DEVELOPMENT OF FIELD-SCALE LYSIMETERS TO ASSESS MANAGEMENT IMPACTS ON RUNOFF

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ABSTRACT. *Most empirical studies of field management effects on runoff water quality rely on edge-of-field monitoring, which is generally unreplicated and prone to high variances, or small plots, which constrain the use of conventional farm equipment and can hinder insight into landscape processes that drive hydrology. We sought to develop field-scale lysimeters that were sufficiently large to support assessment of landscape processes but also replicated to allow quantitative comparisons of hydrologic processes. A hillslope underlain by limestone bedrock with a recent history of hydrologic observation was selected in central Pennsylvania. Twelve 15 m × 27 m plots were established and defined by earthen berms on all sides to isolate and collect overland flow, along with tile drains to collect shallow lateral flow. Over three years, considerable variability in site hydrology was observed between lysimeters, highlighting differences in the extent of hydrologic isolation of some lysimeters as well as in flows that potentially bypassed our collection infrastructure. Even so, clear patterns were observed in surface and subsurface flow that enabled grouping of plots based on hydrologic similarities. Results illustrate the experimental opportunities and limitations of developing field-scale lysimeters for agronomic inference.*

Keywords. *Field-scale lysimeter, Hillslope hydrology, Lysimetry, Overland flow, Subsurface flow.*

In the Chesapeake Bay region, concerns over agricultural impacts on water quality have focused research that improves the understanding of field management on nutrient use, soil conservation, pests, and water quality (NAS, 2010). Hydrologically isolated field plots represent a significant investment, providing long-term insight into factors affecting agricultural sustainability, and are particularly applicable to agricultural areas where water quality is of concern. Despite a plethora of research on soil and water impacts of varying management practices (Bergstrom, 1990; Hansen et al., 2002; Lal et al., 2011), relatively few studies have integrated the measurement of overland flow and shallow lateral flow at a field scale.

Holistic assessment of the water resource impacts of alternative management practices requires lysimetry, i.e., the measurement of major pools within the water balance that neither excludes important pathways of water movement nor interferes with important biogeochemical processes. Many trade-offs are associated with lysimetry, primarily due to differences in size and scale. While smaller lysimeters, such as soil monoliths, pan lysimeters, wick lysimeters, and tensiometers, offer a relatively inexpensive means of collecting water from the soil profile, they are largely considered point measurements that are difficult to scale up (Hendershot and Courchesne, 1991; Webster et al., 1993). Larger versions of these lysimeters exist and can offer insight into interactions with landscape processes such as groundwater fluctuations and lateral flow. For instance, weighing lysimeters can be applied to larger volumes of soil to precisely calculate the water balance, but they are costly and require intensive maintenance (Armijo et al., 1972).

Various designs of hydrologically isolated plots have been used to infer the interaction of management with components of the water balance, without the control of weighing lysimeters but with the advantage of representing field-scale conditions. In some cases, these have been replicated, enabling quantitative comparison of management effects (Lowrance et al., 1992; Schoefield et al., 1993; Haygarth and Jarvis, 1997; Haygarth et al., 1998; Preedy et al., 2001; Houlbrooke et al., 2004; Monaghan and Smith, 2004; Harris et al., 1984; Cannell et al., 1986; Dowdell et al., 1987; Bosch

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et al., 2005). In the U.K., field-scale drainage plots (0.25 to 1 ha) were established at two locations (Brimstone Farm and Rowden Moor experimental drainage site) and monitored to assess drainage impacts on yields and nutrient loss in runoff (Armstrong and Garwood, 1991; Cannell et al., 1984; Harris et al., 1984, Haygarth et al., 1998; Haygarth and Jarvis, 1997; Preedy et al., 2001). Both research experiments in the U.K. were constructed to monitor surface layer flow, which includes movement of water across the soil surface combined with interflow (shallow lateral flow) as well as deeper water movement through artificial drainage (mole and tile) at 55 to 90 cm. Although these plots were isolated with gutters to contain surface runoff, subsurface flow was not always isolated (some plots were undrained).

In the U.S., Bosch et al. (2005) described the development of six 0.2 ha plots where surface and subsurface water was drained, and one 0.4 ha plot for companion rainfall simulation studies. The six plots were each surrounded by earthen berms for the partitioning of surface runoff to H flumes, and tile line installed at 1.2 m depth intercepted lateral subsurface flow measured on HS flumes. Similar to the studies in the U.K., a low-permeability argillic horizon provided the limiting layer for deep percolation loss. While these plots provide an impressive setup for monitoring different management effects on surface runoff and subsurface flow, they only provide for three replications of two treatments.

We sought to develop a set of field-scale lysimeters that would enable replication of agricultural management treatments to quantify impacts on hydrology and nutrient losses in runoff. In this article, we describe the design, implementation, and analysis of the overland and subsurface runoff monitoring systems. Trends in flow are used, in turn, to inform alternative experimental design that control for variability in the surface and subsurface flow between field lysimeters.

Materials and Methods

Site Description

A total of 12 field lysimeters were established on a hillslope within the Pennsylvania State University Russell E. Larson Agricultural Research Center in spring and summer 2010 (fig. 1a; 40.72° N, 77.92° W). Bedrock at the site is Bellefonte formation (Obf), characterized by medium-gray, brownish-weathering, medium-bedded dolomite and minor sandstone, very fine grained (Berg et al., 1980). The site had historically been under no-tillage corn-soybean-small grain production (approx. 15 years), with management typical of dairy production within the Northern Appalachian Ridges

