VM, Gomez-Plaza A, Martinez-Mena M. 2003. The role of antecedent soil water content in the runoff response of semiarid catchments: a simulation approach. *Journal of Hydrology* **284**: 114–130.

Chang C, Lindwall CW. 1990. Comparison of the effect of long-term tillage and crop rotation on physical properties of a soil. *Canadian Agricultural Engineering* **32**: 53–55.

Clayton L, Attig JW. 1990. *Geology of Sauk County, Wisconsin*. University of Wisconsin-Extension Geological and Natural History Survey: Madison, Wisconsin. Information Circular **67**.

Cohrssen JJ, Covello VT. 1989. *Risk Analysis: A Guide to Principles and Methods for Analyzing Heath and Environmental Risks*. Report EPA PB89-137772. U.S.EPA: Washington, D.C.

Dao TH. 1993. Tillage and winter wheat residue management effects on water infiltration and storage. *Soil Science Society of America Journal* **57**: 1586–1595.

Denison RF, Loomis RS. 1989. *An Integrative Physiological Model of Alfalfa Growth and Development*. UC ANR Publication 1926, University of California: Davis.

Detty JM, McGuire KJ. 2010. Threshold changes in storm runoff generation at a till-mantled headwater catchment. *Water Resources Research* **46**: W07525. DOI:10.1029/2009WR008102.

Dick WA, Roseberg RJ, McCoy EL, Edwards WM, Haghiri F. 1989. Surface hydrologic response of soils to no-tillage. *Soil Science Society of America Journal* **53**: 1520–1526.

Dunne T, Black RD. 1970. Partial area contributions to storm runoff in a small New England watershed. *Water Resources Research* **6**: 1296–1311.

Dunne T, Moore TR, Taylor CH. 1975. Recognition and prediction of runoff-producing zones in humid regions. *Hydrological Sciences Bulletin* **20**: 305–327.

Elliott JA, Efetha AA. 1999. Influence of tillage and cropping system on soil organic matter, structure and infiltration in a rolling landscape. *Canadian Journal of Soil Science* **79**: 457–463.

EPA. 2000. National Water Quality Inventory: 2000 Report. Available at: www.epa.gov/305b/2000report, Accessed 1 October 2007.

Freese RC, Cassel DK, Denton HP. 1993. Infiltration in a Piedmont soil under three tillage systems. *Journal of Soil and Water Conservation* **48**: 214–218.

Gajri PR, Arora VK, Prihar SS. 2002. *Tillage for Sustainable Cropping*. Food Products Press: New York, NY.

Hewlett JD, Hibbert AR. 1967. Factors affecting the response of small watersheds to precipitation in humid areas. In *International Symposium on Forest Hydrological Processes*. Pergamon Press, Inc: New York, NY; 275–290.

Hoogenboom G, Jones JW, Wilkens PW, Porter CH, Batchelor WD, Hunt LA, Boote KJ, Singh U, Uryasav O, Bowen WT, Gijsman AJ, du Toit A, White JW, Tsuji GY. 2004. *Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.0 [CD-ROM]*. University of Hawaii: Honolulu, Hawaii.

Horne DJ, Ross CW, Hughes KA. 1992. Ten years of a maize/oats rotation under three tillage systems on a silt loam in New Zealand. 1. A comparison of some soil properties. *Soil & Tillage Research* **22**: 131–143.

Horton RE. 1933. The role of infiltration in the hydrologic cycle. *Transactions of the American Geophysical Union* **14**: 446–460.

Iserman K. 1990. Share of agriculture in nitrogen and phosphorus emissions into the surface waters of Western Europe against the background of their eutrophication. *Fertilizer Research* **26**: 253–269.

Istok JD, Boersma L. 1986. Effect of antecedent rainfall on runoff during low-intensity rainfall. *Journal of Hydrology* **88**: 329–342.

James AL, Roulet NT. 2007. Investigating hydrologic connectivity and its association with threshold change in runoff response in a temperate forested watershed. *Hydrological Processes* **21**: 3391–3408.

Kwaad FJPM. 1991. Summer and winter regimes of runoff generation and soil erosion on cultivated loess soils. *Earth Surface Processes and Landforms* **4**: 281–295.

Lang PM, Mallett JB. 1984. Effect of the amount of surface maize residue on infiltration and soil loss from a clay loam soil. *South African Journal of Plant and Soil* **1**: 97–98.

Linsley RK, Kohler MA, Paulhus JLH. 1982. *Hydrology for Engineers*, 3rdedn . McGraw-Hill Book Company, Inc: New York, NY.

Lipiec J, Kuś J, Slowińska-Jurkiewicz A, Nosalewicz A. 2006. Soil porosity and water infiltration as influenced by tillage methods. *Soil & Tillage Research* **89**: 210–220.

Mahboubi AA, Lal R, Faussey NR. 1993. Twenty-eight years of tillage effects on two soils in Ohio. *Soil Science Society of America Journal* **57**: 506–512.

