Hydrologically Sensitive Areas:
Variable Source Area Hydrology
Implications for Water Quality Risk Assessment

M.Todd Walter, Michael F. Walter, Erin S. Brooks, Tammo S. Steenhuis, Jan Boll, Kirk Weiler

Summary

A conceptual approach to assessing water quality risk in the context of *variable source area* hydrology was developed and applied to the New York City (NYC) water supply watersheds. According to variable source area theory, there are areas in a watershed especially prone to generating runoff and are therefore hydrologically sensitive with respect to their potential to transport contaminants to perennial surface water bodies; the term hydrologically sensitive area (HSA) was used to refer to these regions. Using the NYC watersheds, a cost-benefit method for quantifying HSA's was developed and applied such that water quality protection was balanced with agricultural needs. In accordance with the variable source area concept, the spatial extent of HSA's varies throughout the year. This investigation suggested any area in the NYC watershed with a 30% or more daily probability of runoff is classified as an HSA. On annual average, this HSA definition resulted in approximately 10% of the watershed being designated HSA and accounted for about 20% of the total annual runoff; i.e. the associated contamination risk to NYC's reservoirs would be reduced by roughly 20% if manure application was restricted from HSA's. This example is met to illustrate an approach to dealing with water quality risk assessment rather than provide generally applicable hydrologic sensitivity limits.

Published in *Journal of Soil and Water Conservation*. 2000. 3:277-284.
A web version of this document is at: http://www2.jun.alaska.edu/~jfmtw1/HSAhome.htm

Hydrologically Sensitive Areas: Variable Source Area Hydrology Implications for Water Quality Risk Assessment

M.T. Walter, M.F. Walter, E.S. Brooks, T.S. Steenhuis, J. Boll, K. Weiler

Abstract: *A conceptual approach to assessing water quality risk in the context of variable source area hydrology was developed and applied to the New York City (NYC) water supply watersheds. The term hydrologically sensitive area (HSA) was used to refer to areas in a watershed especially prone to generating runoff that are, therefore, potentially susceptible to transporting contaminants to perennial surface water bodies. As an example, a cost-benefit method for quantifying HSA's was developed and applied such that water quality protection was balanced with agricultural needs for NYC watersheds. In accordance with the variable source area concept, the spatial extent of HSA's varies throughout the year. On annual average, approximately 10% of the watershed is designated HSA and about 20% of the total annual runoff originates on these HSA's. This example is met to illustrate an approach to dealing with water quality risk assessment.*

Key Words: *Variable Source Areas (VSA), Hydrologically Sensitive Areas (HSA), water quality, risk assessment, runoff, watershed, saturation excess, Soil Moisture Routing Model (SMR), manure spreading, agriculture*

The recognition of *Variable Source area* (VSA) hydrology as an important hydrological process has implications on water quality risk assessment that are only recently becoming widely realized. Though water quality is dependent on a wide range of physical, chemical, biological, and societal factors, hydrology is irrefutably fundamental. Non-point source (NPS) pollution often involves a plethora of pollutant constituents including nutrients, pesticides, and pathogens, for many of which the transport and transformation details are not well understood. Relatively speaking then, hydrology is well understood and provides the most secure insights into assessing risks to water quality.

As in the case of phosphorus, there are often no widely accepted or indoctrinated quantifiable contaminant-levels or risk limits. Though regulations are often unpopular, developing risk assessment schemes and water quality protecting practices is greatly facilitated by widely recognized and accepted contaminant-level thresholds. Unfortunately this is a luxury that is often unavailable to farmers, conservation specialists, extension personnel, and others intimately connected to practical aspects of preventing NPS pollution. In lieu of regulatory or other guidance limits for contaminant-levels, hydrologically-based risk quantification provides the most appropriate approach to water quality risk assessment.

In retrospect, it is not surprising that variable source area hydrology, first termed by Hewlett and Hibbert (1967), has not widely been formally considered in water quality protection projects. Historically, water quality protection efforts have been (and continue to be) largely influenced by a dogma developed by the soil conservation infrastructure. Many of the problems with equating soil conservation and water quality have been documented and discussed over the last twenty or more years (e.g. Walter et. al.1979). Primary focus has been in noting that sediment transport processes are not applicable to all pollutants and therefore management practices designed for controlling sediment transport are inappropriate for many other constituents. For example, soil conservation practices are often ineffectual in controlling the transport of soluble chemicals, especially if they also have a low soil partition coefficient, i.e. low absorptivity. Furthermore, much of the early soil conservation research in the United States (1930's & 1940's) was focused on the deep, fertile, soils of the topographically flat U.S. Midwest where VSA hydrology is often not a dominant hydrological process. Also, the precipitation intensity regime most significantly impacting soil erosion often corresponds with Hortonian overland flow processes rather than saturation excess derived VSA runoff generation.

Variable source area hydrology is a watershed runoff process whereby saturated areas are the primary sources of runoff; i.e. rain that falls on saturated areas becomes overland flow. Therefore the propensity of an area to produce runoff is largely independent of rainfall intensity. In places where VSA hydrology is a dominant process, there will be regions within a watershed that are more susceptible to producing runoff than others. Therefore, there is an enhanced hydrologic sensitivity associated with these areas relative to non-runoff generating areas; runoff provides quick transport mechanism for potential pollutants between the landscape and surface water bodies. These areas are appropriately called hydrologically sensitive areas (HSA's). A quantifiable description of HSA's provides a basis or at least a starting-point for water quality risk assessment and developing water quality management practices for NPS pollution.

