Hydrologic dynamics of a large Prairie watershed: Looking for runoff controls in an engineered, mixed use landscape

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1. INTRODUCTION & RESEARCH OBJECTIVE

Despite intense and continued human modification of the Prairie landscape, the consequences of this hydrological management on the runoff regime remain poorly understood. Specifically, **previous research carried out in Prairie watersheds has not explored threshold rainfall-runoff behaviour as has been done in pristine, higher relief hillslopes and catchments.** To address this, we focus here on a large mixed-used Prairie watershed for high temporal resolution hydrometric and meteorologic monitoring.

2. STUDY SITE

The Catfish Creek watershed (CCW; Figure 1) drains an area of 642 km^2 located approximately 90 km north-east of Winnipeg (Manitoba, Canada). Characterized as a low-relief, agro-forested watershed (~45% forest, ~40% crops, ~10% swamp, ~5% other), surface runoff is managed by a network of artificial drains in both the forested and cultivated portions of this watershed. Natural forest cover and wetlands are present throughout the lower CCW as well as on the higher-relief eastern portion of the upper watershed. To the west the landscape is dominated by intensive, large-scale agricultural operations on a near-level landscape.

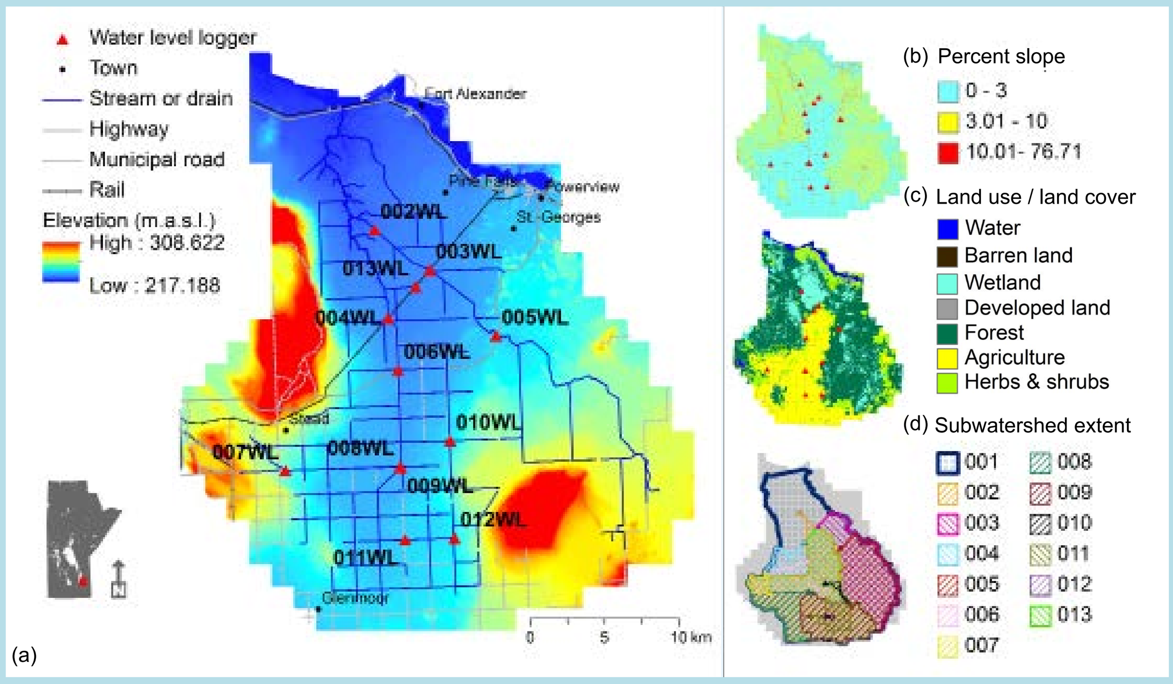

FIGURE 1: Location and characteristics of Catfish Creek Watershed; (a) LiDAR DEM with locations of water level loggers indicated, as well as local infrastructure; (b) percent slope of the region; (c) land use and land cover extent across the region; (d) extent of nested upstream gross drainage area of each of the water level gauging stations, as delineated by ArcGIS.