Mentz R, Busch D, Owens D, Norman J, Karthikeyan K. 2007. Effect of tiled upland infiltration basins on runoff volume and pollutant export from field-scale agricultural basins. Available at: www.uwplatt.edu/pioneerfarm/research/Current_Projects/Tiled Upland Infiltration Basins/index.html, Accessed 19 November 2008.

Meyles E, Williams A, Ternan L, Dowd J. 2003. Runoff generation in relation to soil moisture patterns in a small Dartmoor catchment, Southwest England. *Hydrological Processes* **17**: 251–264.

Müller K, Stenger R, Rahman A. 2006. Herbicide loss in surface runoff from a pastoral hillslope in the Pukemanga catchment (New Zealand): Role of pre-event soil water content. *Agriculture, Ecosystems and Environment* **112**: 381–390.

Packer IJ, Hamilton GJ, Koen TB. 1992. Runoff, soil loss and soil physical property changes of light textured surface soils from long-term tillage treatments. *Australian Journal of Soil Research* **30**: 789–806.

Penna D, Tromp-van Meerveld HJ, Gobbi A, Borga M, Dalla Fontana G. 2011. The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment. *Hydrology and Earth System Sciences* **15**: 689–702.

R Development Core Team. 2007. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing: Vienna, Austria. ISBN:3-900051-07-0.

Ritsema CJ, Stolte J, Oostindie K, Van Den Elsen E. 1996. Measuring and modeling of soil water dynamics and runoff generation in an agricultural loessial hillslope. *Hydrological Processes* **10**: 1081–1089.

Ross CW, Hughes KA. 1985. Maize/oats forage rotation under 3 cultivation systems, 1978–83 2. Soil properties. *New Zealand Journal of Agricultural Research* **28**: 209–219.

Sauer TJ, Clothier BE, Daniel TC. 1990. Surface measurements of the hydraulic character of tilled and untilled soil. *Soil & Tillage Research* **15**: 359–369.

Saxton KE, Rawls WJ, Romberger JS, Papendick RI. 1986. Estimating generalized soil-water characteristics from texture. *Soil Science Society of America Journal* **50**: 1031–1036.

Sharpley AN, Meisinger JJ, Breeuwsma A, Sims JT, Daniel TC, Schepers JS. 1998. Impacts of animal manure management on ground and surface water quality. In *Animal waste utilization: Effective use of manure as a soil resource*, Hatfield JL, Stewart BA (eds). Ann Arbor Press: Boca Raton, FL; 173–242.

Strudley MW, Green TR, Ascough II JC. 2008. Tillage effects on soil hydraulic properties in space and time: State of the science. *Soil & Tillage Research* **99**: 4–48.

Stuntebeck TD, Komiskey MJ, Owens DW, Hall DW. 2008. Methods of data collection, sample processing, and data analysis for edge-of-field, streamgaging, subsurface-tile, and meteorological stations at Discovery Farms and Pioneer Farm in Wisconsin, 2001–2007. U.S. Geological Survey Open-File Report 2008–1015. Available at: http://pubs.er.usgs.gov, Accessed 19 November 2008.

Tromp-van Meerveld I, McDonnell JJ. 2005. Comment to "Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes, Journal of Hydrology 286:113-134". *Journal of Hydrology* **303**: 307–312.

Tromp-van Meerveld HJ, McDonnell JJ. 2006. Threshold relations in subsurface stormflow: 1. A 147-storm analysis of the Panola hillslope. *Water Resources Research* **42**: W02410. DOI:10.1029/2004WR003778.

Watson BG. 1966. *Soil Survey for Lafayette County, Wisconsin*. United States Department of Agriculture, Soil Conservation Service. U.S. Government Printing Office: Washington D.C.

WDNR. 2006. Wisconsin 2006 Water Quality Assessment Report to Congress. Available at: http://dnr.wi.gov/org/water/wm/watersummary, Accessed 19 November 2008.

Wei L, Zhang B, Wang M. 2007. Effects of antecedent soil moisture on runoff and soil erosion in alley cropping systems. *Agricultural Water Management* **94**: 54–62.

Western AW, Grayson RB. 1998. The Tarrawarra data set: Soil moisture patterns, soil characteristics, and hydrological flux measurements. *Water Resources Research* **34**: 2765–2768.

Wisconsin State Climatology Office. 2007. Wisconsin Climate by Division. Revised 31 July 2007. Available at: www.aos.wisc.edu/~sco/clim-history/division/index.html, Accessed 5 May 2008.

Withers PJA, Jarvis SC. 1998. Mitigation options for diffuse phosphorus loss to water. *Soil Use and Management* **14**: 186–192.

Withers PJA, Lord EI. 2002. Agricultural nutrient in-puts to rivers and groundwaters in the UK: Policy, environmental management and research needs. *The Science of the Total Environment* **282**: 9–24.

Zehe E, Graeff T, Morgner M, Bauer A, Bronstert A. 2010. Plot and field scale soil moisture dynamics and subsurface wetness control on runoff generation in a headwater in the Ore Mountains. *Hydrology and Earth System Sciences* **14**: 873–889.