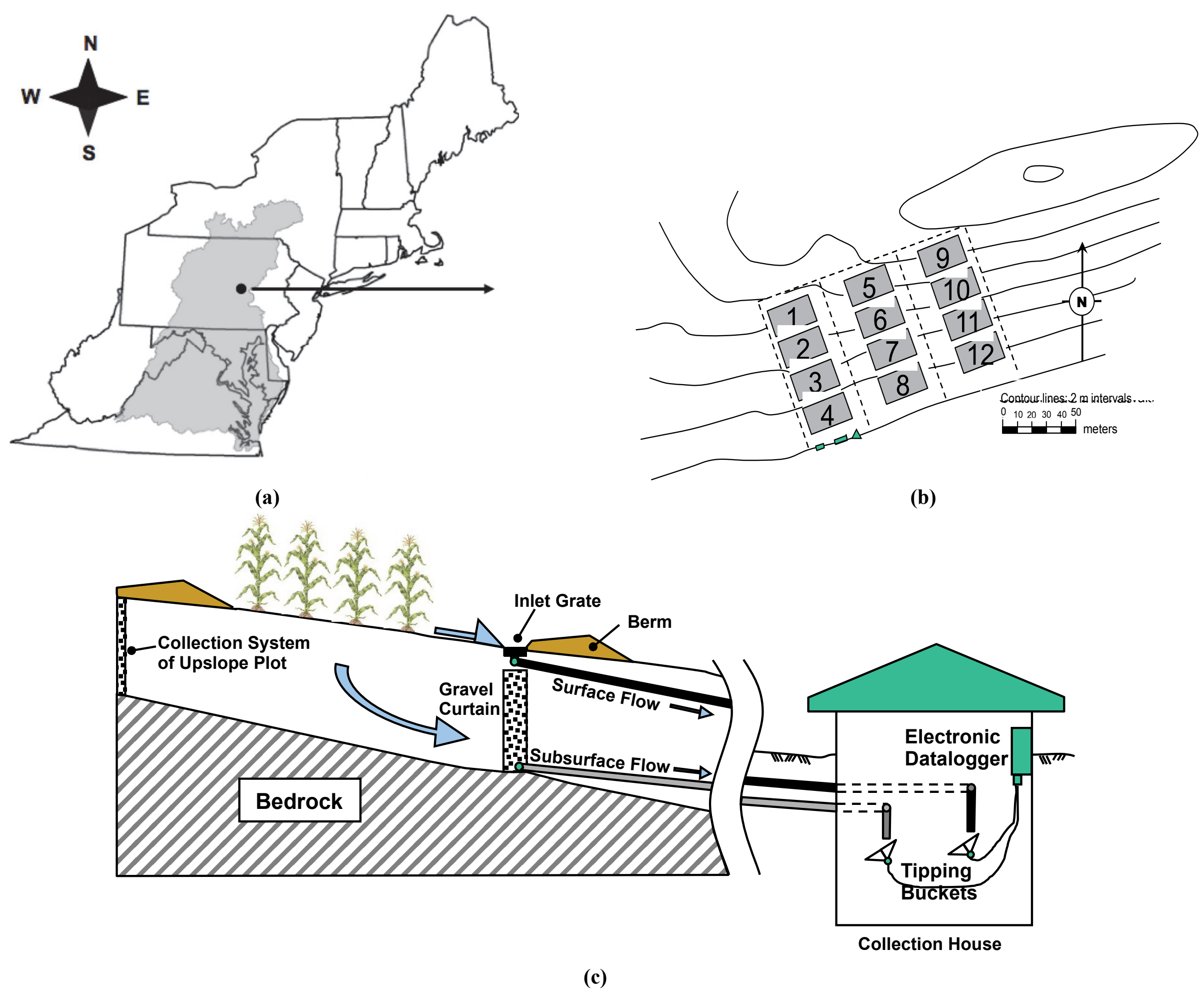


Figure 1. (a) Location of field site in Chesapeake Bay watershed, (b) site layout including runoff collection houses, and (c) schematic profile of the berms and drainage infrastructure associated with each field lysimeter.

Table 1. Soil characteristics: clay content, texture classification, soil depth measured with GPR, slope, bedrock, average soil volume, and topographic wetness index (TWI).

	Clay Content by Depth (cm)				USDA Texture by Depth (cm)[a]				Depth			Avg. Soil	
Field Lysimeter	0-15 (%)	15-30 (%)	30-60 (%)	>60 (%)	0-15 (%)	15-30 (%)	30-60 (%)	>60 (%)	Range[b] (m)	Slope (%)	Exposed Bedrock	Volume (m^3)	TWI
1	30	36	34	21	CL	CL	CL	SCL	0.34 to 1.16	9.8	No	484.8	5.8
2	24	35	71	67	L	CL	C	C	0.14 to 1.13	6.9	No	463.9	5.4
3	28	36	53	49	CL	CL	C	C	0.47 to 1.17	11.1	No	501.6	5.2
4	23	27	30	27	L	CL	CL	CL	1.41 to 1.50	7.6	No	626.9	5.4
5	35	41	56	61	CL	C	C	C	0.17 to 0.56	11.9	Yes	300.9	4.7
6	40	46	73	58	CL	C	C	C	0.31 to 1.17	11.7	Yes	497.4	5.5
7	41	65	64	70	C	C	C	C	0.35 to 1.18	12.3	No	505.7	6
8	31	35	56	74	CL	CL	C	C	0.49 to 1.30	7.9	No	543.4	7.1
9	45	62	69	70	C	C	C	C	0.17 to 0.64	13.1	Yes	305.1	5.5
10	44	60	40	38	C	C	CL	CL	0.22 to 0.74	14.6	Yes	334.4	5.7
11	40	42	64	52	C	SIC	C	C	0.27 to 0.87	13.7	No	351.1	6.3
12	35	44	43	72	CL	C	C	C	0.33 to 1.14	9.8	No	476.5	6.1

[a] CL = clay loam, C = clay, L = loam, SCL = silty clay loam, and SIC = silty clay.
[b] The maximum depth for each field lysimeter is 1.5 m based on the detection limit of the radar antenna.

and Valleys major land resource area (USDA, 2006). This area is representative of a significant portion of the Susquehanna River watershed, which empties to the Chesapeake Bay.

Precipitation averaged 1150 mm annually from 1980 to 2010, with summer (June to September) temperatures ranging from 9°C to 31°C and winter temperatures ranging from 23°C to 16°C (USDA, 2015a). In 2014, snow assessment improved with the implementation of snow tube measurements to quantify snow accumulation throughout the winter season.