Herein is a brief review of variable source area hydrology, an expanded discussion of the definition and water quality implications of HSA's, and an example water quality risk assessment approach for manure-spread fields in the Catskills region of New York State. In the context of this paper, water quality is focused on surface water and NPS pollution.

Variable Source Area Hydrology

In many regions, especially humid, well-vegetated, topographically steep areas with shallow, high infiltration capacity soils, runoff tends to originate primarily on areas in the landscape that are saturated. This process is commonly called saturation excess runoff.

Variable source area hydrology is an extension of the saturation excess process, recognizing that the extent of saturated areas in a watershed will expand and contract (i.e. vary temporally). The variation in the extent of saturated areas has been studied over a range of temporal

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Journal of Soil and Water Conservation. 2000. 3:277-284.

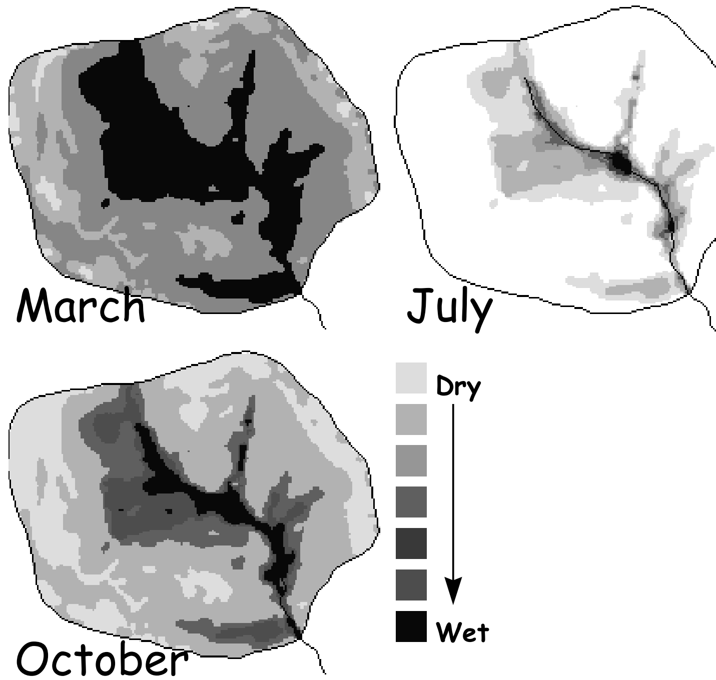

Figure 1: Seasonal changes of saturated areas in a watershed

scales ranging from storm duration, hours and days, to seasonal (figure 1). Though the original concept for this process was developed by the U.S. Forest Service (1961) and the Tennessee Valley Authority, the term *variable source area* is usually attributed to Hewlett and Hibbert (1967). Dunne (1970), Dunne and Black (1970), Hewlett and Nutter (1970), and Dunne et al. (1975) are also commonly noted for their early, foundational contributions to the variable source area hydrology concept.

Some hydrological processes observed in Upstate New York, primarily the Catskills region, can serve to elucidate mechanisms resulting in saturation. Soils in the Catskills are generally permeable relative to rainfall intensity and underlain by a shallow, low-permeable, restrictive layer, typically bedrock or fragipan. Rainwater easily permeates the soil and, by-and-large, runs laterally on top of the restrictive layer down-slope; this is typically called interflow. Figure 2 shows observable evidence of the accumulation of interflow water at the bottom of a slope in the Catskills during wet periods, Spring and Winter, relative to the dry, early Fall. Some common locations where saturation occurs are areas where the soil above the restricting layer is shallow, in places where the down-hill topographic slope decreases such as the toe-slope of a hill, or in topographically converging areas (figure 3). All three incidences are locations in the landscape where the Darcy flow capacity, or interflow capacity, is reduced either by a decrease in hydraulic transmissivity or hydraulic gradient. When interflow capacity is sufficiently restricted the soil will saturate. During periods of enhanced rainfall, interflow will be higher and often expand the extent of saturation around saturation-prone areas; conversely, dry periods will decrease interflow and extent of saturation. This is illustrated for wet and dry seasons in figure 1.

Saturation excess runoff volume is dependent on the aerial extent of saturation within a watershed and the rainfall depth and is largely independent of rainfall intensity. In contrast, infiltration excess runoff volume is directly dependent on rainfall intensity and will not occur at sufficiently low intensities. Infiltration excess is also called Hortonian flow after R.E. Horton (1933,1940) who's work in the area of infiltration capacity provided a conceptual description of the infiltration excess process, whereby runoff initiates when the rainfall intensity exceeds a soil's infiltration capacity.

Hydrological Sensitivity

Effective water quality risk assessment requires a rubric for describing and quantifying the risk of contamination. As discussed in the introduction, contaminant transport and transformation processes are often not well understood and there are often few or no regulatory or other guiding contaminant-level targets. Therefore, accepting the need for water quality risk assessment within these limitations, hydrologic quantification provides the most appropriate avenue to assessing water quality risks at this time. In regions where saturation excess processes govern runoff, the following terminology and conceptual- scheme provides a framework within which risk quantification can begin.

