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THE IMPACT OF RUNOFF GENERATION MECHANISMS ON THE LOCATION OF CRITICAL SOURCE AREAS[1]

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ABSTRACT: Identifying phosphorus (P) source areas and transport pathways is a key step in decreasing P loading to natural water systems. This study compared the effects of two modeled runoff generation processes – saturation excess and infiltration excess – on total phosphorus (TP) and soluble reactive phosphorus (SRP) concentrations in 10 catchment streams of a Catskill mountain watershed in southeastern New York. The spatial distribution of runoff from forested land and agricultural land was generated for both runoff processes; results of both distributions were consistent with Soil Conservation Service-Curve Number (SCS-CN) theory. These spatial runoff distributions were then used to simulate stream concentrations of TP and SRP through a simple equation derived from an observed relation between P concentration and land use; empirical results indicate that TP and SRP concentrations increased with increasing percentage of agricultural land. Simulated TP and SRP stream concentrations predicted for the 10 catchments were strongly affected by the assumed runoff mechanism. The modeled TP and SRP concentrations produced by saturation excess distribution averaged 31 percent higher and 42 percent higher, respectively, than those produced by the infiltration excess distribution. Misrepresenting the primary runoff mechanism could not only produce erroneous concentrations, it could fail to correctly locate critical source areas for implementation of best management practices. Thus, identification of the primary runoff mechanism is critical in selection of appropriate models in the mitigation of nonpoint source pollution. Correct representation of runoff processes is also critical in the future development of biogeochemical transport models, especially those that address nutrient fluxes.
(KEY TERMS: nonpoint source pollution; land use/land cover; runoff modeling; watershed management; TMDL; phosphorus.)

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INTRODUCTION

The failure of more than 25 percent of the nation's monitored rivers and lakes to meet federal Clean Water Act drinking water standards is largely due to nonpoint source (NPS) contamination related to land use (USEPA, 1998a). Many researchers have studied the effects of land use on stream water quality in attempts to facilitate management of NPS pollution by several constituents (Hirose and Kuramoto, 1981; Correll *et al.,* 1992; Brenner and Mondock, 1995; Haan, 1995; Jordon *et al.,* 1997; McFarland and Hauck, 1999). One of the most commonly studied pollutants that lead to impairment of natural water systems in the United States is phosphorus (P), which is of particular concern because it promotes freshwater eutrophication. Agriculture is considered to be a major source of P in streams (USEPA, 1995). Historically, watershed managers have focused on controlling the application rates of manure and fertilizers and the locations and timing of these P applications. For example, the Total Maximum Daily Load (TMDL) program, which is addressing NPS pollutant loading to water bodies within the United States (USEPA, 1998b; National Research Council, 2001; Bosch,

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2003a,b), investigates the feasibility of implementing various best management practices (BMPs) and assesses their impact on pollutant loading. Best management practices have been developed to decrease P transport from agricultural land to fresh water bodies; however, locating areas in which BMPs will be most effective can be difficult.

The sources and transport mechanisms of P are major determinants of P concentrations in surface water and shallow subsurface water. Phosphorus sources have traditionally been the focus of BMP research, but P-transport processes have gained increasing attention in recent years and new transport models are being formulated (Walter *et al.,* 2000; Seibert *et al.,* 2003). Transport processes at the watershed scale (less than 100 km^2) can involve numerous, often complex hydrologic pathways, and studies to characterize these pathways are expensive and time consuming (Osborne and Wiley, 1988). Therefore, modelers have recently begun to focus on the interactions between runoff generation and P transport through simple techniques without compromising predictive power. McDowell and Sharpley (2002) used a series of experiments to demonstrate the role of manure location and runoff generation process in the transport of P. Their results support the concept of critical source areas (CSA) as an objective method to locate BMP implementation (Pionke *et al.,* 1997; Walter *et al.,* 2000,2001; Gburek *et al.,* 2002). Critical source areas are regions where high nutrient loading coincides with high propensity to produce runoff. Areas of high nutrient loading are generally much easier to identify than areas of high runoff generation. A major difficulty in delineating areas of high runoff in a watershed is identifying the dominant runoff generation mechanism.

The two prevailing theories describing mechanisms of runoff (overland flow) generation are infiltration excess, or Hortonian overland flow, and saturation excess. Infiltration excess is based on the concept that runoff begins when rainfall rates exceed soil infiltration capacities (Horton 1933, 1940) assuming runoff amounts are directly controlled by factors that determine soil infiltration rate, such as land use and soil type. Hortonian overland flow is important in many parts of the United States, such as arid regions, where soil crusting and/or surface sealing occurs during rainstorms, and also in urban areas, where impervious surfaces cause surface runoff; it also occurs in extremely heavy intensity storms in nearly all regions. Therefore, a water quality management perspective based on the infiltration excess concept will identify CSAs solely on the basis of land use and, possibly, soil type. The second concept of runoff generation, the saturation excess theory, assumes that runoff is generated by direct precipitation on, or exfiltration from, saturated areas in the landscape (Dunne and Black, 1970), and that once the soils in these areas become saturated to the surface, all additional rain that falls (regardless of intensity) becomes overland flow. The extent of these saturated areas can vary with season and from storm to storm; thus, the saturation excess theory has been extended to encompass variable source area (VSA) hydrology, attributed primarily to Dunne and Black (1970) and Hewlett and Hibbert (1967). The dynamic nature of VSAs further complicates CSA identification. Accurate CSA delineation for modeling and regulating NPS pollution requires correct identification of the runoff generating mechanism (Maas *et al.,* 1987; Endreny and Wood, 1999).