FIGURE 2: Hydrometric and meteorologic monitoring instruments in Catfish Creek Watershed; (a) HOBO weather station, (b) Odyssey water level logger; (c) water level logger installed in agricultural drain.

3. METHODS

Through the spring of 2013, the CCW was instrumented with thirteen in-stream water level recorders (15-minute frequency), 26 perched water table level recorders (15-minute frequency; 1.5 m depth) and five weather stations (1-minute frequency) to monitor the precipitation-runoff dynamics from spring thaw to winter freeze-up (Figure 2). Water level gauging stations monitor sub-watersheds of the CCW, ranging in drainage area from 0.5 to 642 km^2.

Rainfall (RF) events were manually identified and isolated for analysis, and event hydrograph (Q) responses at the twelve gauging stations unaffected by backflow from Lake Winnipeg were calculated. Event parameters considered included:

- Initial abstraction (IA)
- Lag to initial runoff (RFbQb)
- Lag to peak runoff (RFbQp)
- Event water level fluctuation (ΔWL)
- Time of concentration (TC)
- Duration (RF & Q events)
- Rainfall intensity (RFintens)
- Total event rainfall (RFsum)

These parameters were compared with watershed characteristics (area, slope, elevation, drainage density, land use /land cover, geology) and surrogate antecedent moisture condition (AMC) variables in a correlation analysis of all calculated parameters.

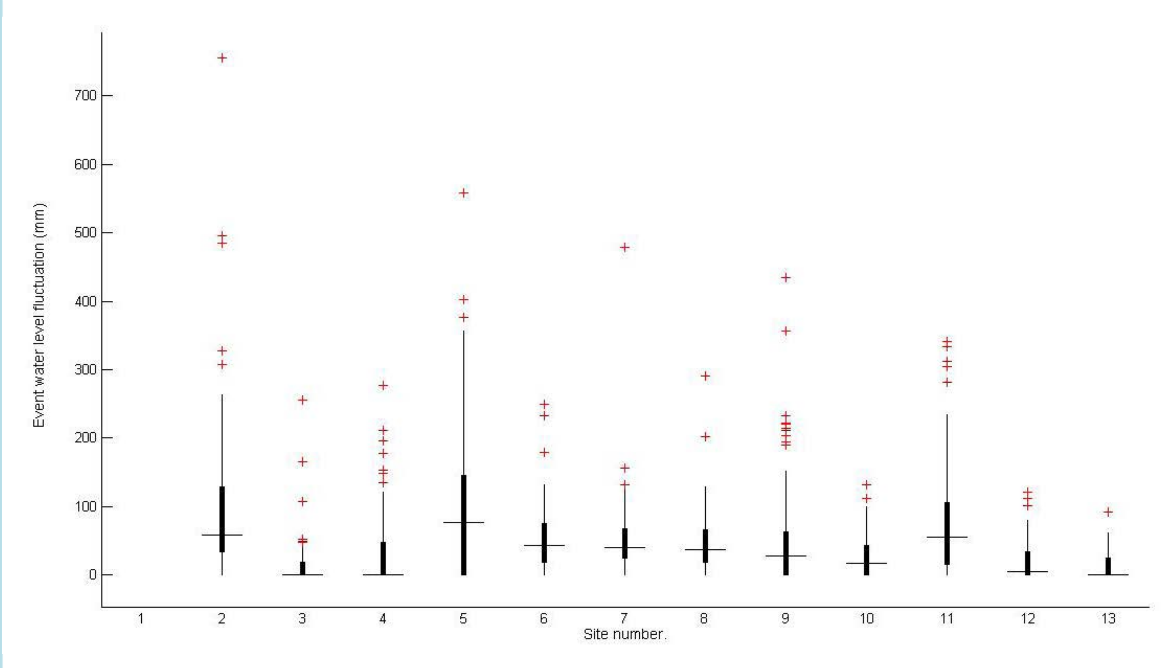

FIGURE 3: Boxplots summarizing runoff event water level fluctuations (defined as the difference of peak event water level and initial event water level) by monitoring site.

