Master of Engineering Report:

Testing a Method for Predicting Variable Source Areas of Runoff Generation

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Executive Summary

This project tested the feasibility of combining the commonly used USDA-Natural Resources Conservation Service's Curve Number method and topographic index concept to predict areas of runoff generation. Baseflow was used to characterize antecedent wetness conditions. Using field monitored shallow, transient water tables at Town Brook in upstate New York, the results showed that the proposed methodology worked well.

Key Words

Variable Source Areas, Curve Number, Nonpoint Source Pollution, Baseflow, Soil Water

Introduction and Background

Engineers have long sought a simple and reliable relationship between rainfall events and the resulting runoff that is physically-based on hydrologic science. Historically engineers have used purely empirical rainfall-runoff methods, which have served them well for estimating order-of-magnitude runoff volumes and rates for designing bridges, flood control structures, culverts, ditches and other hydraulic structures that store or transmit storm runoff from large, intense rainfall events.

The two most widely used rainfall-runoff equations, the Rational Method (a.k.a. Lloyd-Davies method) and the so-called Curve-Number method (e.g., USDA-SCS 1972), estimate runoff from rainfall via tabulated runoff or curve number coefficients, respectively (e.g., Chin 2006). When engineers use these coefficients they implicitly presume that areas with low soil infiltration capacity generate more runoff than areas with high infiltration capacity (e.g., Walter and Shaw 2005); a runoff process commonly referred to as Hortonian flow in acknowledgement of Robert Horton's pioneering work in this area (e.g., Horton 1933, 1940). While this assumption of Hortonian flow is probably acceptable for estimating runoff from large rainstorms, for many places around the world it is a poor assumption for most rainfall events (e.g., Walter et al. 2003). Because nonpoint source pollution is transported by virtually every rainfall-runoff event, more appropriate tools are needed to not only reliably estimate how much runoff is generated by even small rainfall events, but also tools to predict from where in the landscape the runoff is being produced (e.g., Walter et al. 2000, 2001, Gburek et al. 2002, Agnew et al. 2006).

Since the 1960s, hydrologists have recognized that runoff in non-arid and non-urban environments is most commonly produced from rain falling on very wet parts of a watershed (U.S. Forest Service 1961, Beston 1964, TVA 1964, Hewlett and Hibbert 1967). This concept marks a considerable deviation from earlier rainfall-runoff hydrology because it suggests that soil infiltration capacity is not the major control on whether or not runoff is produced. Instead, runoff is produced when and where the effective soil water storage capacity is exceeded. This process of runoff generation is often called saturation-excess runoff. Because saturation-excess yielding parts of the landscape, i.e. "wet areas," expand and contract over time, this runoff process is often termed variable source area (VSA) hydrology. The seminal work on VSA hydrology was carried-out in Sleepers River, VT, by Thomas Dunne and Richard Black in the late 1960s (1970a,b).

Over the past thirty or so years there has been many hydrological simulation models developed based on VSA hydrology; the most common are probably TOPMODEL (e.g., Beven and Kirkby 1979), DHVM (e.g., Wigmosta et al. 1994), and SMR (e.g., Frankenberger et al. 1999) – all of which have been thoroughly tested and have numerous versions, re-conceptualizations, and permutations to account for different field conditions or include larger suites of biophysical processes. Of these, only SMR has been applied to the problem of nonpoint source pollution (e.g., Walter et al. 2001, Easton et al. 2007) because these types of models generally require copious calibration and large input datasets. In response, there has been some recent re-conceptualizations of widely-used water quality models so that they account for VSA hydrology, namely Haith and Shoemaker's (1987) Generalized Watershed Loading Function (GWLF) (e.g., Schneiderman et al. 2007) and the USDA-NRCS' (e.g., Arnold et al. 1998) Soil Water Assessment Tool (SWAT) (e.g., Easton et al. 2008). These water quality models are widely used because they are based on the traditional engineering rainfall-runoff equations mentioned earlier, i.e., the Rational Method and Curve Number Equation, which require very much less input data. However, even these models are somewhat more complicated and computationally intensive than most engineering applications warrant.