The most common approach to predicting runoff in agricultural water quality models, such as SWAT (Arnold *et al.,* 1993), AGNPS (Young *et al.,* 1989), CREAMS (USDA, 1980), and GWLF (Haith and Shoemaker, 1987), is through the Soil Conservation Service Curve Number (SCS-CN) (USDA-SCS, 1972) method. The SCS-CN method is theoretically consistent with the infiltration excess theory (e.g., Hjelmfelt, 1980) as well as the saturation excess theory (e.g., Steenhuis *et al.,* 1995), but is most commonly used in a way that implicitly assumes infiltration excess as the primary runoff mechanism by using land use and soil class to assign runoff potential. In contrast, methods that assume saturation excess theory use landscape and topographical factors rarely used in the SCS-CN method as indicators of runoff potential. Thus, topography driven models, such as the popular TOPMODEL (e.g., Beven and Kirkby, 1979) and similar models (e.g., Beven and Wood, 1983; O'Loughlin, 1986; Sivapalan *et al.,* 1987; Famiglietti and Wood, 1994; Endreny and Wood, 1999) can be used to identify runoff source areas in watersheds where the saturation excess process dominates runoff generation. These models assume, however, that the watershed is underlain by a permanent water table that controls the VSAs – an assumption that is not realistic for the mountainous regions of the northeastern USA where shallow transient interflow controls VSAs (Walter *et al.,* 2002).

Models based on either the infiltration-excess or the saturation-excess theory can be calibrated to correctly simulate flow at the watershed outlet at a wide range of temporal scales, regardless of the true runoff generation process. To date, because of their intrinsic simplicity, runoff models that use the SCS-CN method in a manner consistent with infiltration excess theory have been the choice of land managers and regulatory agencies to predict runoff generation. These models may not be representative of the true runoff generation processes that occur at the watershed scale and may therefore incorrectly predict the locations where the runoff is generated. Accurate characterization of runoff generation is essential in biogeochemical models to correctly estimate flow and nutrient flux; it also is vital in identifying CSAs in which BMPs would be most effective in achieving the goals of the TMDL program. The widespread commitment to models based on the SCS-CN method creates an urgent need to incorporate saturation excess theory for use in watersheds where saturation excess hydrology dominates.

In 2000, a two-year stream sampling program was begun by the United States Geological Survey (USGS) in cooperation with Cornell University to investigate the relations between P concentrations in streams and principal land use in adjacent areas. Data from this sampling program were used in examining the effect of the two runoff generation methods on simulating stream P concentrations for a watershed in the Catskill Mountains of southwestern New York (Figure 1). Stream P concentrations calculated from models based on infiltration excess runoff were compared with those calculated from saturation excess runoff scenarios. The differences resulting from the two

