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Improving risk estimates of runoff producing areas: Formulating variable source areas as a bivariate process

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ABSTRACT

Predicting runoff producing areas and their corresponding risks of generating storm runoff is important for developing watershed management strategies to mitigate non-point source pollution. However, few methods for making these predictions have been proposed, especially operational approaches that would be useful in areas where variable source area (VSA) hydrology dominates storm runoff. The objective of this study is to develop a simple approach to estimate spatially-distributed risks of runoff production. By considering the development of overland flow as a bivariate process, we incorporated both rainfall and antecedent soil moisture conditions into a method for predicting VSAs based on the Natural Resource Conservation Service-Curve Number equation. We used base-flow immediately preceding storm events as an index of antecedent soil wetness status. Using nine sub-basins of the Upper Susquehanna River Basin, we demonstrated that our estimated runoff volumes and extent of VSAs agreed with observations. We further demonstrated a method for mapping these areas in a Geographic Information System using a Soil Topographic Index. The proposed methodology provides a new tool for watershed planners for quantifying runoff risks across watersheds, which can be used to target water quality protection strategies.

1. Introduction

Contamination of freshwater is a chronic problem world-wide that has serious, well-documented ecosystem and human health consequences. Nonpoint source (NPS) pollution from agriculture "is the leading source of water quality impacts on surveyed rivers and lakes, the second largest source of impairments to wetlands, and a major contributor to contamination of surveyed estuaries and ground water" (US EPA, 2005). More recently urban NPS pollution has also been noted as a major contributor to some water bodies. Specific pollutants noted in the *National Water Quality Inventory* reports to congress over the past two decades have included pathogens, nutrients, and sediments, all common in agricultural storm runoff, as well as metal which are common in urban runoff (US EPA, 2009). The fact that the water quality impacts of NPS pollution, especially from agriculture, have persisted for over half of a century suggests that we need more effective, possibly targeted strategies for mitigating this problem.

One for approach for controlling non-point source (NPS) pollution that has been suggested is to restrict or avoid polluting activities in areas where there is a high risk of generating storm flow (e.g., Walter et al., 2000, 2001; Gburek et al., 2002; Agnew et al., 2006; Walter et al., 2007); the term hydrologically sensitive area (HSA) is sometimes used to refer to areas with high risk of generating storm runoff. One challenge to adopting this strategy is easily and accurately predicting and mapping storm runoff risks over a watershed. This is difficult in regions like the northeastern U.S. because most storm runoff in the region is generated from relatively small but dynamic portions of the landscape, i.e., so-called variable [runoff] source areas (VSA) (e.g., Dunne and Black, 1970; Frankenberger et al., 1999; Fiorentino and Iacobellis, 2001). These VSAs are areas in a watershed susceptible to accumulating more water than the soil pore space can accommodate and, once the soil water holding capacity is exceeded, additional rain or snow melt becomes "saturation excess" storm runoff (Ward, 1984). Strictly

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speaking, soils do not always have to be saturated to the soil surface to generate storm runoff. Lyon et al. (2006), Lyon and Lembo (2006) and Dahlke et al. (2012a,b) observed rapid storm runoff in headwater watersheds in upstate, NY when the shallow water table was within 10 cm of the soil surface.

While practical engineering methods for predicting runoff volumes and rates and their associated risks have been developed and are widely accepted (McCuen, 2002; Michele and Salvadori, 2002; Mishra and Singh, 2006), there has been less attention paid to developing similar methods for predicting risks associated with specific locations where runoff is generated, such as VSAs. Typically engineers are interested in designing infrastructure that will withstand very large runoff volumes and rates. These types of events are associated with very intense rainfall that exceeds the infiltration capacity of the soil across most of the landscape (a runoff process attributed to Horton, 1933, 1940). Under these circumstances, it is common to assume runoff volume is related to simple metrics of land use and soil type, and the runoff rate depends on metrics related to watershed size and slope (e.g., USDA-NRCS, 1986). It is also common to assume that the storm runoff frequency, or return period, is equal to the frequency of the associated rainfall event. The most common approaches for estimating storm runoff volumes and rates, which incorporates these assumptions, use the Soil Conservation Service (SCS, currently the Natural Resources Conservation Service – NRCS) Curve Number (CN) method (e.g., USDA-SCS, 1972; USDA-NRCS, 1986).