Soils at the site include Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalf) and Opequon silty clay loam (clayey, mixed, active, mesic Lithic Hapludalf). Soils within each field lysimeter were sampled at different increments to a depth of 60 cm in 2011 and analyzed for texture by hydrometer method (table 1; Gee and Bauder, 1986). The moderate slope (6.9% to 14.6%) of the site supports both overland and shallow lateral flow of runoff. Previously, Zhu and Lin (2009) characterized the hydropedologic properties of the site using a combination of geophysical techniques (electromagnetic induction, ground-penetrating radar) and point measurements of soil properties and soil water content (Zhu and Lin, 2009). Their study was a principal motivation for establishing field lysimeters at the site, as they documented active overland and subsurface hydrology, with the shallow limestone substrate serving as an aquitard that routed infiltrating water into lateral subsurface flow paths.

PLOT DESIGN

The 12 field lysimeters were constructed in a three-column arrangement on the hillslope (fig. 1b). Each field lysimeter was given dimensions of 27 m long × 15 m wide to accommodate a maximum variety of farm machinery while still keeping the total extent of the site within the leased boundary. All field lysimeters were monitored for both overland flow and subsurface flow that was routed to runoff collection houses located at the base of the hillslope. Alleyways with a 30 m width were established along the hillslope between field lysimeters to enable easy access, maneuvering of large farm equipment, and placement of plumbing. In order to satisfy the key criterion of hydrologic isolation for the site, an unmonitored tile drain was placed around the site perimeter and in each of the alleyways. For this perimeter drain, a 0.6 m wide trench was excavated to bedrock with a backhoe. Two 11.6 cm perforated, corrugated plastic pipelines were placed on the bottom of the trench. The trench was then backfilled with crushed stone (ASTM #4). Further hydrologic isolation of the individual field lysimeters was achieved with the berms and subsurface drainage infrastructure used to collect runoff, as described in the following section. While most of the field lysimeters were dominated by the Hagerstown soil, Opequon soils with emergent bedrock were found in the upper right quadrant of the site, primarily associated with field lysimeters 5, 6, 9, and 10.

RUNOFF COLLECTION SYSTEMS

The runoff collection systems were designed with the goal of striking a balance between cost and functionality (fig. 1c). Given the surface area (0.04 ha) of each field lysimeter, even a minimal runoff amount (1 mm) would produce a volume (400 L) so large that capture and storage of runoff, as typically done with smaller lysimeters, would be impractical. Consequently, the designs for both the overland and subsurface collection systems were based on runoff interception and routing, with flow rate, as determined below, being the limiting factor of each design.

Overland Flow Collection

For each field lysimeter, the land surface was bounded on all four sides by a 0.3 m tall earthen berm. The berms were tapered so as not to inhibit passage of farm machinery onto and off the plots. Along the inside toe of the bottom berm, a series of five inlet grates, connected to a single 11.6 cm diameter, schedule 40 PVC collection pipe, routed runoff to a collection house. Schedule 40 PVC pipe was used to ensure strength and crush resistance during and after construction. A pipe with a diameter of 11.6 cm was determined via the Rational Method (Kuichling, 1889) to adequately convey the maximum flow rate of 2.2 L s^{-1} (without causing ponding) from a rainfall burst with a 10 min average intensity of 10.9 cm h^{-1}, which represents a storm with a ten-year rainfall return period (Aron et al., 1986) for the site location.

Subsurface Runoff Collection

In order to intercept lateral subsurface flow, a French drain style collection system was used. For each field lysimeter, a trench (0.3 m width) was excavated to bedrock (average depth to bedrock at the site was 1 m) along the lysimeter's entire downslope edge. The trench was subsequently lined with lightweight, nonwoven geotextile fabric to prevent soil fouling of the drain without introducing any artificial flow restrictions. A perforated, 11.6 cm diameter, PVC collection pipe was then placed along the length of the trench bottom and connected to a solid 11.6 cm PVC (schedule 40) collection pipe. As with the surface drains, a unique collection pipe exists for each lysimeter to route runoff to a collection house. Finally, the trench was filled with stone aggregate (ASTM #4) to within 0.2 m of the land surface and capped with geotextile fabric. The remaining portion (0.2 m) of the trench was filled with soil and compacted to isolate the drain from the land surface. A pipe diameter of 11.6 cm was also selected for the subsurface drain based on the assumption that the design storm used to size the surface drains will produce an attenuated subsurface hydrograph with a lower peak flow rate.

Overland and Subsurface Flow Monitoring

Overland and subsurface flow from individual field lysimeters was routed to the central collection houses, where flow rates were quantified by two approaches (fig. 1). All pipes discharging to the houses were equipped with a tipping-bucket and reed switch device (constructed in-house) to quantify flows less than 0.75 L s^{-1} (average tipping-bucket capacity = 1.5 L). For pipes that produce storm flows greater than 0.75 L s^{-1}, an overflow 0.12 m HS flume and Solinst Levelogger transducer measured the excess flow. Specifically, discharge was estimated via a depth/flow rating curve (USDA, 1979). A datalogger (CR10X, Campbell Scientific, Logan, Utah) records flow rates for all 24 collection lines at 5 min intervals. A slot on the bottom of each tipping-bucket device allows automatic collection of a composite subsample at a rate of 1:25 into a container mounted under the device floor. The container is then manually emptied, ideally within 24 h of a storm event.

Construction Costs

The field lysimeters were constructed over a nine-month period, using mostly USDA employees for labor and machinery from the USDA farm and Penn State's Larson Agronomy Farm (table 2). Approximately 2,000 person-hours were required to complete the construction. Use of in-house construction equipment and labor significantly reduced the overall costs of the project, which totaled roughly \$59,000. If labor and construction equipment had to be contracted out, we estimate that the cost would have been at least \$250,000 higher (approx. \$309,000 total).

Table 2. Estimated construction costs for collection houses, drainage system, monitoring equipment, subcontractors, and equipment rental.