In places where VSA hydrology is a dominant process, there will be regions within a watershed that are more susceptible to producing runoff than others. These areas can be considered hydrologically active areas (HAA). Runoff from most of these areas quickly moves downhill to perennial waterways thus

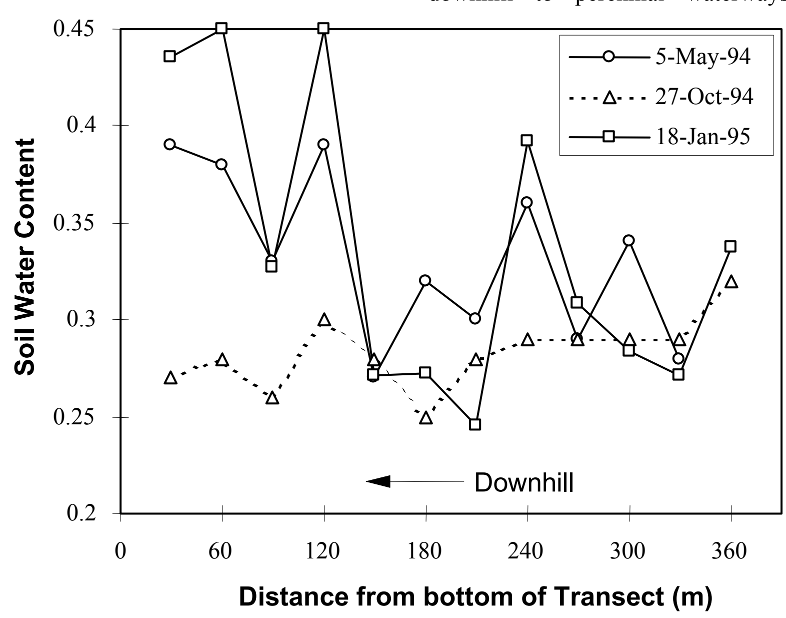

Figure 2: Soil water distribution along a slope in the Catskills. Solid lines represent wet periods a; the dashed line shows a dry period

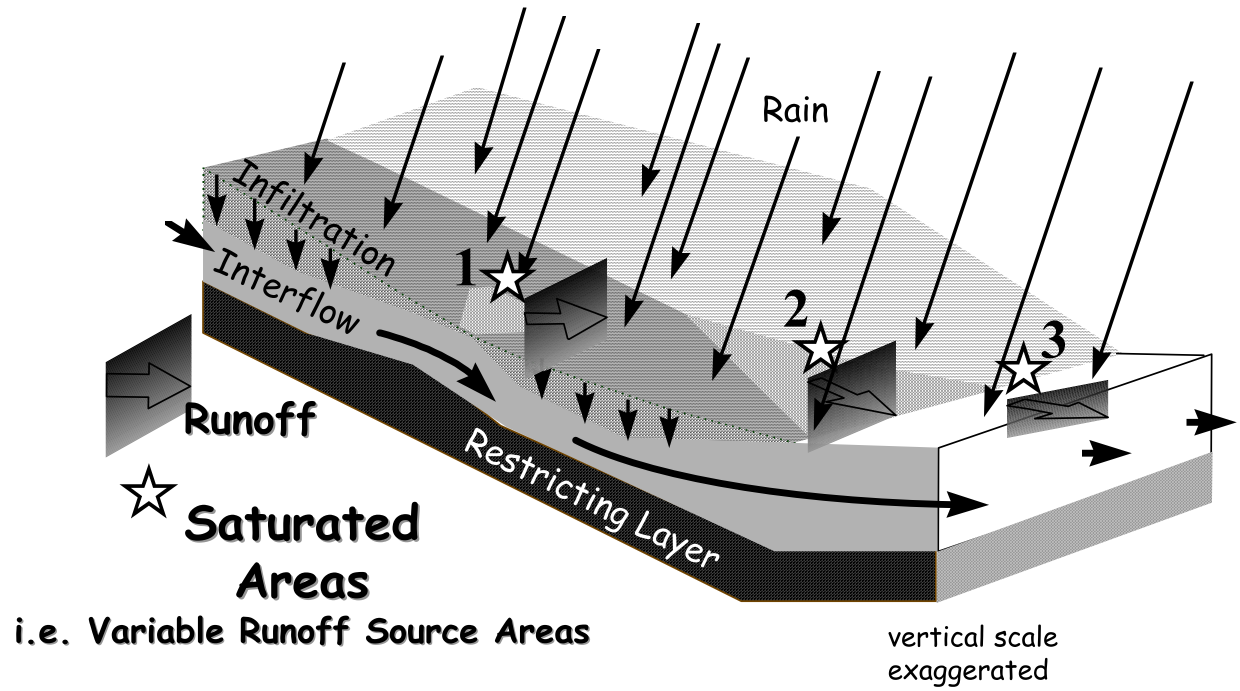

Figure 3: Incidents of saturation excess hydrology: 1) shallow soil, 2) convergence area, 3) downhill slope decreases

providing a potential direct hydrological link between the landscape and primary surface water bodies. When this linkage exists, an HAA can be said to be a hydrologically sensitive area (HSA) and water-born constituents in these areas are likely to be readily transported to surface waters. Though a distinction between HAA's and HSA's is being carefully defined here, practically speaking, there has been little evidence that HAA's are ever hydrologically insensitive. It should be noted that the terminology presented here varies slightly from Gregor and Johnson (1980), who, in a general discussion of non-point source pollution with no reference to variable source area hydrology, identified HAA's as areas in a watershed with a high potential of transporting pollutants to surface water bodies. For the remainder of this discussion we will discuss only HSA's with the recognition that special cases may exist in which an HAA is not intimately hydrologically connected to a surface water body; i.e. runoff may not flow directly from the HAA to a surface water body. For example, one could imagine a number of conditions under which upland runoff might infiltrate downslope; e.g. in a karst landscape runoff may flow into a sinkhole.