FIGURE 4: Engineered drains in the Catfish Creek Watershed; (a) Site 003, (b) Site 007.

4. RESULTS & CONCLUSIONS

Based on observation of a total 126 rainfall events ranging 0.2 mm - 33 mm in depth and 15 mins - 34 hrs in duration, the following conclusions were reached:

i. Runoff events of greatest ΔWL magnitude are associated with infiltration excess overland flow

- ΔWL correlates strongly and positively with RFintens.
- Initial water level at the beginning of rainfall events correlates significantly and strongly negatively with event ΔWL, indicating the greatest contributor to runoff is infiltration excess overland flow.
  - Although, due to the low relief of the CCW, infiltration excess overland flow occurring outside of the engineered slope of drains is not expected to reach the stream channel before reinfiltration or evaporation.
- Variable runoff response to extreme rainfall events among monitoring sites may be explained by rainfall heterogeneity beyond which the weather station network could capture; such rainfall heterogeneity is common with convective storms generated during the hot summer months (Fang et al., 2007; Reaney et al., 2007).

ii. Summer storage is effectively unlimited

- Event initial abstraction is strongly and positively correlated to total event rainfall at monitoring sites (see Table 2).
- No threshold effects related to AMCs (depth to perched water table or rainfall from previous month, days or hours; e.g., see Figure 6).

iii. Poor downstream connectivity and limited contributing area exist

- TC does not correlate significantly with any rainfall event parameters, indicating limited transit of event water through the watersheds
- Hydrograph characteristics do not correlate significantly with watershed characteristics, suggesting runoff from upstream areas contribute minimally to the hydrograph at the stream gauge
- ΔWL does correlate with stream and drain morphometrics, which vary throughout the watershed (e.g., Figure 4)
  - Partial Spearman correlation of RFsum and ΔWL while controlling for drain width yields $r = 0.8540$ ($p = 0.0670$)
- ΔWL correlates strongly with RFintens, indicating local rainfall and infiltration excess generates event water level fluctuations
- Outside of the snowmelt runoff period water conditions in stream channels was most frequently observed as stagnant during field work, similar to observations made in other Prairie watersheds (Shaw et al., 2012)

iv. The input-output relationships observed in the CCW (Figure 6) exhibit a shape differing from those found in other threshold studies (Figure 5)

- Specifically, a critical point where, when exceeded, a sudden change in the rainfall-runoff relationship exists. This is generally the opposite of previously observed input-output relationships (Ali et al., 2013). However, previous hydrologic threshold research has focused on perennial rather than intermittent or ephemeral streams in pristine watersheds of higher relief (e.g. Tromp-van Meerveld & McDonnell, 2006 (humid, subtropical Georgia, USA); James & Roulet, 2007 (humid temperate southern Quebec, Canada)). The distinct input-output relationship shape observed in the CCW may be an indication of non-linear rainfall-runoff relationship shape where contributing area is limited, storage is effectively unlimited and streams run ephemerally.

TABLE 1: Summary of select mean and median event characteristics by monitoring site

	Site no.	IA (mm)	ΔWL (mm)	RFbegQbeg (hrs)	RFbegQpeak (hrs)	TC (hrs)	Q event duration (hrs)	RFsum (mm)
Mean	2	1	101	0.45	3.25	5.25	7.00	3.38
	3	2	17	1.15	4.25	7.00	9.00	3.17
	4	2	35	1.45	3.25	4.00	6.25	3.38
	5	2	101	1.15	3.25	5.75	8.25	3.17
	6	3	52	1.50	4.50	6.00	6.75	4.09
	7	3	52	1.50	5.00	6.50	7.75	4.09
	8	2	49	0.50	4.50	6.25	8.00	3.71
	9	2	55	0.50	3.75	6.00	7.25	3.71
	10	2	26	0.50	5.25	10.00	11.25	3.71
	11	2	77	1.00	4.00	7.25	8.00	3.71
	12	2	20	0.50	1.50	5.00	8.25	3.71
	13	4	12	1.25	4.50	9.75	12.75	3.38
Median	2	0	10	0.75	2.50	3.25	5.50	1.20
	3	1	11	0.75	2.75	2.25	3.50	1.20
	4	1	10	1.00	2.50	3.25	5.00	1.20
	5	1	10	1.00	2.50	3.75	5.50	1.20
	6	1	9	1.00	2.00	3.50	4.25	1.40
	7	1	14	0.75	3.50	5.00	6.25	1.40
	8	0	10	0.75	2.50	4.00	5.50	1.00
	9	0	7	0.75	1.75	3.75	5.00	1.00
	10	1	14	1.00	3.50	6.00	7.50	1.00
	11	0	8	0.75	1.50	4.50	5.25	1.00
	12	0	8	0.75	2.00	3.00	5.00	1.00
	13	3	12	1.00	3.00	8.00	11.25	1.20