The Cornell Soil and Water Lab has been working on re-conceptualizing the widely used SCS-Curve Number (CN) method as a tool for predicting VSA runoff (Steenhuis et al. 1995, Lyon et al. 2004, Shaw and Walter 2008, Walter et al. 2008) [see Appendix A for the fundamental re-derivation of the CN-method]. Although this work has lead to new simulation models (e.g., Schneiderman et al. 2007, Easton et al. 2008), it has not been tested as an event-specific tool for predicting where runoff will likely be generated. Currently, such tools either crudely assume areas near streams are most likely to generate runoff (e.g., Gburek et al. 2002) or are based largely on long-term average results from simulation models (e.g., Agnew et al. 2006). The objective of this project is to test a method for predicting runoff source areas (or VSAs) using the CN-method (Steenhuis et al. 1995) and topographic indices (e.g., Beven and Kirkby 1979, O'Loughlin 1986, Lyon et al. 2004). Baseflow is used to characterize initial wetness conditions as initially proposed by Troch et al. (1993) and recently adopted by Shaw and Walter (2008) for estimating CNs.

Predicting Variable Source Areas

Steenhuis et al. (1995) showed that the widely used CN equation could be re-arranged to predict the fraction of a watershed that is wet enough to generate runoff:

$$A_f = 1 - \frac{S^2}{P^2 + S^2} \tag{1}$$

Where A_f is the fraction of a watershed generating runoff, P is the rainfall depth, and S is the available water storage in the watershed [units of depth]. Shaw and Walter (2008) showed that S could be reliably correlated to baseflow such that high baseflow is related to low S, i.e., wet conditions, and *visa versa*, i.e., dry conditions.

Using streamflow data to estimate total runoff depth, Q, and assuming that there is no substantial initial abstractions, S for each precipitation event's depth, P, can be directly calculated by re-arranging the original CN-equation.

$$S = \frac{P^2}{Q} - P \tag{2}$$

Note: S is traditionally determined from tabulated CN values (e.g., USDA-SCS 1972). In this study S was directly calculated for several events and then correlated to the baseflow immediately preceding the event using a power-function.

Although equation 1 estimates the total fraction of a watershed generating runoff, it does not predict where those areas are. Following the CN-VSA method of Lyon et al (2004), the A_f was computed for several storm events and the specific region of runoff generation was assumed to conform to the Soil Topographic Index (*STI*):

$$STI = \ln\left(\frac{a}{\tan(\beta) D K_s}\right) \quad (3)$$

where *a* is the area of the upslope watershed per unit contour length (cm), tan(*β*) is the local surface topographic slope, *D* is the depth of the soil layer (cm), and K_s is the saturated hydraulic conductivity (cm day^{-1}). The *STI* is calculated for each cell within a raster map of a given watershed. Starting with the wettest regions as based on *STI*, cell areas are cumulatively summed until an area as large as A_f is reached at a threshold *STI* value. Thus, runoff is assumed to occur in all regions with an *STI* exceeding the threshold *STI*. Figure 1 illustrates how equations 1 and 2 are used together to predict the saturated runoff contributing area for a watershed.

