Simple Estimation of Prevalence of Hortonian Flow in New York City Watersheds

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Abstract: This study was a statistical evaluation of the prevalence of infiltration excess runoff (i.e., Hortonian flow) for undeveloped areas within New York City (NYC) watersheds. Identifying the hydrological processes generating runoff is central to developing watershed management strategies for protecting water quality. Fifteen-minute rainfall data from East Sidney, N.Y. (1971–2002) were used as maximum observed intensities. Maximum exceedance analyses were performed on a monthly basis to investigate seasonal rainfall intensity trends. Hortonian flow was assumed to occur whenever the rainfall intensity exceeded the soil permeability. Soil permeabilities were obtained from the U.S. Natural Resource Conservation Service soil survey. Results show that Hortonian flow is unlikely to occur anywhere for events smaller than the 3-year 15-min event. Only for the summer months, May–August, is Hortonian flow expected for 15-min intensities of $<$10-year magnitude. However, the summer results are overpredicted by this analysis because these months typically have the driest soil conditions and thus the highest infiltration capacity. This analysis concludes that infiltration excess runoff is not a dominant runoff process in undeveloped portions of NYC watersheds.

CE Database subject headings: Infiltation; Watersheds; New York; New York City; Rainfall intensity; Storm runoff.

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Introduction

Two of the primary hydrological mechanisms that generate overland flow are *infiltration excess* and *saturation excess*. Infiltration excess results when water is applied to a surface at a rate higher than the surface's infiltration capacity. This is often called *Hortonian flow* after R. E. Horton, whose early work in infiltration has become the conceptual basis for describing this process (Horton 1933, 1940). Saturation excess is fundamentally different, in that in this process, overland flow is generated in locations where the soil is saturated to the surface. Unlike Hortonian flow, for which soil type and land use typically play a controlling role in runoff generation, landscape position, local topography, and soil depth are some of the primary controls on saturation excess runoff, especially in the New York City (NYC) watersheds. Saturation excess is the basis for the concept of *variable source area* hydrology that acknowledges that the spatial extent of saturation will vary seasonally, depending on the relative rates of rainfall and evapotranspiration. In most watersheds, both Hortonian and saturation excess processes contribute to runoff generation; however, one or the other often dominates.

Determining which process dominates has a profound effect on determining methods for developing watershed management plans to protect water quality (Walter and Walter 1999). For example, many management practices are developed with the aid of hydrological models that were developed empirically using data from watersheds with one or the other of these two processes dominating. Also, many early models were developed for engineering, to size hydraulic structures and design erosion controls. This type of application will commonly revolve around very intense rainfall events that are likely to produce Hortonian flow. The application of these models to non-Hortonian situations is problematic though surprisingly common.

In the NYC water-supply watersheds, located in the Catskill Mountains of New York State (Fig. 1), non-point-source pollution from manure-spread fields is an acute concern. This concern has led to efforts aimed at understanding and evaluating the regional hydrology. This understanding, in turn, is used to develop improved manure management schemes for reducing the risk of surface water contamination via polluted overland flow (Walter et al. 2000, 2001). The Catskills are characterized by steep hilly topography and shallow ($>$50 cm) permeable soils above bedrock and fragipan restricting layers. The area is humid ($\sim$1.5 m of rain

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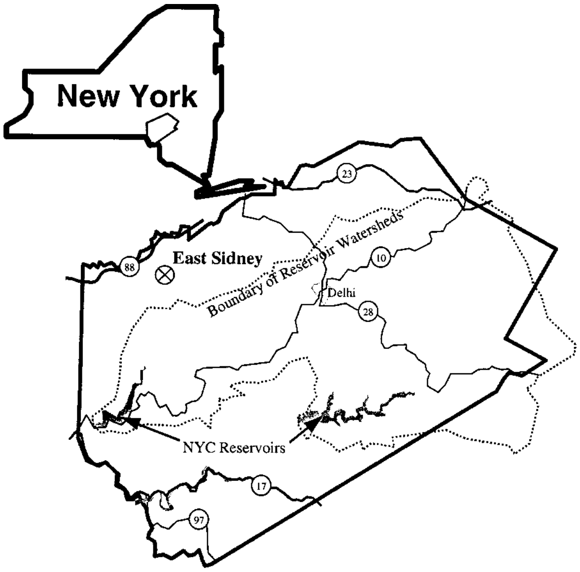