Recognizing the existence of HSA's limits the scope of watershed-scale water quality problems to only those areas where HSA's coincide with landuses that potentially contribute pollutants. This concept is schematically presented in figure 4 in which the intersection is referred to as the critical management zone. The most obvious best management practice for this area would be to limit or prohibit potentially polluting activity from this region. A contrasting approach is finding methods and means of eliminating the hydrological sensitivity of the critical zones; the philosophy of manipulating the environment verses adapting to environmental constraints is fodder for another discussion. Recent research suggests attempts to remove hydrological sensitivity through drainage practices may simply reroute pollutants from overland flow to subsurface flow with little reduction in concentration (Shalit and Steenhuis 1996, Gachter et. al. 1998).

In this study, an area can be defined as a HSA based on its proneness to generate runoff; i.e. the likelihood that the area will be saturated during a rainfall event.

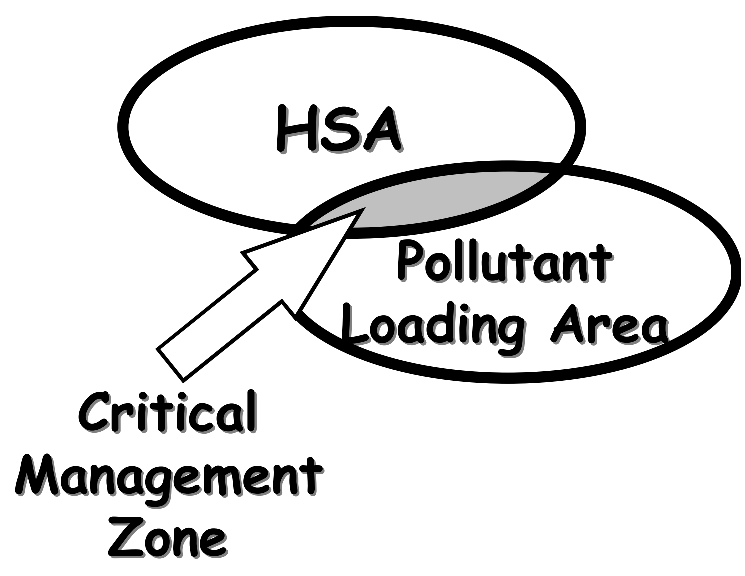

Figure 4: Schematic of HSA's and critical management zones.

Expressed as a probability, a HSA is any area, A_i, which has a probability, P, of being hydrologically sensitive (HS) greater than a hydrological sensitivity limit, L_{HSA}:

$$A_i = \text{HSA if } P(A_i = HS) \geq L_{HSA} \qquad (1)$$

Where $P(A_i = HS)$, the probability cut-off point separating HSA's from non-HSA's, is the fraction of the total number of days that an area, A_i, produced runoff:

$$P(A_i = HS) = \frac{\sum_j^n day_{ro.j}}{\sum_j^n day_j} \qquad (2)$$

Where $day_{ro.j}$ is a day in which A_i produced runoff.
day_j is any day.
n is a total number of days.

Currently there are no guidelines for determining L_{HSA}; one approach is outlined in the example in the next section of this paper. Another point to consider is that there are very few direct measurements of the extent of saturated areas. Therefore, VSA hydrological models like the Soil Moisture Routing model (SMR) (Frankenberger et al., 1999) are used to predict saturated areas in the landscape and the volume of runoff generation from each.

An important ramification of the HSA concept is that, due to the seasonal variability of saturated areas, HSA's will also vary seasonally. Therefore it is entirely possible for a specific location to be hydrologically sensitive at one time of the year and insensitive another. Thus, some potentially polluting activities might only need to be restricted from an area for part of each year. Of course this would depend on the persistence of an activity to potentially pollute. For example, the land application of biodegradable materials may have sufficiently short potential-polluting time-frames due to the materials' breakdown that the activity need only be restricted from an area during and immediately before its hydrologically sensitive period.

HSA Example: Field-Spread Dairy Manure in the Catskills

This example explores one quantifiable approach to determining a HSA cut-off limit, L_{HSA}, which can be used to classify hydrologically sensitive areas. This example also demonstrates a practical application of a VSA hydrological model, namely SMR (Frankenberger et al., 1999), to a real water quality risk assessment situation. While the L_{HSA} determined by this study is currently recognized by the Watershed Agricultural Project, a.k.a. the New York City (NYC) project, it best serves as an illustrative example of how VSA hydrology can provide a framework for water quality risk assessment. The discussion points-out modifications to the example presented which serve to give direction to possible further study.

Background: Researchers at Cornell University's Agricultural and Biological Engineering Department (ABEN) are currently working with farmers and planners in an effort to protect New York City (NYC) water supply reservoirs located in the Catskill Mountain region of New York State. ABEN researchers have made great strides in describing and modeling the Catskill's unique hydrology and are researching methods to use their understanding to help with the problems of NPS pollution from manure-spread fields. The goal of the NYC project is to ensure high standards of water quality while maintaining the economical viability of agriculture within the NYC watersheds.

The Catskill region is hydrologically characterized by steep slopes (averaging 20%) and shallow (<50 cm deep), permeable soils over a restrictive layer. Surface runoff generally arises as saturation excess and can be described by the principles of variable source hydrology, i.e. surface runoff is generated primarily from saturated areas, as opposed to precipitation intensities exceeding infiltration capacity. The spatial extent of runoff-generating, saturated areas changes throughout the year making some portions of a watershed more prone to runoff in one month than at another. The SMR model is well suited to this region's hydrology and can be used to locate saturated areas throughout the landscape (Frankenberger et al., 1999).

The Catskill region is dominated by dairy farms. Developing environmentally sound practices for land application of manure is a primary issue. From an environmental quality standpoint the optimal solution is to spread no manure on the land, therefore making none available for runoff transport. Conversely, agriculture would most benefit from no restrictions to land applications of manure. By the terminology and philosophy outlined in the previous section, HSA's would be areas unsuitable to manure spreading; i.e. runoff originating on HSA's would be protected from contaminants.