Item	Cost
Collection houses	\$16,000
Instrumentation:	
Three data loggers	\$6,000
Solar panels and attic fans	\$1,000
24 tipping-bucket flow recorders and hardware	\$3,600
Meteorological station	\$2,400
Pipe	\$13,000
Subcontractors:	
Bedrock excavation for drain lines	\$800
Access road construction	\$7,200
Stone	\$6,000
Filter fabric	\$2,000
Skidsteer rental for berm construction	\$1,000
Total	\$59,000

Meteorological Data Collection

A meteorological station (CR10X, Campbell Scientific) was installed next to the collection house to monitor precipitation, temperature, wind speed, and solar radiation at 5 min intervals. Recorded precipitation (rainfall and snow) from 2012 totaled 860 mm, while precipitation in 2013 totaled 837 mm. Snow was measured as water equivalent, either by antifreeze displacement or manual measurements (snow tube measurements began in 2014). Data gaps (due to equipment malfunction) were infilled using observations from a nearby meteorological monitoring location. Specifically, the majority of the data came from the field lysimeter weather station, but when necessary, the data came from a meteorological station located 1.6 km from the field lysimeters and operated by USDA-ARS that exhibited a strong relationship with data from the field lysimeter site (R^2 = 0.92) (unpublished precipitation data from Jeff Gonet, USDA-ARS, 2012-2014).

Surface and Bedrock Topographic Characterization

Depth to bedrock at the site was mapped using a ground penetrating radar (GPR) system (SIR-3000, Geophysical Survey Systems, Inc., Salem, N.H.) with a 400 MHz antenna. A handheld GPS unit (GeoExplorer 2008 Series, Trimble, Westminster, Colo.) connected to a serial data recorder (DataBridge SDR, Acumen Instruments, Ames, Iowa) recorded geographic coordinates every second. Twenty-four GPR transects (approx. 4 m apart) were established up and down the hillslope in fall 2012, and an additional 30 transects were added in fall 2014. Soil depth was calibrated by burying a metal object at 60 cm and determining the propagation velocity (0.095 m ns^{-1}). Notably, the antenna configuration used in the GPR assessment possessed a maximum depth of detection of 1.5 m given the reflectance properties of the soil.

Radar images were processed using RADAN7 software (GSSI, Salem, NH). Post-processing steps included time zero position correction, horizontal stacking, and low-pass filtering to remove high-frequency noise and migration. Ordinary kriging of bedrock depth was performed in ArcGIS 10.0 (ESRI, Redlands, Cal.).

Topographic wetness index (TWI; Beven and Kirkby, 1979) layers for the surface and bedrock layers were generated from the surface and bedrock topography gridded raster files (3.2 ft, approx. 1 m resolution) using ArcMap 10.1 (ArcGIS Desktop, release 10.1, ESRI, Redlands, Cal.). TWI estimates the influence of topography on hydrological processes, specifically using upstream drainage area (α) and local slope (β):

$$\mathrm{TWI} = \ln\left(\frac{\alpha}{\tan\beta}\right) \quad (1)$$

Table 3. Annual overland, subsurface flow, and runoff coefficients.

Field	Overland Flow (mm)			Subsurface Flow (mm)			Runoff Coefficient[e]		
Lysimeter	2012[a]	2013[b]	2014	2012	2013	2014	2012	2013	2014
1	3	9	1[c]	1	5	-[d]	0.005	0.017	0.001
2	1	8	32	31	48	82	0.037	0.067	0.131
3	3	5	63	24	24	23	0.031	0.035	0.099
4	1	3	59	221	423	202	0.257	0.509	0.299
5	5	5	44	84	56	87	0.103	0.073	0.150
6	0.2	8	14	6	2	23	0.007	0.012	0.042
7	1	4	21	155	129	102	0.180	0.159	0.141
8	1	1	54	67	54	53	0.079	0.066	0.123
9	5	5	40	105	81	79	0.127	0.103	0.136
10	2	3	13	46	15	29	0.055	0.022	0.048
11	1	3	68	57	23	9	0.067	0.031	0.088
12	1	4	42.82	33	16	26	0.039	0.024	0.079

[a] Data lost for field lysimeters 1 to 4 in May-June 2012 (18% of annual precipitation missed).
[b] Data lost for all field lysimeters during a storm event in June 2013 (11% of annual precipitation missed), and data lost for lysimeters 5 to 12 during an event on 1-3 July 2013 (1.4% of annual precipitation missed).
[c] Data lost from January to June 2014 (25.7% of annual precipitation).
[d] Data lost for all of 2014.
[e] Runoff coefficient = (overland flow + subsurface flow) / precipitation.

TWI indicates the likelihood of each landscape unit to become saturated. Low TWI values indicate a low likelihood of saturation, whereas the highest TWI values represent areas of the highest likelihood of saturation.

Data Analysis

Data loss and equipment malfunction occurred on the site periodically over the three years of data analyzed. Annual totals of overland and subsurface flow may be underestimated in all three years of analysis due to the following data gaps. In May-June 2012, data for field lysimeters 1 to 4 were lost when the logger malfunctioned in the small collection house. During a storm in June 2013, data were lost for all of the field lysimeters. Finally, in 2014, overland and subsurface flow data were lost for field lysimeter 1: overland flow was lost for January-June 2014, and subsurface flow was lost for all of 2014 (table 3). All missing data were left out of the statistical analysis.

Statistical analysis was performed on the runoff data for 2012, 2013, and 2014 (table 3). Differences in surface and subsurface flow between plots were evaluated using analysis of variance. Pearson's correlation was used to assess relationships between overland flow (depth, mm) and subsurface flow (depth, mm) for all runoff events (2012-2014) for all plots (Minitab, 2010). Linear regression (Minitab, 2010) was used to generate models of relationships for variables that had Pearson's correlation values of 0.60 and higher and p-values < 0.01. To calculate runoff thresholds, all of the runoff volumes for each field lysimeter and the associated maximum precipitation intensity were analyzed in an NLIN SAS model to determine if there was a threshold point at which the field lysimeters would produce runoff. Statements of significance in the text refer to $\alpha = 0.05$.