Fig. 1. Location of Delaware County, East Sidney, and relevant NYC reservoir features

annually) and well-vegetated. This physical description fits that usually associated with saturation excess (Dunne and Leopold 1978); however this is not a well-quantified conclusion. The assumption that runoff in this region is dominated by saturation excess is the basis for much of the work that has taken place in developing manure management strategies. Researchers at Cornell University's Biological and Environmental Engineering Department developed the Soil Moisture Routing (SMR) model to simulate saturation excess runoff for the region. The model corroborates well with field data (Frankenberger et al. 1999; Mehta et al. 2002) and is being used to develop new watershed-management practices (Walter et al. 2000, 2001). The success of SMR supports the hypothesis that saturation excess dominates in this region and that Hortonian flow is minimal. However, watershed hydrological models should not be unilaterally accepted as good indicators of a particular set of physical processes, so this study provides a simple, independent analysis to determine the prevalence of Hortonian flow in the Catskills.

Methods

Delaware County, which contains two of NYC's reservoirs and most of the associated watersheds, was used as a representative area (Fig. 1). Fifteen-minute precipitation data from 1971 to 2002 were obtained from a National Weather Service's meteorological station at East Sidney, N.Y.; this was the most complete data set available, and the annual precipitation distribution compared well to other stations in Delaware County (Fig. 1). These short duration (15-min) data were used to approximate maximum observed intensities; average precipitation intensity decreases for longer duration data. We chose to use high intensities to investigate a worst-case scenario. This study considered all precipitation to be rain. Monthly frequency analyses were performed using maximum exceedance series and a lognormal distribution function for the most recent 30-year period. Data were adjusted to reflect continuous data collection (Hershfield 1961).

The surface-layer soil permeability, k, for each soil in Delaware County, was obtained from the USDA, Natural Resource Conservation Services' Soil Survey Geographic (SSURGO) database. Permeability is synonymous with saturated hydraulic conductivity in these data ("Soil" 1993), and is used here as an approximation of soil infiltration capacity. The digital SSURGO maps duplicate the original soil survey maps that were compiled to 1:24,000 scale, 7.5-min orthophoto quadrangles. The SSURGO digital maps of each of the 43 quads in Delaware County were merged in a geographic information system (GIS) to create a comprehensive map of the soils in Delaware County (3,800 km^2). The database provided minimum and maximum k values for the surface layer of each soil, which we used to determine the spatial distribution of median soil permeability for Delaware County. Because the distribution function for these data was not obvious, this information was curve-fitted using an empirical equation of the form

$$\Phi = 1 + \frac{1}{2}\,\mathrm{erfc}(\alpha_1 k + \alpha_2)\exp\left(-\frac{1}{\alpha_3 + k}\right) \qquad (1)$$

where Φ=fraction area with permeability greater than k; k=soil permeability (cm$\cdot$h^{-1}); and α_j=constants.

Though some researchers have shown that soil saturated hydraulic conductivity is often much higher than the soil permeabilities reported in soil surveys (Burger 1922; Topp and Binns 1976; Troch et al. 1993; Rossing 1996), the soil survey values provide a worst-case scenario for this analysis. Our analysis assumes that all precipitation data are rain, and it ignores melting snow. Assuming a rainfall intensity, i, that is greater than the soil permeability will generate Hortonian flow, the percent of the area that is producing Hortonian flow, H, is

$$H = 1 - \Phi(i) \qquad (2)$$

Eq. (2) was used to determine the fraction of the area generating Hortonian flow for rainfall intensities with different return periods.