When considering NPS pollution, engineers and managers are often interested in runoff events large enough to happen several times a year, not the events that only happen once a decade or more that are most often considered when designing stormwater infrastructure. In the northeastern USA, where this research is focused, Hortonian runoff is relatively uncommon (Walter et al., 2003) and methods are needed to predict the location and frequency of the more common VSAs. Indeed, there have been very few methods proposed to predict VSAs for water quality protection. The methods that have been proposed either require complicated, continuous watershed modelling (e.g., Agnew et al., 2006) or are overly simplistic, assuming that VSAs can be approximated with stream buffers and that the frequency of runoff generation is equal to the rainfall frequency (e.g., Gburek et al., 2002). The objective of this project was to develop a simple approach to estimate the fraction of runoff generating areas and the corresponding probability. We explore potential watershed characteristics that might be used to quantify VSAs in unguaged watersheds and we also propose a method for mapping the predicted runoff producing areas, i.e., VSAs based on the topographic wetness index concept (e.g., Beven and Kirkby, 1979; Walter et al., 2002).

2. Materials and methods

2.1. Quantifying VSA risk estimates

Over the past decade a few researchers have suggested that the SCS-CN method could be used to predict areas generating storm runoff for watershed planners and land managers (e.g., Gburek et al., 2002; Walter et al., 2009). The SCS-CN method was originally developed to predict storm runoff (USDA-SCS, 1972):

$$Q = \frac{P_e^2}{P_e + S} \tag{1}$$

where Q is the runoff volume over the watershed (mm), S is the maximum available soil storage (mm), and P_e is the effective precipitation (mm); P_e = total precipitation (P) minus initial abstraction (I_a); I_a is the minimum amount of rainfall that is necessary to initiate runoff. Although $I_a = 0.2S$ is a traditional assumption, recent research shows I_a varies for different study areas or events (Jiang, 2001; Shaw and Walter, 2009; Dahlke et al., 2012a). In our study, we set $I_a = aS$, in which a is constant for each basin and can be calibrated so that the least-squares differences between observed and predicted runoff is minimized. We chose this rainfall-runoff equation in part because of its persistent popularity largely attributed to its simplicity and reliance on readily available data (Ponce and Hawkins, 1996; Garen and Moore, 2005).

Although it is typical to determine S using tables that implicitly assume the runoff mechanism is Hortonian flow (Walter and Shaw, 2005), Steenhuis et al. (1995) showed that the SCS-CN equation can be interpreted as predicting saturation excess runoff from VSAs. Gburek et al. (2002) introduced a simple approach to estimating the amount of area producing runoff (A_p) based on the following equality:

$$Q(A_{ws}) = P_e(A_p) \tag{2}$$

where A_{ws} is the total watershed area. The VSA-fraction of a watershed that is generating runoff ($A_f = A_p/A_{ws}$), i.e., "saturated" areas, can be calculated as (Gburek et al., 2002; Walter et al., 2009):

$$A_f = \frac{Q}{P_e} \tag{3}$$

Q/P_e is also referred to as the runoff coefficient (Merz and Blöschl, 2009). Substituting Eq. (1) into Eq. (3) gives:

$$A_f = \frac{P_e}{P_e + S} \tag{4}$$

One implicit problem in the way the SCS-CN method is used is that the runoff exceedence probability or return period is assumed to be the same as that of causative storm events. This is generally not the case (Shaw and Riha, 2011) and almost definitely not true for areas where the process of runoff production is governed by VSA hydrology (Walter et al., 2009). Besides precipitation, antecedent soil moisture conditions also influence runoff generation, often in complex ways (Macrae et al., 2010; Merz and Blöschl, 2009). Because it is derived from the traditional SCS-CN method, Eq. (4) faces the same challenge, i.e., the risk that a given fraction of a watershed will generate runoff needs to be linked to both the precipitation amount and antecedent wetness conditions.

Shaw and Walter (2009) addressed this issue with respect to runoff risk by using a bivariate approach to the SCS-CN method (Eq. (1)). Based on work by Troch et al. (1993), they accounted for antecedent wetness conditions by linking antecedent soil storage volume, which influences S in Eq. (1), to base-flow (Q_{base}) immediately preceding the storm event. The same approach can be applied to estimate risks associated with the fraction of a watershed generating runoff (A_f):

$$\Pr\left(A_f = A_{f_i}\right) = \sum_{M(A_{fi})} \Pr(P_e = P_{e_i}) \times \Pr(S = S_i) \tag{5}$$

where $M(A_{fi}) \in \{(P_{ei}, S_i) | h(P_{ei}, S_i) = A_{fi}\}$, h is determined from Eq. (4), and $\Pr(S = S_i)$ is a function of $\Pr(Q_{base} = Q_{base,i})$; note, we assume the occurrence of P_e and S are independent over short time spans. Descriptively, this function calculates the probability of a given A_f by summing the joint probabilities of all pairs of P_e and S that result in the A_f value of interest.

Researchers have yet to link identifiable watershed characteristics to S in the context of VSA hydrology; recall, in the context of Hortonian storm runoff engineers typically assume S is related to land use and soil type. So, following Shaw and Walter (2009), antecedent