Results and Discussion

Annual Trends in Precipitation and Runoff

Substantial differences in annual water balance components (with the exception of ET, which is not included) were observed between 2012 and 2014 even though annual precipitation totals were similar across the three years (865, 837, and 872 mm, respectively, 278 to 313 mm lower than the long-term average). Linear regression analysis of collected data versus historical data provided evidence of similarities ($R^2 = 0.8$). In general, 2012 was characterized by several prolonged dry periods, whereas 2013 was characterized by an even distribution of precipitation over the year with very few dry periods, and 2014 precipitation was dominated by events during the growing season (from late spring to late summer). Statistically significant (one-way ANOVA, t-test, $\alpha = 0.05$) differences in runoff, both overland and subsurface, were observed between the years, largely as a function of the distribution of precipitation (table 3). In 2014, there was 8-fold more overland flow than in 2013 and 20-fold more overland flow than in 2012. The study period was punctuated by several extreme events, such as Hurricane Sandy in October-November 2012, which accounted for 50% of overland flow and 40% of subsurface flow measured over the 2012 flow year. Storm events ranged from one-year to five-year average recurrence intervals (NOAA, 2006), with mean annual runoff coefficients ranging from a minimum of 0.08 in 2012 to a maximum of 0.11 in 2014.

Hydrologic Trends across Field Lysimeters

Considerable variability in hydrology was observed across the 12 field lysimeters, as revealed by the runoff coefficients for combined runoff ([OF + SSF]/P), which ranged from <1% to 50% (table 3). Overland flow depths were greatest in 2014, while subsurface flows were similar in all years (2012-2014, yearly averages of all lysimeters). The absence of significant relationships between annual overland and subsurface flow of individual field lysimeters ($r^2 < 0.29$ for all years) highlights a surprising disconnect between these two forms of runoff. In general, overland flow and subsurface flow accounted for a wide range (<1% to 50%) of annual precipitation. Despite this disconnect, analysis of all runoff (overland and subsurface flow) and corresponding precipitation for all events from 2012-2014 revealed an average runoff threshold of 25.4 mm h^{-1}. This threshold indicates that after an event of approximately 25.4 mm (1 in.) of rain, most of the field lysimeters will produce overland flow, depending on antecedent soil moisture conditions. This provides good preliminary indicators of when this site will activate.

Recovery of runoff water from the field lysimeters (overland and subsurface flow) points to a variety of potential additions and losses within the site (table 3). Roughly half of the field lysimeters yielded runoff within the range of reported values for the region (field lysimeters 2, 3, 5, 8, 10, 11, and 12; Cinotto et al., 2005). Overland and subsurface flow from these field lysimeters was approximately 2% to 10% of precipitation inputs in 2012 and 2013, and 5% to 15% of precipitation in 2014. In contrast, field lysimeters 1 and 6 had lower than expected recoveries of overland and subsurface flows (<1% of annual precipitation in 2012 and 2013, and <4% of annual precipitation in 2014), suggesting runoff losses that bypassed our monitoring infrastructure (e.g., deep percolation), and field lysimeters 4 and 7 produced higher than expected subsurface flows (up to 51% of 2013 precipitation), suggesting hydrologic inputs from outside the lysimeter area. Prior to the construction of the field lysimeters, a large seep had been observed in the region around plots 4 and 7. Despite the installation of perimeter drains, surface runoff observations suggest continued activity related to the seep.

Trends in Subsurface Flow

Total subsurface flows ranged from 1 to 423 mm on an annual basis and from 1 to 80 mm for individual events (80 mm produced by lysimeter 4 on 19 May 2014, three days after 50 mm of precipitation that fell on 16 May 2014.). Despite this variability between field lysimeters, there were consistent trends in flow response, runoff volume, and total annual flows for subsurface flow among individual lysimeters, enabling groupings of lysimeters based on internal consistencies that suggest similarities in landscape controls on hydrology. These groupings were based on relative comparisons of flows (total annual flows, mm). Similarities in subsurface flow response were apparent for two field lysimeters in the northeast corner of the study area (lysimeters 5 and 9; fig. 1b). Subsurface flows from these lysimeters fell in the upper 70th percentile of flows observed from the site (table 3). Field lysimeters 5 and 9 contained the shallowest soils, with exposed bedrock (Opequon soil series; fig. 2). On an event basis, subsurface flows between these two lysimeters responded within the period of rainfall (as opposed to after the rainfall period) and were strongly related on an annual total flow basis (r^2 = 0.96 in 2012, 0.87 in 2013, and 0.82 in 2014). A hydrograph typical of these two lysimeters from a storm with a five-year return frequency (15 May 2014) exhibits a short delay in subsurface flow initiation after the onset of precipitation, followed by a hydrograph peak during the storm event (maximum flows were 0.4 and 0.3 L s^{-1} for plots 5 and 9, respectively) that rapidly diminishes, reflecting high hydrological connectivity and limited storage within these lysimeters (fig. 3e).

On the eastern flank of the site (fig. 1b), field lysimeters 10, 11, and 12 also exhibited strong similarities in annual subsurface flows (r^2 > 0.70), typically manifesting single-peak storm hydrographs (rising limb and falling limb of the hydrograph fell within duration of the storm; figs. 3c and 3f) that were similar in shape to those associated with lysimeters 5 and 9 but not as flashing in nature (figs. 3b and 3e). While lysimeter 10 contained exposed bedrock (as with lysimeters 5 and 9), soil depths in these eastern field lysimeters were intermediate for the site (averaging 0.74 to 1.14 m; fig. 2), and subsurface flows were in the median of those observed at the site.

On the western side of the site (fig. 1b), field lysimeters 2 and 3 produced subsurface flows that were well related in 2012 and 2014 (r^2 > 0.75) but were poorly related in 2013 when flows were very high (no significant relationship, r^2 <