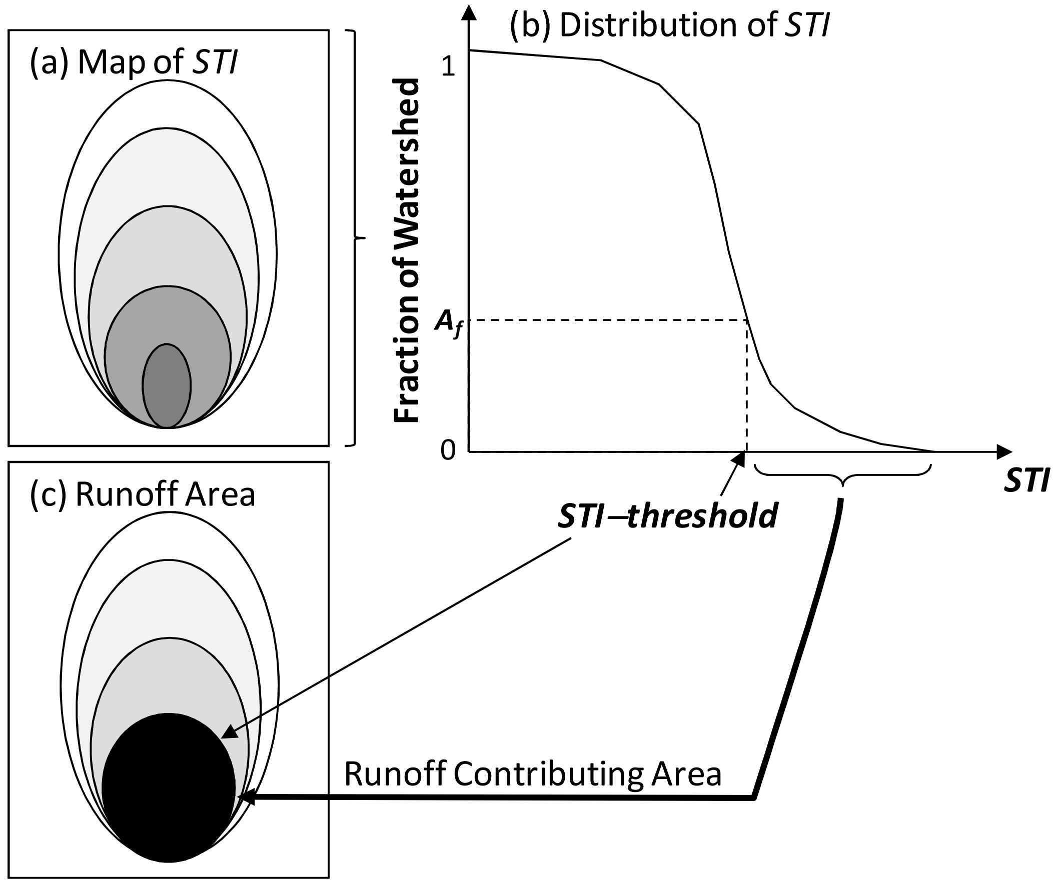

Figure 1 - Schematic illustrating how we determine runoff contributing areas; (a) a “map” of soil topographic indices, *STI*, (equation 3) is analyzed to determine (b) the continuous distribution of soil topographic indices - for any fractional contributing area (A_f) (equation 1) there is a threshold *STI*-value that (c) corresponds to the boundary of the runoff contributing area. (Figure used with permission from Walter et al. 2008).

Site Description

To test our method of predicting VSAs, we compared predictions to observed VSAs in the Town Brook watershed in Delaware County, NY (figure 2). Shallow water table depth was monitored continuously using a network of capacitance probes that covered a 2.4 ha sub-section of the larger 37 km^2 Town Brook watershed (Lyon et al. 2006). The monitored hillslope ranged in elevation ranged from 585 m to 600 m above mean sea level with slopes ranged from 0^o to 8^o. The soils are gravelly silt loams over fractured bedrock. These shallow soils are typified as higher conductivity (5 cm/hr) surface material (< 40 cm deep) overlaying less conductive material (0.5 cm/hr) base material (> 40 cm deep) with large fractures. The landuse on the hillslope is uniformly grass/shrub with forested regions above the study area. Rainfall was measured at the site using a tipping bucket rain gauge with data logger was set on the site to sample rainfall amounts at an interval of 10 minutes. For periods when the on-site gauge malfunctioned, precipitation data were obtained from a National Oceanic and Atmospheric Administration (NOAA) weather station located in Stamford, NY located approximately 1 km north of the site. It should be noted that this analysis was limited to events for which the initial abstraction played no obvious role. Shaw and Walter (2008) propose a method for best-fitting that accounts for an initial abstraction and is more complicated than equation 2. Daily stream discharge was measured at the watershed outlet by the USGS.