Methods

In keeping with the NYC project's balanced approach between water quality and agricultural viability, one possible means of quantifying L_{HSA} is to determine the probability cut-off that balances these conflicting objectives. A cost-benefit type approach is used which essentially equates the value of *land available for spreading* and *runoff that may transport contaminates to a water supply*. As P decreases from L_{HSA} the rate at which land is removed from the pool of land viable for spreading is disproportionately higher than the rate at which runoff is being protected and visa versa for P increasing above L_{HSA}. The L_{HSA}, then, is the probability that an area will generate runoff such that a watershed's HSA's account for largest volume of runoff per area classified as HSA. The ratio, t, as a function of an HSA cut-off P, is defined as:

$$t = \frac{r_{HSA}(P)}{a_{HSA}(P)} \qquad (3)$$

Where r_{HSA} describes the volume of runoff from HSA's as a function of P.
a_{HSA} describes the area classified as HSA's as a function of P.

Dimensionless values R and A of r_{HSA} and a_{HSA} respectively can be derived by dividing by the total runoff produced in a watershed and the total area of the watershed respectively. The R and A parameters can be physically described as the fractions of total watershed runoff volume generated on HSA's and of total watershed area classified HSA respectively. As described earlier (equations (1) and (2)), a probability cut-off point of P means that any area with a daily probability of P or greater of producing runoff is designated an HSA. For example, probability cut-off, P, of 10% means that any area producing runoff on 10% or more of the days in a "month[1]" is considered an HSA. The lower the probability cut-off point, P, the more land is considered HSA; e.g. every point in the watershed produces runoff at least 0% of the time ($A_{HSA}(0\%)=100\%$) and virtually no area, excluding some unique cases like springs, generate runoff 100% of the days ($A_{HSA}(100\%)=\varepsilon$). Likewise, the lower the probability cut-off point, P, the greater the fraction of the total runoff originating on HSA's. For example, about 30 cm of

[1] In general HSA's are determined monthly but at the request of NYC project participants March, April, October, and November are divided into biweekly segments due to their agricultural importance and potentially dynamic hydrologic behavior arising from rapid evapotranspiration changes. HSA's are determined separately for the first two weeks and last two weeks of these months.

runoff is produced in January. If P is 40%, r_{HSA} is about 3 cm and thus R 10%; if P is 10%, R increases to 60%. Using the dimensionless values R and A, a new ratio, T, is defined as:

$$T = \frac{R(P)}{A(P)} \quad (4)$$

The P cut-off limit which balances water quality protection and agricultural manure-spreading needs, L_{HSA}, is the P value which maximizes equation (4):

$$T_{\max} = \frac{R(L_{HSA})}{A(L_{HSA})} \quad (5)$$

Two subbasins within the Cannonsville watershed served as the main focus of this investigation: a relatively flat, 36.2 mi^2 (93.8 km^2) catchment (I) and a steeper 15.5 mi^2 (40.1 km^2) catchment (II). Using ten years of hydrological simulation, the SMR model determined the fraction of time that each point (10 m X 10 m area) in the two sub-basins generated runoff each "month." Grouping areas by ranges of P, 0% to 10%, 10% to 20%, etc., revealed, as expected, that all the drier months generally had no areas producing runoff a large fraction of the time. However, every month, regardless of precipitation, had a few areas that generated runoff in the P=90%-100% range. During the very driest months these areas accounted for springs and rivers and flow from these was removed from the study. The SMR generated data were used to determine average values for R and A for various values of P. Functions for R(P) and A(P) were empirically determined. Equation (5), and thus L_{HSA}, was calculated through analytical differentiation of equation (4) with respect to P.

Results

Table 1 shows values for R and A relative to P as determined by the SMR based on 10 years of hydrological simulation. The data for the percent of watershed area defined as HSA, A, in Table 1 were fitted with exponential curves with respect to runoff probability cut-off:

$$A(P) = A_\infty + \left(A_o - A_\infty\right)e^{-K_A P} \quad (6)$$

Where A is the percent of the watershed area defined as HSA's (%).
P is the runoff probability cut-off defining HSA's (%).
A_o, A_∞ and K_A are constants.

Table 1: Summary of SMR results for watersheds I and II.

P (%)	A (%)		R (%)	
	I	II	I	II
0	100.0	100.0	100.0	100.0
10	35.6	37.6	59.8	62.7
20	17.8	20.1	33.5	35.1
30	8.8	9.9	17.4	17.8
40	5.6	5.9	10.3	9.5
50	4.5	4.5	7.3	6.5
60	3.8	3.8	5.3	4.9
70	3.2	3.3	3.6	3.5
80	2.7	2.8	2.0	1.9
90	2.1	2.2	0	0
100	-	-	0	0

Due to the simple mathematical description, physical limitations suggest A_o must equal 100. Best fits were obtained with A_∞ equal to 1.60 and K_A equal to 0.10 for watershed I and equal to 2.00 and 0.095 respectively for watershed II. The A_∞ values are greater than 0 because of the persistent spring areas.

A simple exponential description was unsatisfactory for R(P) so the data for percent of the total runoff originating from HSA's, R, in table 1 were fitted with an exponential function for P less than the probability of rain (approximately 40%)[2] and with a linear equation for P greater than the probability of rain:

$$R(P) = R_\infty + \left(R_o - R_\infty\right)e^{-K_R P} \qquad P \le 40\%$$

$$R(P) = mP + b \qquad P > 40\% \quad (7)$$

Where R is the percent of the total runoff originating from HSA's.
R_o, R_∞, and K_R, m and b are constants.