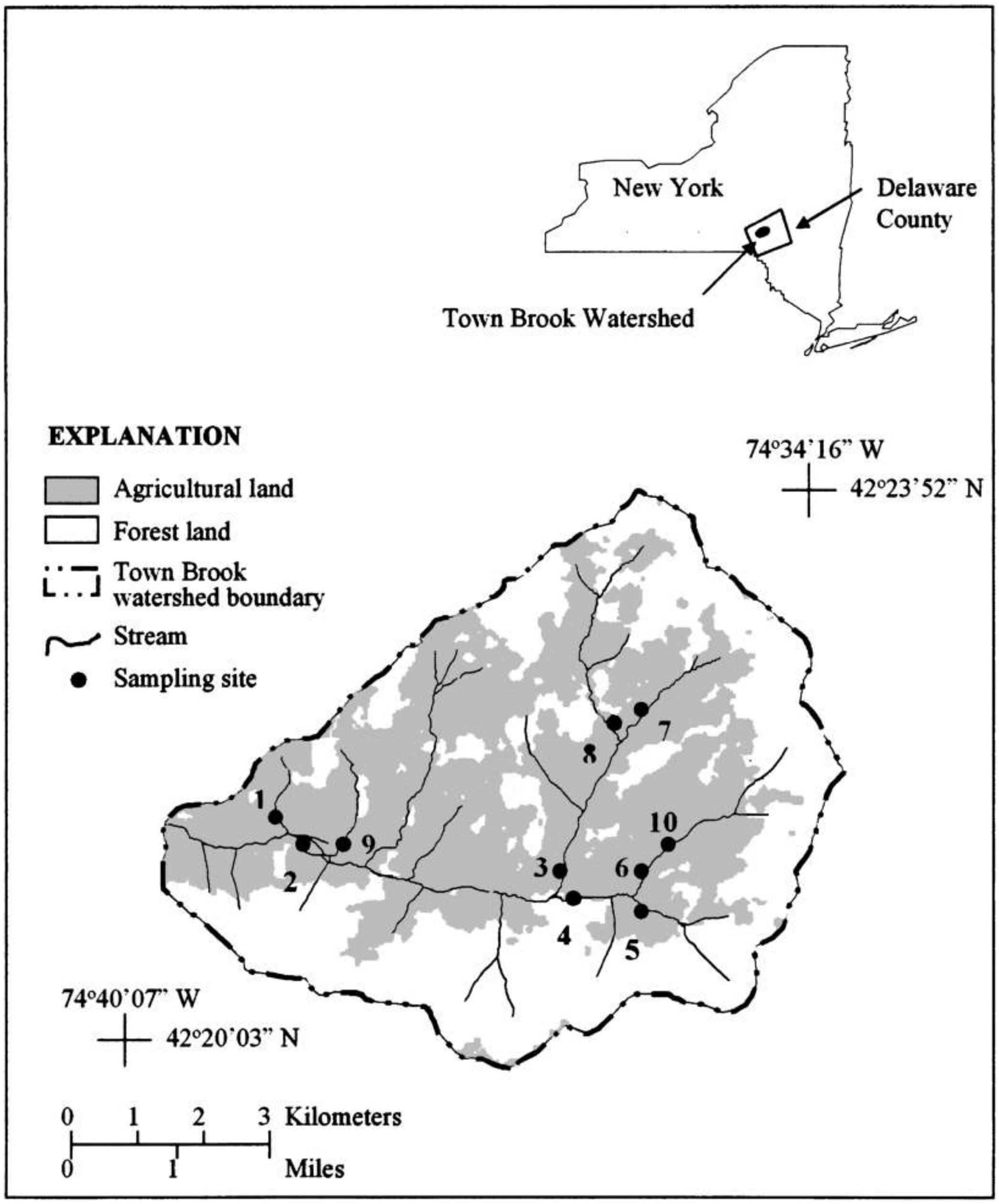

Figure 1. Location of the 10 Sampling Sites and of Forested and Agricultural Land in the Town Brook Watershed in Southeastern New York State (Land Use Base Map, D. Lounsbury, New York City Department of Environmental Protection, personal communication, January 2002).

methods indicate the importance of selecting the appropriate runoff mechanism for modeling the stream P concentrations and locating CSAs for implementation BMPs.

STUDY AREA AND METHODS

This study was conducted in the Town Brook watershed (latitude 42°21´N, longitude 74°39´W), a 37 km^2 watershed in the headwaters of the Cannonsville Reservoir basin in Delaware County, New York. The Cannonsville Reservoir is part of the New York City reservoir system. The Town Brook watershed ranges in elevation from 493 to 989 m above mean sea level and slopes from 0 to 43 degrees. Land use was obtained from Thematic Mapper imagery from 1999 (D. Lounsbury, New York City Department of Environmental Protection, personal communication, January 2002) and consists mainly of dairy farming with pasture and rotated corn and hay cropping, the watershed also contains forested areas and small amounts of impervious area. For this study, land was classified either forest or agricultural to create binary land cover for the 10 catchments that constitute the study area (Figure 1). The forest category consisted of deciduous and coniferous; the agricultural category encompassed cropland and pasture. Impervious and semi-pervious areas were neglected because they represented only about 0.5 percent of total land area and minimal runoff. Table 1 gives the area for each of the catchments in the study and the percentage of the total watershed the catchment covers. The catchments ranged in size from the largest (No. 2) at 33.9 km^2, covering 91.6 percent of the watershed, to the smallest (No. 1) at 0.6 km^2, covering 1.5 percent of the watershed.

Soils in the study area are typical of the Catskill region and consist primarily of shallow, well-structured loams on the hilltops and upper slopes, and deeper silt loams on the lower slopes (Frankenberger *et al.,* 1999). The predominant soils are Lewbeach and Halcott loams and Willowemoc and Onteora silt loams for the upper and lower slopes, respectively. The region is underlain by relatively impervious fragipan in upland regions and by fractured, well drained sedimentary bedrock in lower regions. Weather data, May 1996 to April 2001, were obtained from the National Oceanic and Atmospheric Administration weather station in Stamford, New York, about 1 km north of the study area's northern boundary (NCDC, 2002).

Sampling and P End Members

The 10 catchments that were selected for the study provide a land use distribution that was representative of the Catskill region. The percentages of forested and agricultural land in each catchment are given in Table 1. Stream water samples were collected monthly at the outlet of each catchment (Figure 1) with a combination of automated samplers and manual grab samples monthly from January 2000 through

TABLE 1. Catchment Areas and Percentage of Agricultural and Forested Land, Percentage of Contribution to Total Runoff for Each Land Use as Predicted by Saturation Excess and Infiltration Excess Methods, and Flow Weighted Concentrations of Total Phosphorus (TP) and Soluble Reactive Phosphorus (SRP) Over the Entire Two-Year Sampling Period, in Each of the 10 Catchments Studies in the Catskill Mountain Region of Southeastern New York.