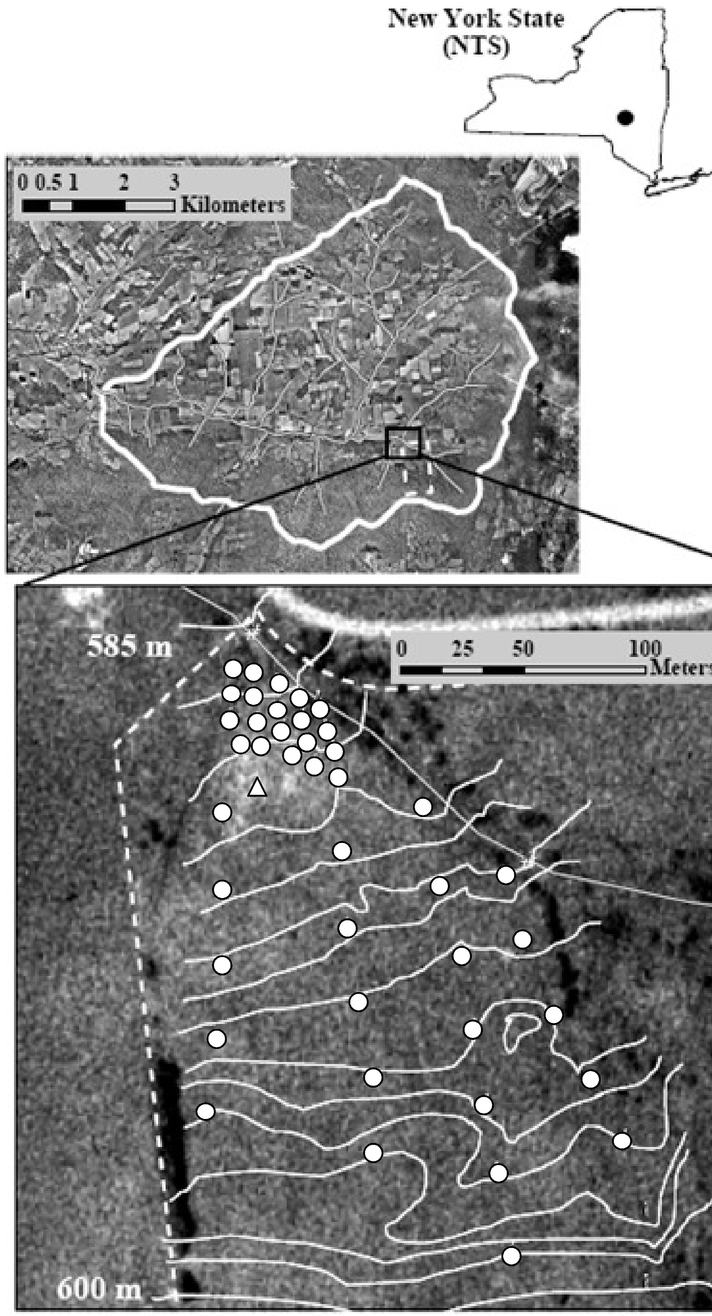

Figure 2 – Field site location at Town Brook and arrangement of water table monitoring capacitance probes (circles) and rain gage (triangle).

Soil topographic indices (equation 3) were calculated using a 5m digital elevation model (DEM) that was created from Light Detecting And Ranging (LIDAR) data. A diversion ditch that runs across the top of the site (not shown in figure 2) was not captured by the LIDAR data and was manually "burned" into the DEM prior to calculating *STI*. Soils information needed for equation 3 was obtained from the Soil Survey Geographic Database (SSURGO).