Like A_o, R_o is restricted to 100 due to mathematically implied physical limitations. For best fits with data, R_∞ is -5.0 and -9.0, K_R is 0.050 and 0.045, m is -0.17 and -0.16, and b is 15.4 and 15.0 for watersheds I and II respectively. It should be emphasized that equations (6) and (7) are simply curve-fitted and have limited physical interpretation. It may be arguable that other functions are better suited to this analysis but the approach outlined here is suitable for the demonstration purpose of this analysis.

[2] The probability of rain was determined from Walton, NY weather data (1958-96): probability of rain on any day is 36% and the chance of rain or snowmelt is 40%.

Figures 5 and 6 show equations (6) and (7) with respect to the data in table 1.

The ratio of equation (7) to equation (6) is T(P), the percent of the total runoff generated by HSA's per percent of land defined as HSA. Limiting analysis to P less than the probability of rain (0 ≤ P ≤ 40%), T, is ordinary and contains a unique maxima. The T maxima (T_{max}) in the P=0 - 40% range was the largest value in the entire 0 to 100% range. The maxima of T(P) corresponds to the probability cut-off, P, which results in the highest percent of runoff coming from the least amount of land; i.e. the optimal cut-off P=L_{HSA}. The maxima of T is determined with differentiation:

$$\frac{dT}{dP} = \frac{C_1 e^{-(K_A+K_R)P} - C_2 e^{-K_R P} + C_3 e^{-K_A P}}{\left[\left(A_o - A_\infty\right)e^{-K_A P} + A_\infty\right]^2} \qquad P \le 40 \quad (8)$$

Where:

$$C_1 = \left(K_A - K_R\right)\left(R_o - R_\infty\right)\left(A_o - A_\infty\right) \quad (9)$$

$$C_2 = A_\infty K_R \left(R_o - R_\infty\right) \quad (10)$$

$$C_3 = R_\infty K_A \left(A_o - A_\infty\right) \quad (11)$$

Solving equation (8) for $\frac{dT}{dP} = 0$ to find the value of P=L_{HSA} corresponding to T_{max} results in the following logarithmic equation:

$$L_{HSA} = \frac{\ln(x)}{K_R} \quad (12)$$

Where:

Journal of Soil and Water Conservation. 2000. 3:277-284.

$$x = \left(\frac{C_2 x^{\frac{K_A}{K_R} - 1} - C_3}{C_1} \right)^{-1} \qquad (13)$$

Equation (13) converges rapidly and is solved iteratively.

The optimal cut-off points, L_{HSA}, from equation (12) using the best-fit constants for equations (6) and (7) are 29% and 28% for watersheds I and II respectively; L_{HSA}, is essentially 30%. From figures 5 and 6 essentially 30%. From figures 5 and 6 this cut-off corresponds to about 10% of the land area and 20% of the runoff.

Table 2 shows the results from a sensitivity analysis. The optimal HSA cut-off point, L_{HSA}, is most sensitive to K_R; for both watersheds; plus and minus 10% changes in K_R change L_{HSA} by -10% and +10% respectively. L_{HSA} is relatively insensitive to all the other parameters; 10% perturbations in the constants change L_{HSA} by less than 3%.

Using L_{HSA}=30%, figures 7 and 8 show the monthly break-down of average A, R, T and "monthly" runoff based on a 10 year SMR simulations for both watersheds. The results for the two watersheds are relatively similar though watershed II generally has slightly more land classified as HSA during the wet months. The T ratio is relatively consistent, between 1 ration is relatively constant between 1 and 5. The percent of total runoff is highest for wet months in spring and late fall. The T ratio is slightly higher in the first half of October for watershed II than in any other month. The exact reason for this anomaly is unclear; it may be related to the way watershed II reacts during hurricane generated rainfall.

Discussion

Using the cost-benefit approach discussed earlier, an HSA cut-off, L_{HSA}, of 30% daily probability of runoff was determined optimal for classifying HSA's in two Catskills watersheds. Incidentally, this value was corroborated by the same sort of analysis on two additional watersheds, one larger and one smaller than the two detailed in this study (data not shown). This cut-off resulted in an annual average of approximately 10% of the land being classified as HSA and protected about 20% of the total runoff volume. Considering both watersheds, only March, the first half of April, and the last half of November have HSA's in excess of the annual average of 10% of the total area. These are between

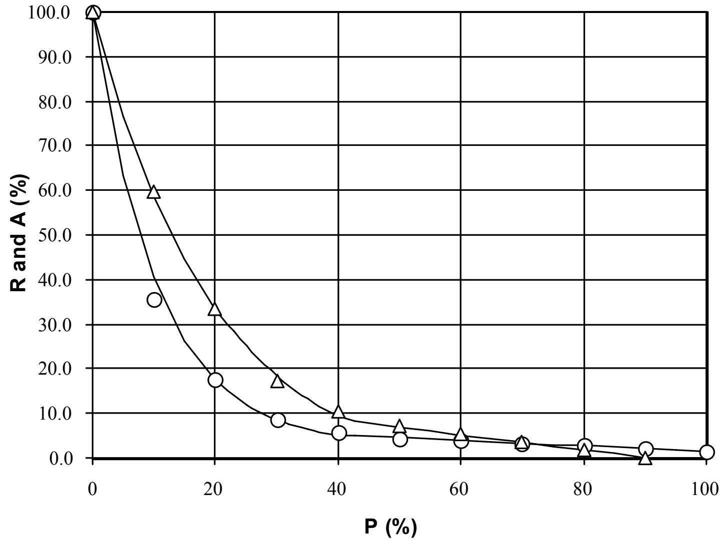

Figure 5: Watershed I: Runoff, R (triangles), and HSA, A (circles), data fitted with equations (6) and (7) (lines).