Catchment	Area (km^2)	Percentage of Total Area	Percentage of Catchment by Forest or Agricultural Land		Percentage of Total Runoff Generation by Method: Saturation Excess		Infiltration Excess		Flow Weighted Concentration in Stream (mg/l)	
			Forest	Agriculture	Forest	Agriculture	Forest	Agriculture	TP	SRP
1	0.6	1.5	48.5	51.5	36.7	63.3	56.8	43.2	0.081	0.017
2	33.9	91.6	20.9	79.1	6.0	94.0	21.6	78.4	0.163	0.040
3	11.3	30.4	50.7	49.3	32.2	67.8	57.1	42.9	0.104	0.019
4	8.6	23.4	47.5	52.5	24.7	75.3	55.9	44.1	0.168	0.031
5	2.5	6.8	60.6	39.4	47.9	52.1	67.7	32.3	0.109	0.028
6	4.2	11.3	79.9	20.1	60.4	39.6	85.4	14.6	0.087	0.018
7	3.3	9.0	46.0	54.0	34.6	65.4	53.8	46.2	0.128	0.019
8	4.3	11.6	56.4	43.6	20.8	79.2	65.9	34.1	0.086	0.009
9	1.2	3.1	58.9	41.1	33.9	66.1	68.1	31.9	0.087	0.013
10	3.9	10.5	29.7	70.3	24.4	75.6	28.3	71.7	0.139	0.025

December 2001. Samples were analyzed for TP through Kjeldahl digestion and colorimetry using USEPA Method 365.4 (USEPA, 1983) and for SRP through spectophotometry using USEPA Method 365.3 (USEPA, 1983). The minimum detection levels for the TP and SRP analysis were 0.01 mg/l and 0.005 mg/l, respectively. Values below detection limits were not included in the analysis. The measured monthly concentrations were then weighted by observed monthly flows at the Town Brook watershed outlet to obtain average concentrations from each the 10 catchments for the two-year sampling period. The relation between land use and stream TP and SRP concentrations is plotted in Figures 2A and 2B, respectively. The final concentrations (end members) were obtained through a linear fit to the data (Figure 2). In this analysis, “end member” refers to the stream concentration expected from the hypothetical situation where the land use is homogeneously forest or agriculture.

Modeling Runoff Generation

The two methods that were used to evaluate the landscape’s propensity to generate runoff were a saturation-excess method and an infiltration excess method, both based on the SCS-CN method to predict runoff amounts, to represent the extremes in hydrologic theory. The method of Lyon *et al.* (2004) was applied to create a runoff generation map consistent with saturation excess theory for the summer storms of the available weather data period (1996 to 2001). This method, termed distributed curve number variable source area (CN-VSA) method, uses a derivation of the SCS-CN equation consistent with saturation excess theory to predict runoff amount, and a topographical index to distribute runoff generation predictions. The traditional SCS-CN method (USDA-SCS, 1972) was also applied to the Town Brook watershed data over the same period for an infiltration excess runoff generation method. The traditional SCS-CN method uses CNs based on land use and soil characteristics that have been calibrated to outflow from the watershed to distribute runoff generation predictions. The CNs used in this study ranged from 30 to 87 with area averaged values of 72.5 and 67.4 for forested and agricultural lands, respectively. Maps of distributed runoff generation were developed in a geographic information system (GIS) environment from the runoff models then normalized by their maximum annual runoff depth. These maps were then divided into catchments contributing to each sampling location with the Hydro Data Model extension for ArcGIS v8.2™ (ESRI, 1999) in addition to a 10 m Digital

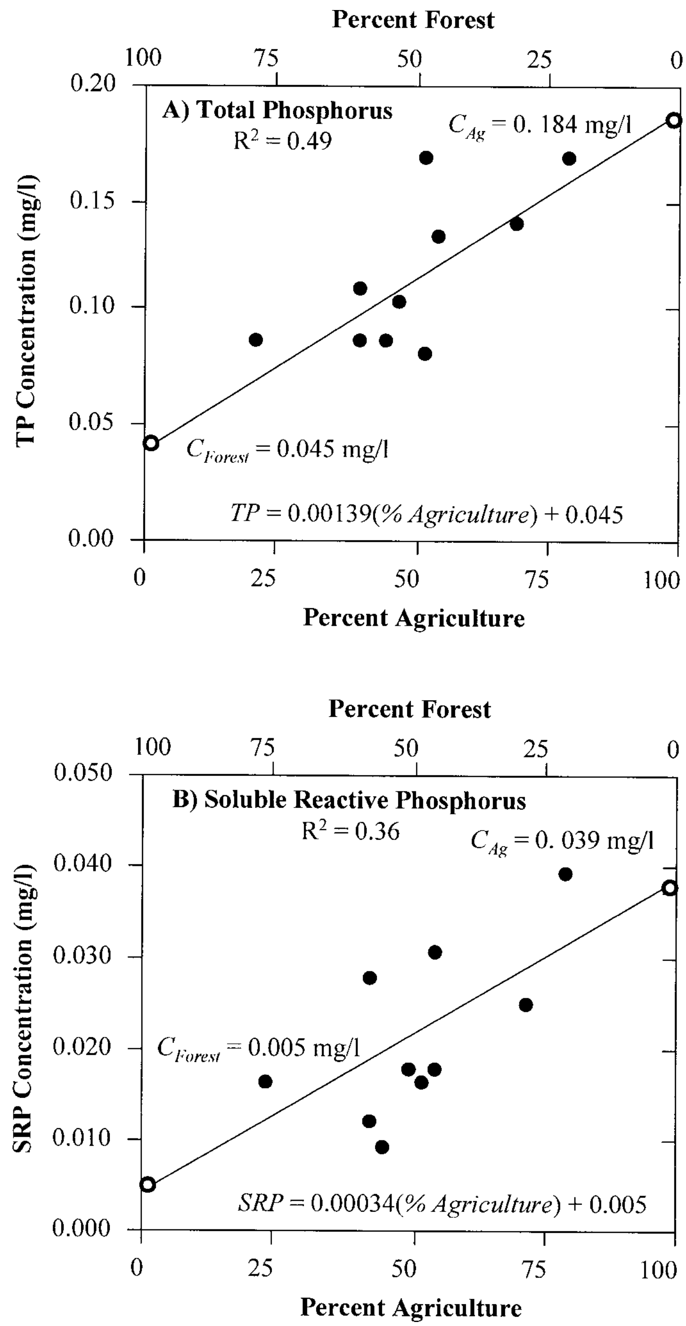

Figure 2. Stream P Concentrations as a Function of the Amount of Forested and Agricultural Land in all 10 Catchments of Town Brook Watershed for (A) TP and (B) SRP (open symbols indicate end members).