This analysis does not account for infiltration capacity changes with soil moisture or soil frost, and assumes that the published soil permeability is a good estimate of soil infiltration capacity. Consequently, we expect our results to overestimate the prevalence of Hortonian flow in the summer months when the soil tends to be dry and the infiltration capacity is high. Our analysis may also underpredict the frequency of Hortonian flow in the winter months when soil frost may reduce soil infiltration rates, especially on tilled fields (Post and Dreibelbis 1942; Bloomsberg and Wang 1969). Note also that because the Catskills region is primarily rural, the isolated areas where development has changed the soil infiltration characteristics were not addressed; e.g., asphalt parking lots.

Results and Discussion

Fig. 2 shows the monthly frequency analyses for Walton, N.Y.'s 15-min rain data. The highest intensities are in the summer, usually associated with short duration convection storms. September also has relatively high intensities, due to periodic hurricanes that travel inland. December and January typically have the lowest intensity rainfall. The spring and fall months have intermediate rainfall intensities.

Fig. 3 shows the distribution of soil permeability in the study area. Essentially all soils (99.7%) have permeabilities above 4 cm$\cdot$h^{-1}, and less than 10% have permeabilities above 7.5 cm$\cdot$h^{-1}. Eq. (1) fits the data well, with an R^2 of 0.999 and a standard error of 2%. The constants for α_1–α_3 were 0.85, 5.39, and 4, respectively.