○ **A**: % of the watershed area defined as HSA's; data fit with equation (6) using A_∞ = 1.60 & K_A = 0.10 (best fit). R^2 = 0.998; standard error, Ste = 1.37%

△ **R**: % of the runoff originating from HSA's; data fit with equation (7)

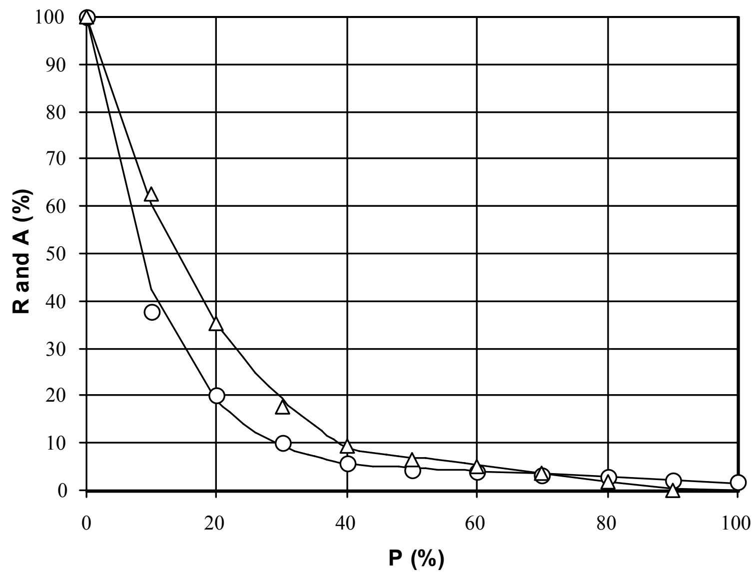

Figure 6: Watershed II: Runoff, R (triangles), and HSA, A (circles), data fitted with equations (6) and (7) (lines).

○ **A**: % of the watershed area defined as HSA's; data fit with equation (6) using A_∞ = 2.0 & K_A = 0.095 (best fit). R^2 = 0.998; standard error, Ste = 1.47%

△ **R**: % of the runoff originating from HSA's; data fit with equation (7) using R_∞ = -9.0 & K_R = 0.045 (best fit). R^2 = 0.9993; standard error, Ste = 0.89%

Table 2: Sensitivity analysis for constants in equations (1) and (2) fitted for watersheds I and II.

Basin	A_∞	K_A	R_∞	K_R	$R^2(A)$	Ste(A)	$R^2(R)$	Ste(R)	L_{HSA}
I	1.60	0.10	-5.0	0.050	0.998	1.37	0.9996	0.66	33.9
	1.76	0.10	-5.0	0.050	0.998	1.37	0.9996	0.66	33.2
	1.44	0.10	-5.0	0.050	0.998	1.37	0.9996	0.66	34.6
	1.60	*0.11*	-5.0	0.050	0.997	1.58	0.9996	0.66	33.4
	1.60	*0.09*	-5.0	0.050	0.995	2.09	0.9996	0.66	33.7
	1.60	0.10	*-5.5*	0.050	0.998	1.37	0.9996	0.70	33.2
	1.60	0.10	*-4.5*	0.050	0.998	1.37	0.9996	0.69	34.6
	1.60	0.10	-5.0	*0.055*	0.998	1.37	0.9980	1.66	30.7
	1.60	0.10	-5.0	*0.050*	0.998	1.37	0.9996	2.03	37.1
II	2.0	0.095	-9.0	0.045	0.998	1.47	0.9993	0.89	31.3
	2.2	0.095	-9.0	0.045	0.998	1.48	0.9993	0.89	30.7
	1.8	0.095	-9.0	0.045	0.998	1.47	0.9993	0.89	31.9
	2.0	*0.105*	-9.0	0.045	0.996	1.86	0.9993	0.89	31.3
	2.0	*0.086*	-9.0	0.045	0.996	2.01	0.9993	0.89	30.6
	2.0	0.095	*-9.9*	0.045	0.998	1.47	0.9993	0.92	30.4
	2.0	0.095	*-8.1*	0.045	0.998	1.47	0.9993	0.92	32.2
	2.0	0.095	-9.0	*0.050*	0.998	1.47	0.9980	1.47	27.9
	2.0	0.095	-9.0	*0.041*	0.998	1.47	0.9980	1.48	34.8

Note: the first row for each watershed corresponds to the best-fit constants for both equations (1) and (2).

15% and 35%. For watershed II the first half of November also exceeded 10% of the area as being classified HSA.

Assuming the HSA's are evenly distributed on and off fields, this method for determining HSA's, on average, only eliminates about 10% of the land from manure spreading leaving 90% of the area free for manure-spread scheduling. Depending on which watershed is observed, 80% to 85% of the year has more than 90% of the area free for spreading and, except for the first week in April, the whole year has more than 70% of the land area free for spreading. June through September have virtually no area designated HSA, less than 1%, which translates into very few restricted areas for spreading. The advanced crop stage in the summer may offset the hydrologic advantages of this spreading period for some of the cropland. A potential problem with this method, however, is that there is generally more than half the runoff unprotected, i.e. not coming from HSA's. Only the first week in April finds HSA's accounting for half or more of the runoff. This means there may still be a substantial risk of runoff transported contamination.