Elevation Model (DEM) (USGS, 2001). Land use maps were overlaid on the runoff maps to partition runoff by land use classification (agriculture or forest). Hypothetical stream P concentrations were simulated as

$$C_s = Q_{Ag} C_{Ag} + Q_{Forest} C_{Forest} \tag{1}$$

where C_s is the stream P concentration as (mg/l), Q is the contribution to total runoff (in percentage), C is the P end-member concentration as (mg/l) estimated from Figure 2, and the subscripts *Ag* and *Forest* refer to agricultural and forested land, respectively.

RESULTS

The cumulative runoff volume (13,300 liters) for the simulation period – the growing seasons from April 1996 through April 2001 – predicted by distributed CN-VSA method was similar to that of the traditional SCS-CN method (13,200 liters). The small difference (0.8 percent) between the two results reflects the ability to consistently calibrate models using the SCS-CN method, whether infiltration excess or saturation excess is assumed as the dominant runoff process. The discrepancy between the two results is clear when the propensity to contribute runoff is plotted on maps (Figure 3A and 3B); the percent contribution to total runoff from forested land differed from the contribution of agricultural land (Table 1). Saturation excess theory, applied in the distributed CN-VSA method, predicts that most runoff is coming from regions near the stream. These are locations with large upslope areas, converging topography, and shallow soils. These locations also correspond mainly to agricultural land; therefore, saturation excess theory predicts more contribution from agricultural land. Infiltration excess theory, applied in the traditional SCS-CN method, predicts forest land to contribute more to the total runoff. This is due to larger areas of forest land creating more of the total runoff for each catchment. The differences in these methods could adversely affect land management decisions, such as where to locate BMP implementation.

The relation between P concentration and land use (Figure 2) indicates that the concentration of TP and SRP in stream water increased with increasing percentage of agricultural land (TP: $R^2 = 0.49$; SRP: $R^2 = 0.36$). End member concentrations were calculated for each sampling site from Equation (1) with the end-member concentrations from Figure 2, and the contribution to total runoff per land use for each runoff mechanism given in Table 1. The resulting stream TP and SRP concentrations calculated by the saturation-excess method averaged 31 percent and 42 percent higher, respectively, than those calculated by the infiltration excess method (Figure 4). The saturation excess theory implies that agricultural land produces more runoff than forested land because of its topographic locations and because it is closer to the stream. Given the increasing linear relation between P concentration and land use, predictions through saturation excess theory yield higher predicted P stream concentrations.

Figure 5 shows the predicted TP and SRP concentrations compared to the measured stream concentrations based on saturation excess method (closed circles) and infiltration excess method (open circles). For both TP and SRP, the saturated excess method and the infiltration excess method predict slightly above measured concentrations at low concentrations and slightly below measured concentrations at higher concentrations. The predicted results from the infiltration excess method have slightly higher R^2 values, while the results from the saturation excess method have slightly lower relative difference (i.e., the ratio of standard to the mean observed value). The disagreement between modeled and predicted results demonstrates the complex nature of nutrient transport in natural systems. Regardless, these runoff models give reasonable predictions of P concentrations while remaining simple. Predictions from both methods cluster around the 1:1 line and would be reasonable without further knowledge of the mechanism occurring in the watershed. Both methods can be calibrated to represent P concentrations in the stream. The true difference between the methods is where the runoff is generated. The dominant runoff generating mechanism must be identified, however, before CSAs can be located or BMPs implemented to effectively lower P concentrations.

DISCUSSION

Many researchers have reported the accumulation of interflow water in the form of increased soil moisture at the hill bottoms relative to the steep parts of the hills in the Catskill Mountain region during wet periods (Frankenberger *et al.,* 1999; Ogden and Watts 2000; Mehta *et al.,* 2004). Some observed locations where saturation commonly occurs are those where the soil above the low conductivity layer is shallow; the slope decreases downhill, such as the toe slope of a hill; or the topography converges. These observations suggest that saturation excess is the dominant runoff process in this region and that models based on this method provide more representative results than those based on infiltration excess. It has been shown, however, that for extremely large rain events, both infiltration excess and saturation excess runoff processes may be possible (Srinivasan *et al.,* 2002). Most likely, the runoff mechanisms presented in this study represent the extremes of a continuum existing in nature. Walter *et al.* (2004) demonstrated that infiltration excess runoff is only likely to occur when