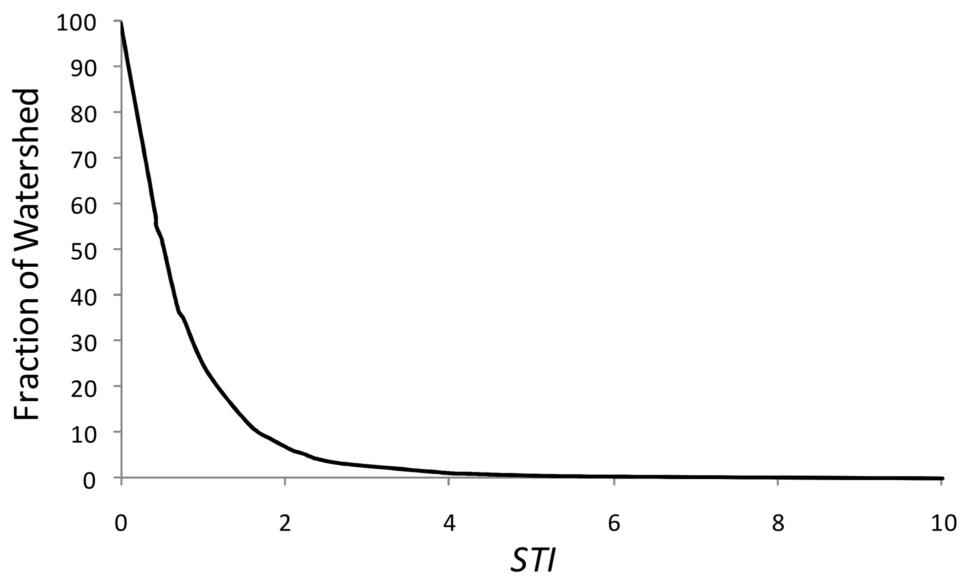

Figure 3 – Cumulative distribution of STI over the Town Brook Watershed. The highest *STI* was about 25, but figure only shows through *STI* = 10; our highest *STI* with a field observation is 8.

In order to reduce the point-to-point noise in the water table data, water table depths were averaged over or binned-over integer values of *STI* (i.e. Values for *STI*s between 1 and 2 were averaged and assigned an *STI* of 1.5). This method of data-smoothing was also used by Agnew et al. (2006).

Fifteen well defined hydrographs were identified and runoff, *Q*, was determined by subtracting the pre-event baseflow from the peak daily discharge. For each event, *S* was calculated using equation 2 and paired with pre-event baseflow (Figure 4)

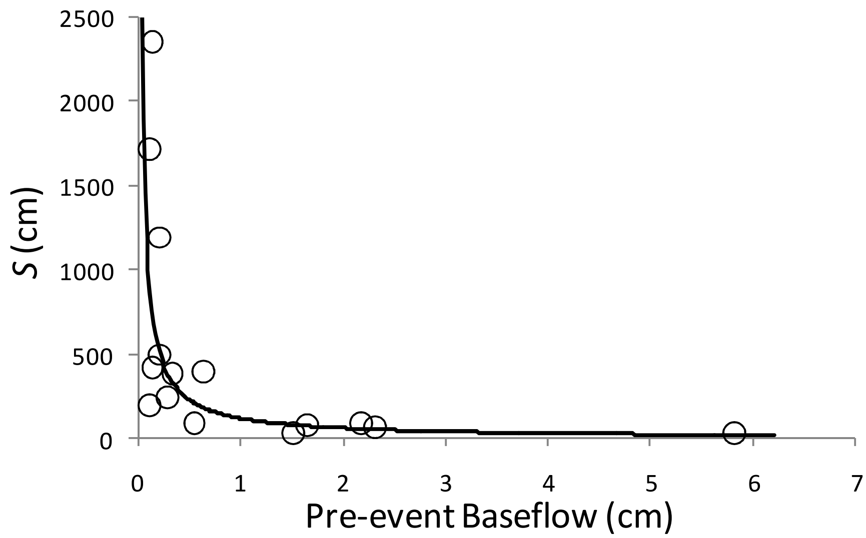

Figure 4 – *S* (equation 2) as a function of pre-event baseflow for Town Brook $S = 122.9Q_b^{-0.93}$ ($R^2 = 0.70$).

Analysis

We analyzed eighteen independent events to assess our methodology for predicting variable source areas. For each event, we used the pre-event baseflow to determine *S* using figure 4 and then calculated a predicted fraction of runoff contributing area, A_f, using equation 1. Using figure 3 we determined the threshold *STI* above which we predict runoff generation. We then compared the observed water table depths for areas with *STI*-values above and below the threshold. If our methodology is valid, we anticipate that at sites with *STI*-values above the threshold-*STI* the water table will be systematically above a depth at which runoff generation begins. Lyon et al. (2006) found this depth to be around 100 mm at this site.

Results and Discussion

The calculated values for the analysis for all eighteen events are summarized in Table 1.