Assuming, an even application of manure across all fields before HSA classification and an even application over all non-HSA fields after classification, this technique for determining HSA's would be expected to reduce the risk of contamination by 20%. While this estimate of risk reduction is based on some gross assumptions, it is more than likely that this method for classifying HSA's will account for less than half the total runoff. Better confidence in this risk reduction estimate requires verification that HSA's are evenly distributed among agricultural and non-agricultural land.

This study suggests the increase in runoff return for each unit increase in land area designated HSA will progressively diminish when trying to account for more than 20% of the runoff with HSA's. The first 20% of the runoff required only 10% of the land to be designated as HSA. Now, designating another 10% of the land as HSA (20% total) results in only 15% more of the runoff being generated from HSA's (35% total). The return rate continues to diminish and the next 10% of land designated HSA (30% total) returns only about 13% additional runoff (48% total).

As a final comment, improved understanding of the details of VSA hydrology may provide insights for modifications to the approach described here. For example, though the physical reasonableness is uncertain, slightly

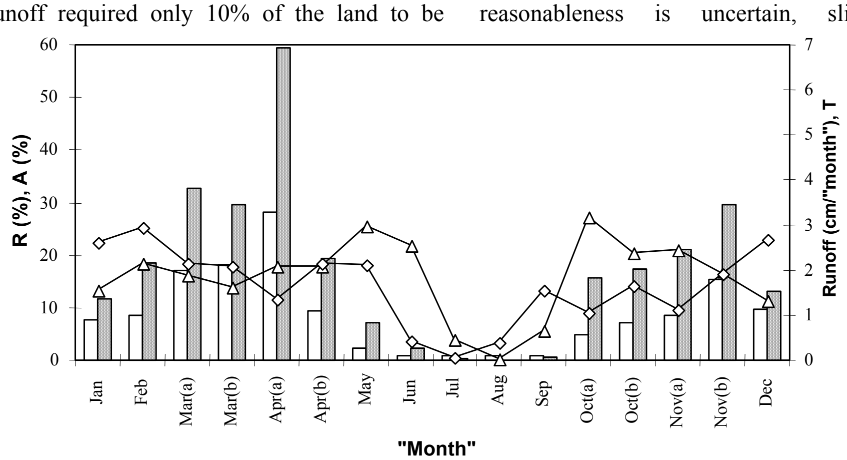

Figure 7: Watershed I: "Monthly" results of A (open bars), R (shaded bars), T (triangles), and total monthly runoff (diamonds).
□ **A:** % area classified HSA (left axis)
■ **R:** % of total runoff originating from HSA's (left axis)
△ **T: R/A** (right axis)
◇ Average total monthly runoff: (right axis)

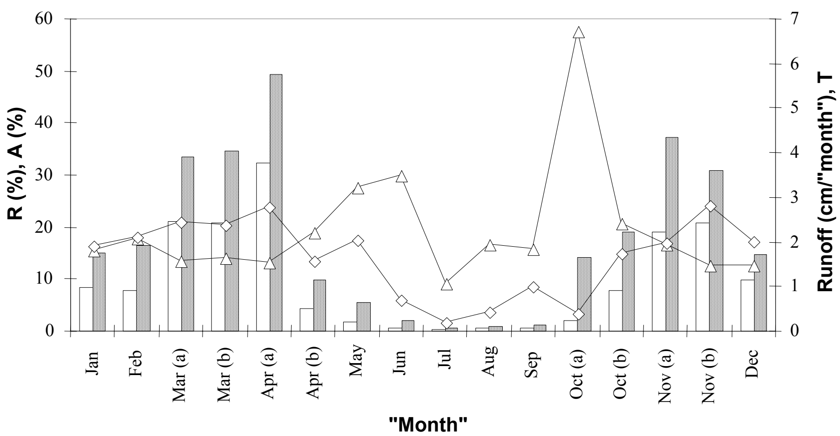

Figure 8: Watershed II: "Monthly" results of A (open bars), R (shaded bars), T (triangles), and total monthly runoff (diamonds).

□ **A:** % area classified HSA (left axis)

■ **R:** % of total runoff originating from HSA's (left axis)

△ **T: R/A** (right axis)

◇ Average total monthly runoff: (right axis)

Note: a "month" designated with (a) or (b) in figures 7 and 8 refer to first half and last half of the month respectively.

different results can be obtained by relaxing the constraints on A(P) and R(P) which force the functions through 100% at P=0%; e.g. it is plausible that all the runoff (100%) is coming from HSA's at some small P greater than 0%. Both hyperbolic and simple exponential functions were found to fit this relaxed description well and, following the procedure outlined in the methods discussed earlier, L_{HSA} were determined as high as 15%.

This cut-off protects approximately 50% of the runoff but restricts manure-spreading on about 30% of the land area. Work continues to determine the best approach for determining L_{HSA}.

Conclusion

In lieu of a concrete contamination risk reduction target, hydrologically-based risk assessment is an alternative. This type of approach is applicable to regions hydrologically characterized by variable source area though little work has currently been done in this arena. One plausible approach is to classify HSA's using an optimized "daily probability of runoff" cut-off which simultaneously maximizes available land for manure spreading and minimizes the risk of pollutant transport in surface runoff. While this technique for quantifying an HSA cut-off attempts to balance agriculture's need for adequate land for manure spreading with water quality protection, it may not be stringent enough to meet the contamination risk reductions needed to adequately protect the NYC drinking water supply. Though the NYC project currently recognizes the L_{HSA} as 30%, further hydrological and pollutant transport investigation may provide guidance for refining this value. This work demonstrates practical application of the variable source area concept to water quality risk assessment.

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