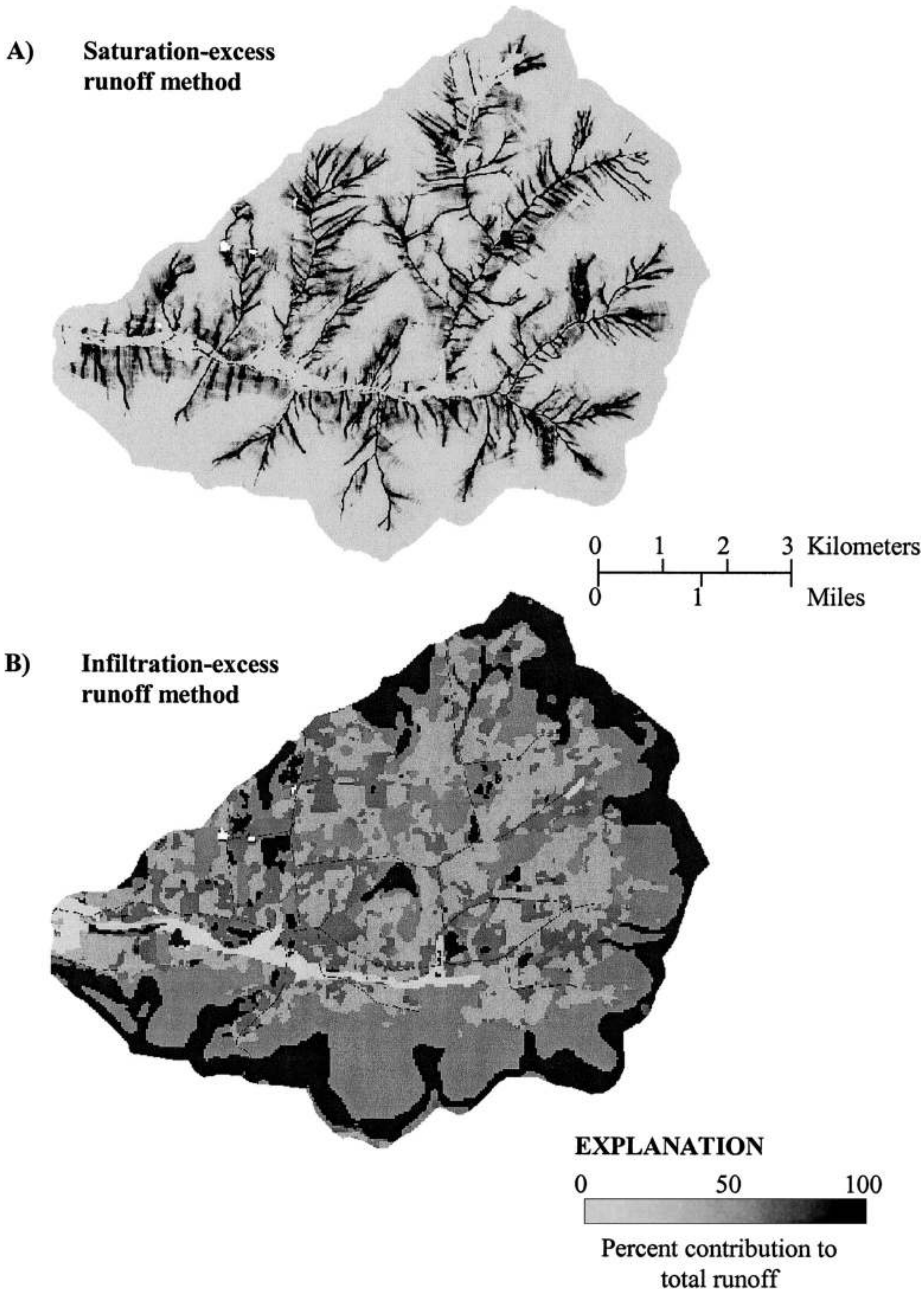

Figure 3. Normalized Percent Contribution to Total Runoff for Town Brook Watershed Over the Simulation Period as Predicted by the Two Runoff Processes: (A) Saturation Excess Runoff Method and (B) Infiltration Excess Runoff Method.

15-minute rainfall intensities exceed three-year return periods for watersheds in this region. Thus, the occurrence of infiltration excess runoff is possible in the watershed but only in relatively small amounts and is not likely the dominant process. For CSA identification and TMDL assessment, infiltration excess runoff theory would lead to the implementation of BMPs in locations that do not contain the expected runoff mechanisms in the majority of rainfall events and, thus, may have little effect on water quality. It has been demonstrated how, by including VSA concepts in BMP implementation, cost effective management scenarios can be accomplished when the proper runoff mechanism is included (Walter *et al.,* 2000; Qiu, 2004).