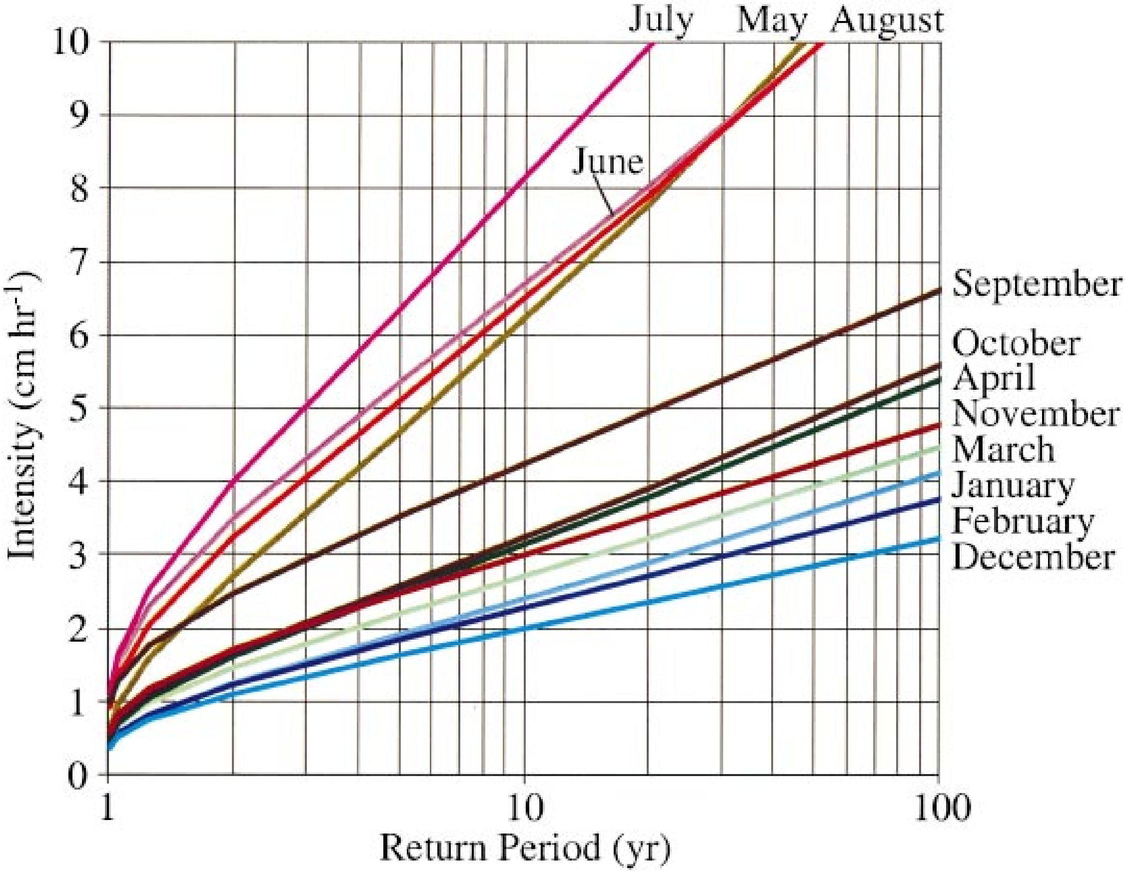

Fig. 2. (Color) 15-min rainfall frequency analysis for East Sidney. Each curve corresponds to month shown at right-hand end.

Fig. 4 shows the monthly probability of generating Hortonian flow. This analysis suggests that none of the watersheds will produce Hortonian flow for rainfall below the seasonal ~three-year intensity. The winter months, January, February, and December, do not produce Hortonian flow for any part of Delaware County for events less intense than the 100-year, 15-min storm. For May–August, there is a steep jump in the percent area generating Hortonian flow over a very narrow range of recurrence interval (Fig. 4). This jump reflects the "steplike" shape of the soil permeability distribution illustrated in Fig. 3. In fact, the probability of any given month generating Hortonian flow is essentially the return period for a 4 $\mathrm{cm \cdot h^{-1}}$ event. The summer months, June–September, have the highest prevalence of Hortonian flow, reflecting the high intensity storms that are more common during this period.

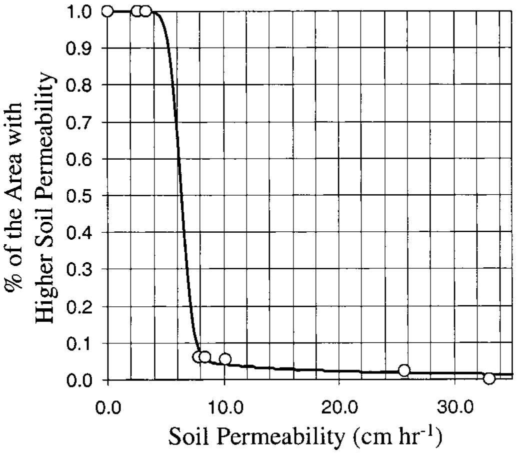

Fig. 3. Distribution of soil permeability in Delaware County. Symbols from GIS analysis of soil data and line is Eq. (1). Equation fits data with $R^2 = 0.999$ and standard error of 2%.

In the NYC watersheds, the concern is non-point-surface water pollution from manure-spread fields. While this analysis gives some insight into the likelihood of Hortonian flow, it does not address the likelihood of contamination due to pollutant transport via Hortonian flow. First, this analysis is based on 15-min rainfall intensity, which is not a sufficient duration for overland flow generated far from a stream to reach a stream. Also, we have not analyzed the correlation between runoff generating locations and probable pollutant loading areas. Finally, it is possible that heavy tillage associated with the region's cornfields changes the soil hydraulic behavior—though to what degree is unknown.

As stated in the Methods section, this analysis is based on a number of assumptions that make this analysis a worst-case scenario. In general, these results overpredict the frequency of Hortonian flow for months shown to have the highest probability for generating Hortonian flow—namely, May–September. These months will typically have the driest soil conditions and therefore the highest capacity for infiltration. The results for the winter months, for which this study shows to have a low likelihood of producing Hortonian flow, are based on the inherent assumption that most of the precipitation during this period falls as rain, which also leads to an overprediction of the Hortonian flow frequency. On the other hand, the spring months, March and April, may produce Hortonian flow more often than this study suggests