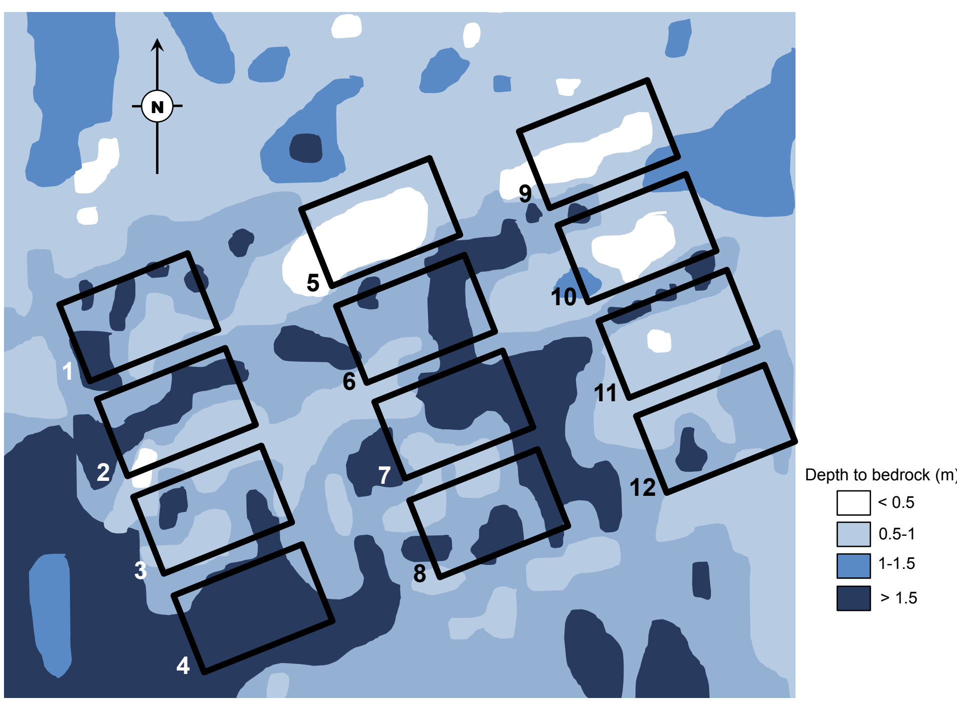


Figure 2. Interpolated depth of limestone bedrock inferred from GPR mapping. Rectangles show the locations of the 12 field lysimeters. The sensitivity of the instrument did not permit bedrock depth estimation > 1.5 m.

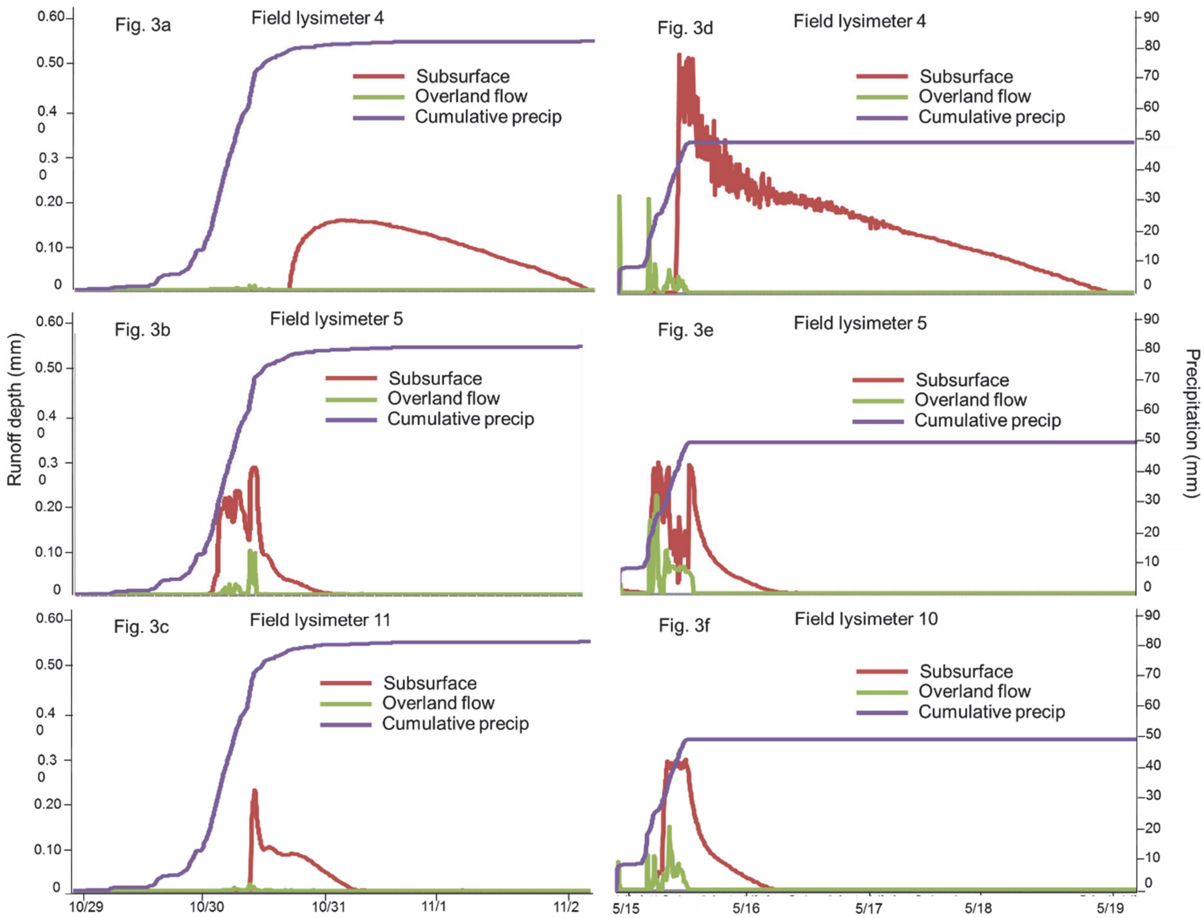


Figure 3. Storm hydrographs for representative field lysimeters for (a through c) Hurricane Sandy (30 October 2012) and (d through f) a 50 mm storm with a two-year recurrence interval (15 May 2014).

0.50). These field lysimeters were characterized by hydrographs during events similar to field lysimeter 10 during the May 2014 event (fig. 3f). The GPR-estimated soil depths for both field lysimeters are very similar, which could explain some of the consistencies found in their subsurface flow.