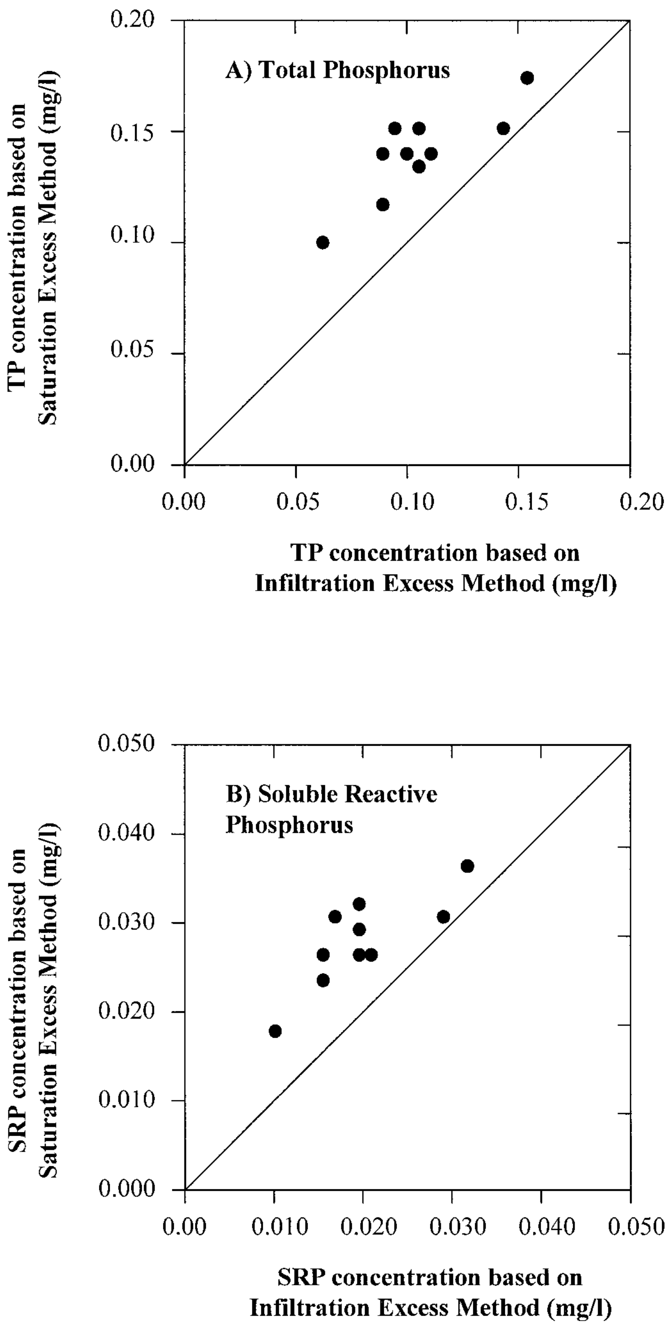

Figure 4. Phosphorus Concentrations in the 10 Town Brook Catchments Predicted by the Saturation Excess Method in Relation to P Concentrations by the Infiltration Excess Method for: (A) TP and (B) SRP.

Hypothetical CSAs identified by the saturation excess method and the infiltration excess method are depicted in Figures 6A and 6B to demonstrate how differences in spatial distribution of contribution of runoff affect BMP implementation. This figure is based on the assumption that regions contributing more than 12.5 percent of the annual maximum

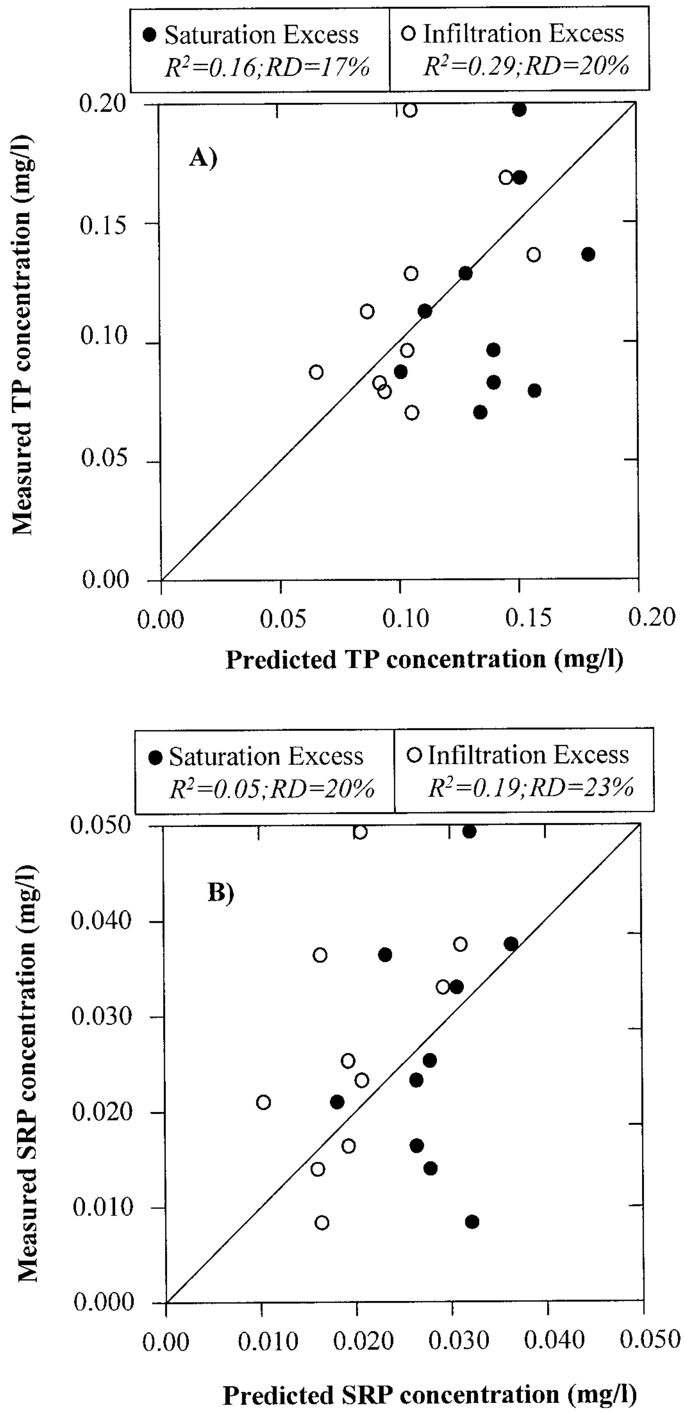

Figure 5. Phosphorus Concentrations in the 10 Town Brook Catchments Predicted by the Saturation Excess Method (closed circles) and the Infiltration Excess Method (open circles) in Relation to Measured P Concentrations for: (A) TP and (B) SRP. The R2 and relative difference (RD) are shown with RD expressing the ratio of standard error to mean observed value.