Of our eighteen events, five had fractional runoff contributing areas, A_f, greater than 15%; specifically 15, 17, 19, 20, and 22% (light to dark symbols, respectively, in Figure 5a) with corresponding threshold *STI* values of 6.0, 5.9, 5.8, 5.7, and 5.6. These *STI* values were all very close and an average of 5.8 is shown in figure 5a. For these high A_f events, our method appears to work well, with all the sites with *STI*-values above the threshold experiencing water tables within 100 mm of the surface and all sites with *STI*-values below the threshold seeing water table depths deeper than 100 mm.

We also had two moderate events in our data set, with A_f = 5 and 6% (light to dark symbols, respectively, in Figure 5b). The threshold-*STI* values were 7 and 6.8, respectively. The proposed method for predicting VSAs appears to have also worked reasonably well in this situation, although for the A_f = 5%, the water table depth for the STIs above the threshold lie very close to 100 mm, actual average depth was 103 mm. The sensitivity of the capacitance probes is on the order of 10 mm, so this difference is not operationally significant.

We had eleven events for which $A_f < 1\%$ (table 1) of which the events with the five largest A_f are graphed in figure 5c (smallest to largest A_f a represented by lightest to darkest symbols, respectively). Unfortunately the threshold-*STI* for all of these events was larger than the highest *STI* for which we had observations, ie. *STI* > 7.5 (table 1). Given that the A_f ranged from only 0.4% to 0.001% of the total watershed area, it is not surprising that a probe did not fall into one of the regions expected to generate runoff. However, all but one observed water table depth was below 100 mm, the depth at which Lyon et al. (2006) suggested storm runoff was initiated, which is largely consistent with the expectations of our method for predicting VSAs. The one *STI* with average water table depth shallower than 100 mm was at approximately 80 mm, which we have used to set an upper (shallow) limit on our estimate of the water table depth at which runoff is generated (i.e., the upper dashed line in figure 5a-c).

Table 1. Values calculated as part of the analysis of eighteen storm runoff events from Town Brook, NY

Event	Rain (mm)	*Q* (mm)	*S* (mm)	A_f (%)	Threshold *STI*	Avg Water Table depth below threshold *STI* (mm)	Avg Water Table depth above threshold *STI* (mm)
1	14.7	10.9	27.9	22	5.6	222.7	21.4
2	46.5	17.8	92.1	20	5.7	145.6	36.2
3	41.9	14.2	86.9	19	5.8	145.6	45.8
4	87.9	27.4	195.2	17	5.9	138.3	39.9
5	33.3	11.4	79.8	15	6.0	138.1	73.3
6	7.4	3.0	28.4	6	6.8	186.7	103.3
7	15.8	5.4	65.9	5	7.0	191.6	72.0
8	39.9	3.0	620	0.4	9.5	153.8	-
9	22.4	1.2	496	0.2	10.2	318.8	-
10	15.0	1.9	471	0.1	10.9	173.1	-
11	11.7	0.7	385	0.09	11.0	315.7	-
12	11.4	0.5	419	0.07	11.2	365.2	-
13	17.5	1.1	647	0.07	11.2	198.7	-
14	37.6	0.9	1716	0.05	11.6	327.8	-
15	19.8	0.5	1193	0.03	12.2	249.1	-
16	2.3	0.6	393	0.003	14.2	186.1	-
17	1.3	0.3	243	0.003	14.4	351.3	-
18	5.6	0.2	2358	0.001	16.0	297.5	-