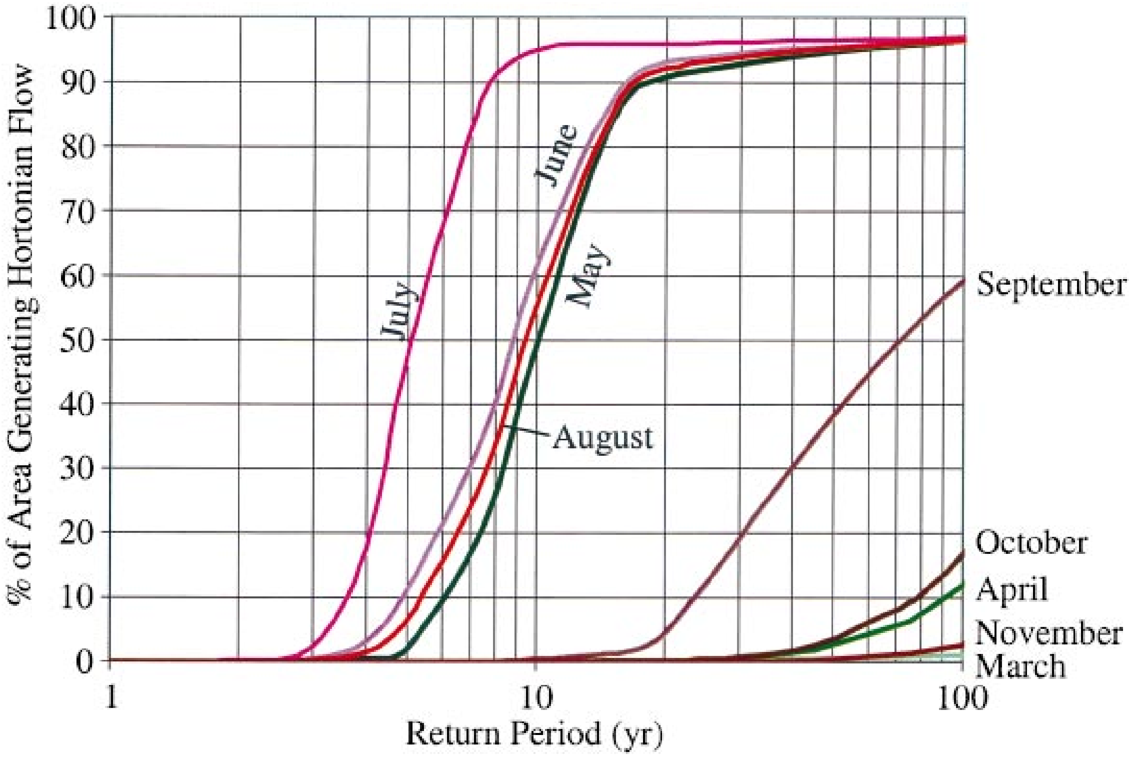

Fig. 4. (Color) Return periods for the percent of Delaware County, generating seasonal Hortonian flow. Return period for January, February, and December generating Hortonian flow is greater than 100 years.

due to additional water in the forms of snowmelt and soil frost. This study showed that March and April only produce Hortonian flow for rainfall intensities greater than their 30-year events, so the effects of our assumptions would have to be substantial for these months to generate substantial Hortonian flow. Overall, our assumptions have probably exaggerated the differences among the curves in Fig. 4; i.e., they are probably much more similar than Fig. 4 shows. In short, based on this simple analysis, Hortonian flow is uncommon for most of Delaware County, even for relatively short, high-intensity rain (i.e., 15-min events). The probability of Hortonian flow for longer duration rainfalls, i.e., lower average intensity rainfalls, will be even smaller.

One feature that we have not incorporated into this study is the role of preferential flow, especially via macropore flow. This phenomenon has been shown to substantially increase infiltration capacity (Childs et al. 1957) and the effective saturated hydraulic conductivity by as much as one to two orders of magnitude (Burger 1922). Including preferential flow behavior in our study would result in Hortonian flow being even less frequent than currently suggested.

Conclusion

This study presents a simple methodology for estimating the frequency of Hortonian flow for an area. Though the method involves some identifiable sources of uncertainty, the results nevertheless provide an initial indication of the importance of Hortonian flow over a region. The Catskills area of New York State, in which the NYC watersheds reside, appears to have a low frequency of Hortonian flow, which supports previous anecdotal evidence that saturation excess is the primary process involved in generating overland flow.

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