TABLE 2: Select statistically significant ($p<0.05$) Spearman rank correlation coefficients (r) between event response parameters by monitoring site

	Rainfall event sum			Rainfall event duration				RF Intensity	Initial event WL
Site No.	QDuration	ΔWL	IA	QDuration	RFbegQpeak	ΔWL	IA	ΔWL	ΔWL
2	0.52	0.62	0.50	0.56	0.70	0.42	-	0.31	-0.67
3	-	0.27	0.74	-	0.47	-	0.36	-	-0.92
4	0.59	0.57	0.61	0.63	0.65	0.46	-	0.23	-0.94
5	0.59	0.75	0.64	0.60	0.70	0.48	-	0.37	-0.57
6	-	0.32	0.81	0.34	0.50	-	0.32	0.32	-0.59
7	0.43	0.67	0.62	0.38	0.53	0.38	-	0.54	-0.28
8	0.50	0.78	0.49	0.53	0.42	0.62	0.36	0.50	-0.32
9	0.46	0.43	0.49	0.41	0.73	-	0.39	0.46	-0.77
10	-	0.51	0.61	0.34	0.43	0.29	0.50	0.54	-0.74
11	0.46	0.62	0.58	0.59	0.49	0.42	0.43	0.46	-0.56
12	0.35	0.47	0.66	0.41	0.53	0.32	0.33	0.39	-0.87
13	0.74	0.54	0.64	-	0.54	0.43	-	0.25	-0.96

Spearman's r colour scale: -1, -0.5, 0, 0.5, 1
"-" = no significant correlation

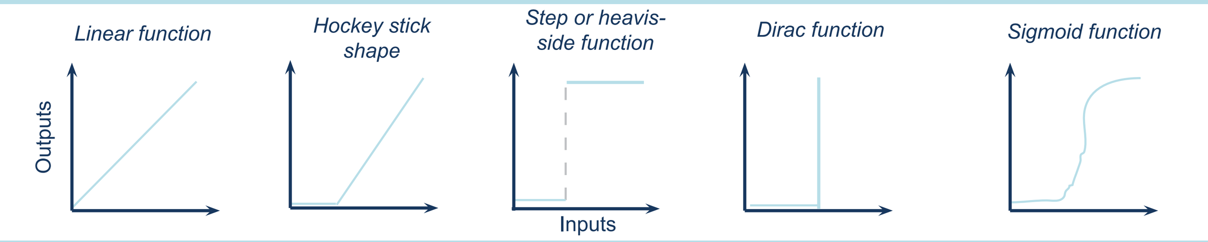

FIGURE 5: Examples of threshold shapes observed in previous study (after Ali et al., 2013).