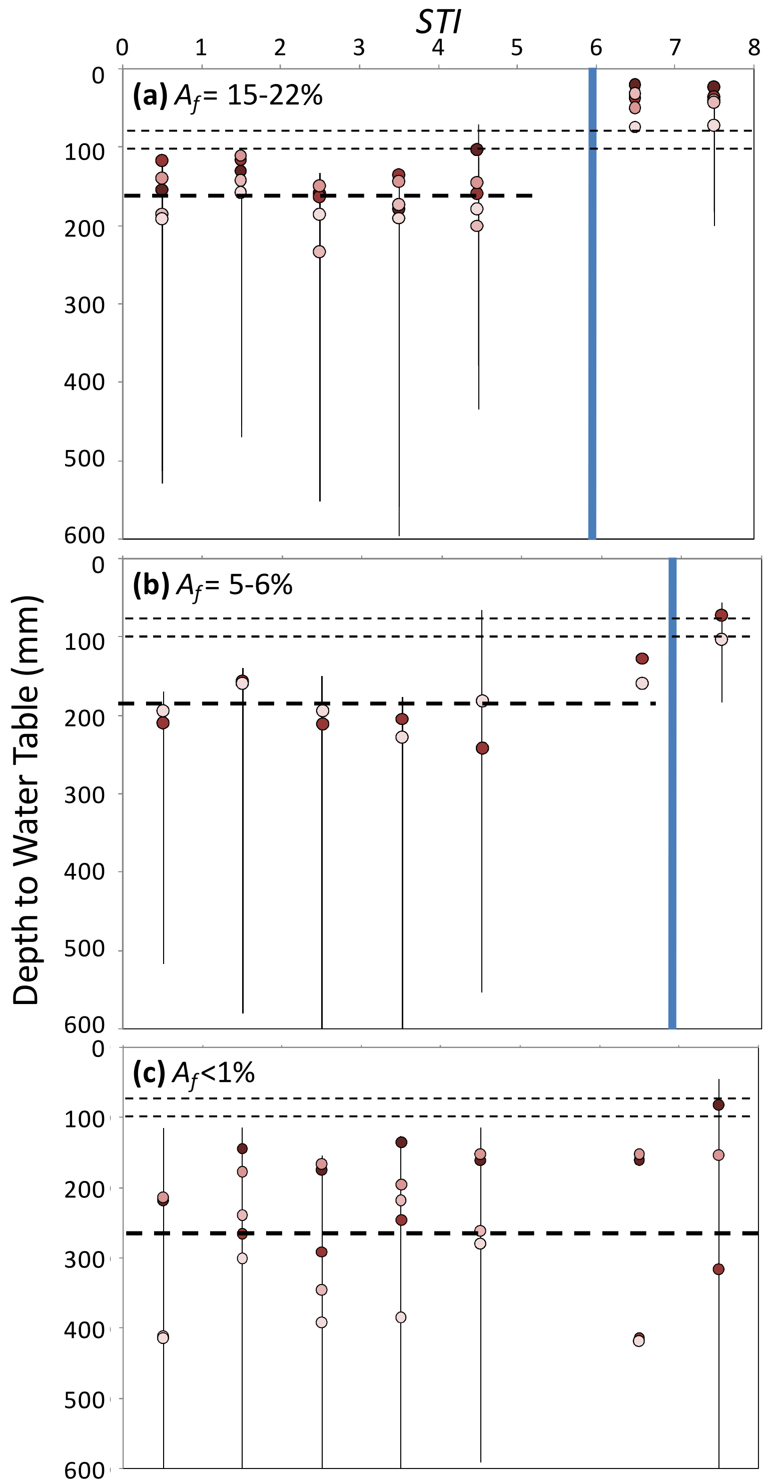

Figure 5 – Average water table depths (filled circles) compared to *STI* for (a) large, (b) moderate, and (c) small contributing areas. Each different symbol fill color indicates a unique storm event within each graph. The vertical blue lines show predicted threshold *STI* above which saturation excess runoff should be generated, for (c) the threshold-*STI* > 8. The thin dashed lines show the range of water table depths at which these data suggest runoff generation is initiated. The heavy dashed line is the average depths of non-runoff areas for each set of data. Solid vertical lines show the range of observed water table depths.

On average it appears that the proposed methodology for predicting VSAs captures the general patterns observed in the field. However, there is substantial variability within any *STI*. Figure 5 suggests that there is more variability among observations at *STI* < threshold-*STI*, however, the *STI* below the threshold generally have more observations. For example, the averages for *STI* 0.5-4.5 shown in figure 5 are based on an average of 7.6 observations compared to 2.5 observations per point for *STI* > 4.5. However, comparing observations from *STI* = 7.5 (n = 4) to those of *STI* = 3.5 and 4.5 (n=4 and 3, respectively), it appears from figures 5a and 5b that the variability for the *STI* > threshold-STI (i.e., *STI* = 4.5) is considerably less than for the *STI* < threshold-*STI* (i.e., *STI* = 3.5 and 4.5). Also note that the variability in water table depth for *STI* = 7.5 in figures 5a and 5b, when these are over the threshold-*STI*, is greater than the variability in figure 5c, when these sites are below the threshold-*STI*-values. Thus, these limited data suggest greater variability in water table depth for areas predicted to be non-runoff contributing than those predicted to be runoff contributing. Furthermore, the water table depths are generally skewed towards lower depths, i.e., most sites have depths near the average and relatively few are lower, although sometimes much lower than the average.