Three of the 12 field lysimeters consistently yielded subsurface flows that were inconsistent with site design and expectations. Specifically, lysimeter 6 rarely produced subsurface flows. Field lysimeter 6, located in the middle of the site, contains fairly shallow soils (fig. 2). Drainage from this field lysimeter was clearly bypassing the monitoring infrastructure. There was little relationship between antecedent site conditions (as estimated by cumulative precipitation during the preceding seven days) and subsurface flow generation. In extreme contrast with field lysimeter 6, field lysimeters 4 and 7 had the greatest subsurface flows of all lysimeters at the site. As illustrated by the Hurricane Sandy hydrograph and the hydrograph from the May 2014 event (figs. 3a and 3d), flows produced by field lysimeters 4 and 7 were typically delayed and persisted for 48 h after the event and for up to 40 h after subsurface flow ceased in other lysimeters. Given the strong coincidence in flow timing and duration, it is likely field lysimeters 4 and 7 are hydrologically connected to a similar landscape water flow path. Indeed, one hypothesis is that subsurface flow in field lysimeters 4 and 7 can be attributed to a seep that was observed forming at the base of the hillslope before construction of the field lysimeters. These lysimeters could be capturing some of this seep flow, which might explain the large volumes of subsurface flow that they periodically produce. It can also be noted that field lysimeter 4 produced more runoff in 2013 than entered the system according to our water budget equation. While TWI assessment suggests greater potential for connectivity in the vicinity of these two lysimeters, no conclusive quantitative relationship was found between the TWI of field lysimeters and their subsurface flow.

The dynamic nature of subsurface flow hydrology is manifest with field lysimeter 8, which sometimes behaved like field lysimeter 3 and, under very wet site conditions, behaved like field lysimeters 4 and 7 (fig. 3d). Indeed, during Hurricane Sandy, field lysimeters 4, 7, and 8 all produced very similar hydrographs (fig. 3a). As reflected in the bedrock topography of the site, large variability existed in shallow groundwater storage potential. Under saturated conditions, it is likely that hydrologic connectivity increased due to lesser storage within the different areas of the hillslope.

TRENDS IN OVERLAND FLOW

Patterns in overland flow between field lysimeters and over time were different from those observed for subsurface flow. Considerable variability in overland flow was observed between individual lysimeters; each year, two different field lysimeters produced the highest amounts of overland flow (table 3). In particular, field lysimeters 5 and 9 generated the most total overland flow in 2012, while field lysimeter 6 had the least overland flow in 2012 (table 3). The clustering of field lysimeters 5 and 9 in the northeast area of the slope points to local edaphic controls (shallow soil less than 0.6 m to bedrock) on overland flow. Bedrock in these lysimeters was generally very shallow, including exposed bedrock.

The large number of events observed during the three-year study period afforded a range of climatological and hydrological conditions. In general, there was no significant relationship between cumulative precipitation over the seven days prior to a storm event and the depth of overland flow produced during that event. Similarly, when TWI values were analyzed against GPR depth, or runoff flows, no relationship could be determined. This would suggest a limited role of lateral flow processes, such as saturation excess runoff generation (Dunne and Black, 1970), at the site. However, a threshold in runoff generation was observed as a function of total event precipitation and volume of overland flow (May to October 2014 runoff events) for many of the field lysimeters, with runoff generation increasing at precipitation events of ≥2 cm. Notably, field lysimeters 1 and 2 tended not to exhibit a threshold relationship, pointing to potential for different controls on overland flow. Storm intensity played the most apparent role in runoff generation; during high-intensity events (5 cm h^{-1}) all of the field lysimeters tended to produce overland flow. Possible inconsistencies in overland flow patterns could be attributed to the time of year, cover crop versus cash crop, thaw events in winter and early spring, and the type of precipitation event.

Hurricane Sandy represented the first opportunity to monitor an event where all the field lysimeters produced overland flow. Field lysimeters 1, 3, 5, and 9 produced the most overland flow during the event. Field lysimeters 5 and 9 behaved similarly in overland flow during other events, but none of the other field lysimeters had any regular or predictable patterns. Besides Hurricane Sandy, 2014 proved to be a big year for overland flow. All of the field lysimeters produced significantly greater amounts of overland flow as compared to 2012 and 2013 (fig. 4). Steady amounts of precipitation fell in the spring and summer of 2014 (May to July), and even though precipitation was only 8 mm greater than in 2012, there was significantly greater overland flow (fig. 4). The spring of 2014 was a particularly wet season, with four precipitation events totaling 101 mm in May, four events totaling 88 mm in June, and another 88 mm of precipitation in July. Despite the increase in volume of runoff during 2014, no clear relationships could be determined between field lysimeters such as those found for subsurface flow.

Interpretations for Experimental Management

Based on analysis of the first three years of data, some treatment blocking suggestions can be made to enhance the use of the field lysimeters. The plots can be blocked for treatment assignment using separate analyses of subsurface flow and overland flow. Depending on what a potential researcher is interested in investigating (overland, subsurface flow, or both), treatments could be assigned to lysimeters according to relationships drawn from Pearson's correlation coefficients, regression analysis (R^2 values), and total annual depth of runoff. Field lysimeters can be paired differently based on overland or subsurface flow (fig. 5). Field lysimeters that are paired had high Pearson's correlation coefficients ($p < 0.005$) and significant regression relationships ($R^2 > 0.60$) and produced similar annual total depth of overland flow. Although overland flow could be used to pair field lysimeters for experimental testing, trends in subsurface flow were more consistent over the study period, pointing to subsurface flow similarities as a better criterion for assigning treatments.

Application of the field lysimeters to experimental designs comparing treatment means, such as a paired t-test or analysis of variance, clearly requires consideration of the similarities in hydrology. For example, field lysimeters 4 and 7 both produce high volumes of subsurface flow; therefore, they should represent different treatments in the future. Conversely, field lysimeters 1 and 6 are the opposite and should also be assigned different treatments. Treatment blocking for field lysimeter 1 was based on data from 2013 due to the 2014 data loss. Given the high variability in flow between plots, no more than two management treatments should be imposed to reduce variance and increase statistical power when making treatment comparisons. Implementing some type of spatial statistics incorporating GPR imagery and TWI analysis would provide an enhanced analysis of water movement at the site. Increasing the use of spatial analysis tools would greatly improve the future use of the site for management comparison purposes.