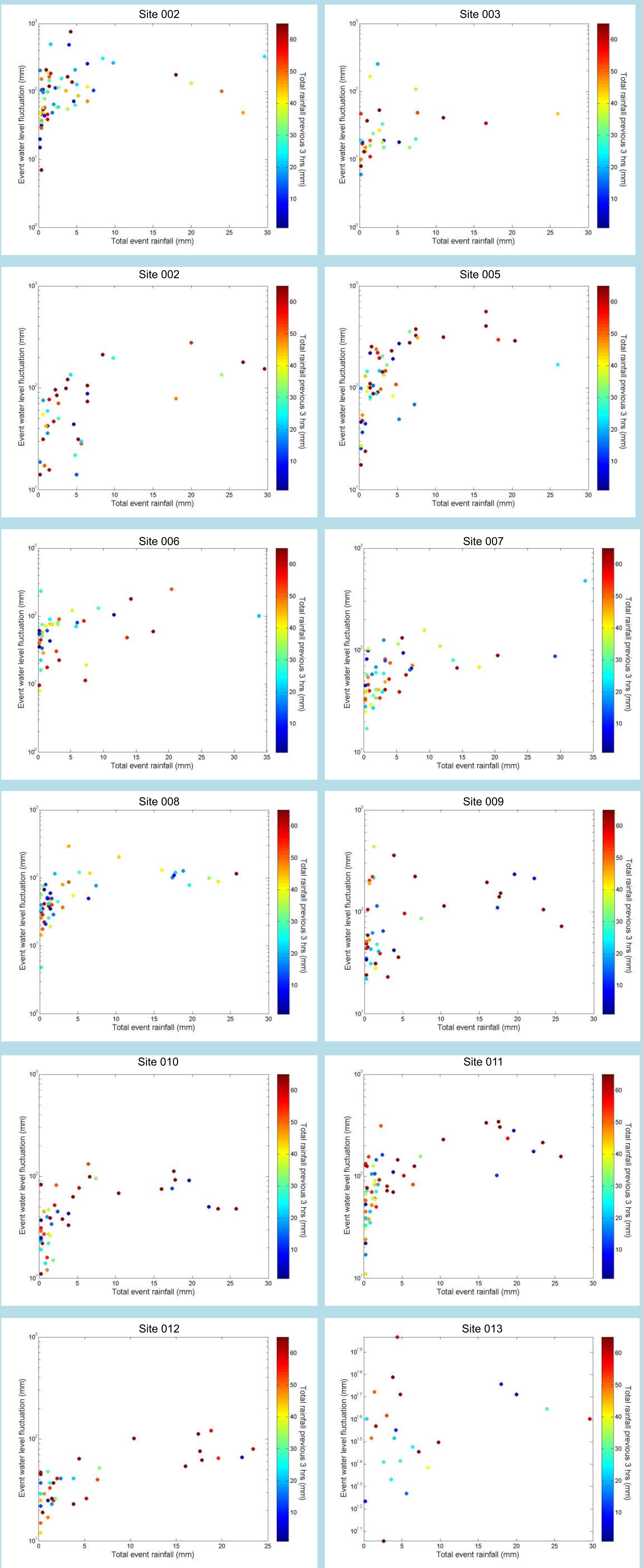

FIGURE 6: Event rainfall-runoff relationships and antecedent moisture conditions (cumulative precipitation in the 3 hours preceding initial event rainfall) observed at the 12 monitoring sites of CCW through the 2013 open water season.

REFERENCES

Ali et al., (2013): Towards a unified threshold-based hydrological theory: Necessary components and recurring challenges; Hydrological Processes, 2013, 27(2), pp.313-318.
Fang et al., (2007): A review of Canadian Prairie hydrology: Principals, modeling and response to land use and drainage change; Centre for Hydrology, University of Saskatchewan, 32p.
James & Roulet (2007): Investigating hydrologic connectivity and its association with threshold change in runoff response in a temperate forested watershed; Hydrological Processes, 21, pp.3391-3408.
Reaney et al., (2007): Use of the connectivity runoff model (CRUM) to investigate the influence of storm characteristics on runoff generation and connectivity in semi-arid areas; Hydrological Processes, 21, pp.894-906.
Shaw et al., (2012): The fill-spill hydrology of prairie wetland complexes during drought and deluge; Hydrological Processes, 26, pp.3147-3156.
Tromp-van Meerveld & McDonnell (2006): Threshold relations in subsurface stormflow: 1. A 147-storm analysis of the Panola hillslope; Water Resources Research, 42 pp.1-11.

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