This analysis emphasizes the difficulty in predicting VSAs based on any one simple parameter. In fact, precipitation can explain only ~44% of the variation in A_f, ($R^2 = 0.44$, $A_f = 9\text{x}10^{-6}P^{2.15}$, data not graphically shown) and available storage, S, only explained about 63% ($R^2 = 0.63$, $A_f = 353S^{-2.075}$, data not graphically shown). Notice, however, that the wetness of the watershed, i.e., the available storage, is somewhat more influential than the rainfall.

Appendix A

The traditional SCS-CN equation, in the traditional form (Rallison, 1980), is given as:

$$Q = \begin{cases} \frac{(P - I_a)^2}{(P + S - I_a)} & for\ P > I_a \\ 0 & for P < I_a \end{cases} \tag{A.1}$$

Where Q is the runoff depth (cm), P is precipitation (cm), S is the available water storage within the soil (cm), and I_a is the inial abstraction (cm). In a 1980 paper, Mockus first proposed dropping the inial abstraction from the equation “on the ground that it prodices rainfall runoff curves of a type found in natural watersheds.” This approach was later adopted by Steinhus. By dropping the initial abstraction from the equation and rearranging we obtain:

$$S = \frac{P^2}{Q} - P \tag{A.2}$$

Rearranging and employing partial fraction decomposition we arrive at equation A.3

$$Q = P - S + \frac{S^2}{P + S} \tag{A.3}$$

The fractional area of a landscape that contributes to runoff can be expressed mathematically as:

$$A_f = \frac{\Delta Q}{\Delta P} \tag{A.4}$$

Finally, applying equation A.4 and differentiating equation A.3 we arrive at equation A.5. Using the storage calculated earlier, we can then calculate the fractional area:

$$A_f = 1 - \frac{S^2}{P^2 + S^2}$$

(A.5)

Appendix B

Table B.1– Summary of data for individual STI values. The numbers below each “STI values of observation sites” are average depths to water table (mm)

A_f	Thresholdl *STI*	*STI* Values of Observation Sites						
		0.5	**1.5**	**2.5**	**3.5**	**4.5**	**6.5**	**7.5**
0.00001	15.96	338.1	197.1	225.6	251.1	302.1	416.7	351.8
0.00003	14.41	460.0	263.3	360.1	229.4	312.6	411.9	421.6
0.00003	14.20	295.8	149.2	162.3	172.1	220.5	159.1	143.7
0.0003	12.15	299.7	172.0	263.6	164.3	276.0	409.7	158.1
0.0005	11.61	332.7	304.2	330.0	370.5	335.3	418.3	203.5
0.0007	11.19	288.0	173.1	194.0	131.6	177.5	297.7	129.2
0.0007	11.18	414.8	300.8	391.9	384.9	280.0	418.7	-
0.0009	10.98	411.0	239.2	345.7	218.0	261.9	418.5	-
0.0010	10.88	213.9	177.2	166.6	195.4	152.0	152.7	153.7
0.0020	10.20	413.6	265.9	291.4	245.6	279.6	414.2	315.6
0.0041	9.51	218.7	144.3	174.8	135.4	161.1	160.7	81.5
0.05	6.99	208.9	156.2	210.7	204.6	241.8	127.5	72.0
0.0633	6.84	194.9	159. 8	194.9	228.8	181.8	160.1	103.3
0.15	6.01	192.1	158.1	185.9	191.3	178.9	74.4	72.3
0.17	5.88	184.9	142.5	233.5	173.0	200.0	31.2	42.6
0.19	5.77	139.9	111.5	149.8	144.2	145.0	51.0	40.6
0.20	5.70	116.9	116.3	164.0	135.8	158.9	37.0	35.3
0.22	5.63	154.7	130.9	159.1	179.8	103.3	19.7	23.1

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