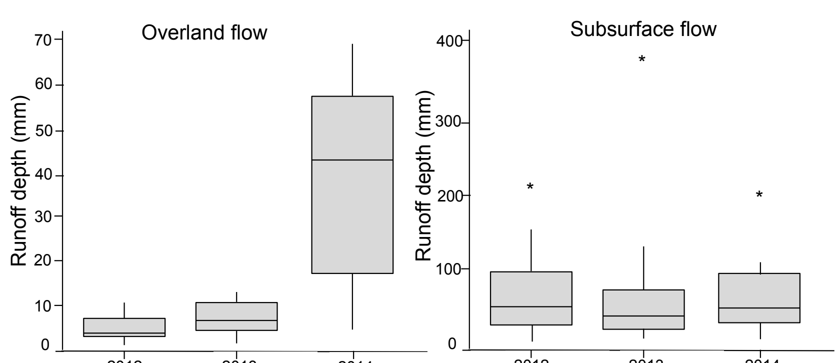
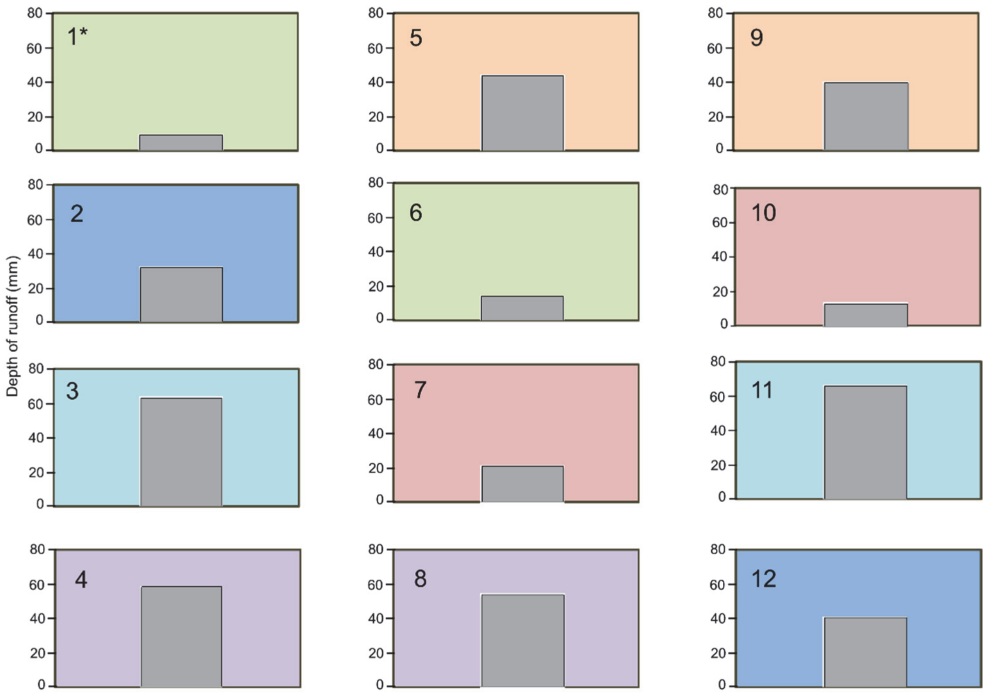
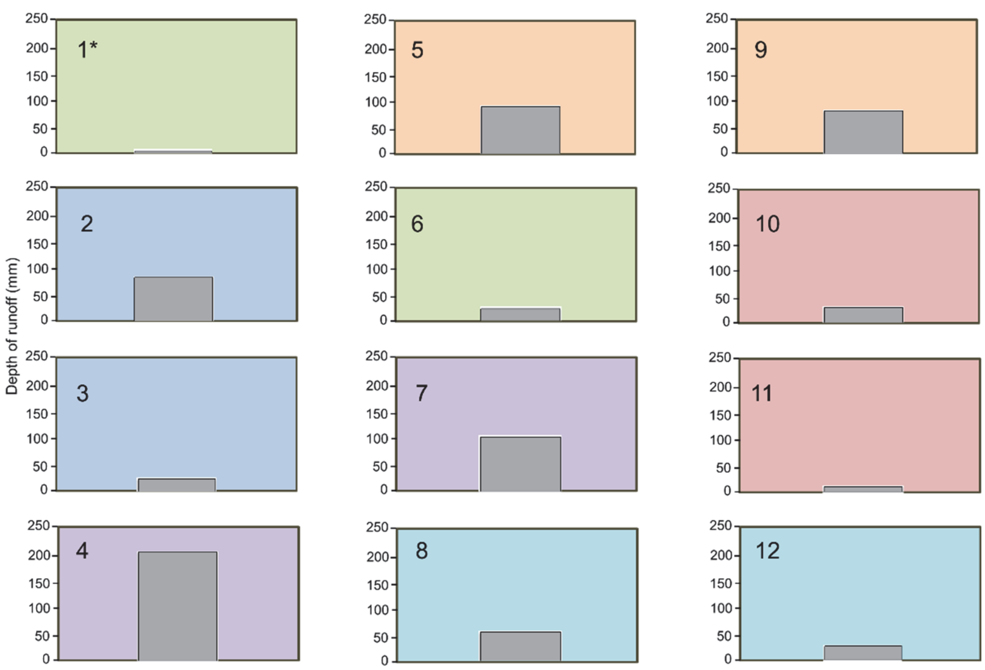


Figure 4. Boxplots of overland flow and subsurface flow depth (mm) for 2012-2014. Asterisks (*) indicate outliers.



(a) Overland flow treatment blocking.



(b) Subsurface flow treatment blocking.

Figure 5. Proposed experimental groupings of field lysimeters along with (a) overland and (b) subsurface flow depths (mm) using 2014 data as an example. Matching colored graphs represent treatment pairings for future research based relationships of total annual depth of runoff over the three years of the study. Asterisk (*) indicates that data for field lysimeter 1 are from 2013 due to missing data in 2014.

CONCLUSION

The development of field-scale lysimeters to quantify water and nutrient balances from alternative management practices represents a major investment in resources. Over three years of observation, we identified significant variability in the hydrology and geophysical characteristics of 12 field lysimeters. Results highlight the importance of accounting for shallow subsurface flow in evaluating plot hydrology. Due to the complex geology at this site, some field lysimeters are likely hydrologically connected (lysimeters 4 and 7), while flows from other lysimeters likely bypassed our monitoring systems (e.g., lysimeters 1 and 8, where deep percolation was suspected). Despite these issues, sufficient similarities existed between the field lysimeters to enable pairing of plots for robust statistical comparison of field management treatments.

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