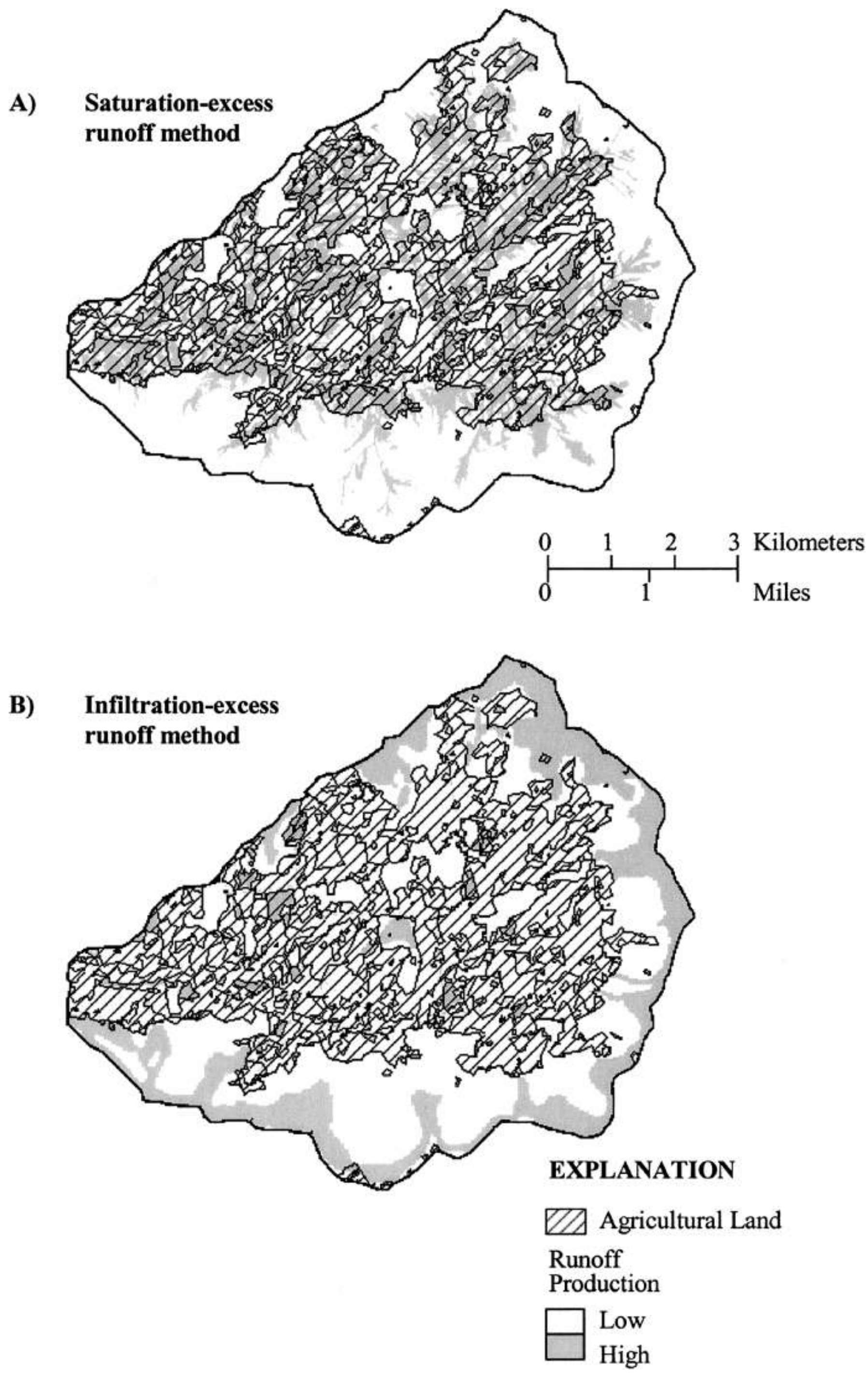

Figure 6. Locations of Critical Source Areas Based on the Intersection of Areas Contributing More Than 12.5 Percent of the Annual Maximum Runoff Depth for a Given Runoff Method and Agricultural Land Use for Town Brook Watershed as Predicted by the Two Runoff Processes: (A) Saturation Excess Runoff Method and (B) Infiltration Excess Runoff Method.

runoff depth for a given method have a high propensity to produce runoff and that agricultural lands provide large nutrient loadings. Therefore, overlaying regions of high propensity to produce runoff and large nutrient loadings represents CSAs. Visual inspection indicates that BMP implementation and management decisions based on infiltration excess theory would probably do little to decrease stream P concentrations because the focus would be on upslope regions, which are dominated primarily by forest. For example, stream buffer zones placed in the CSAs based on infiltration excess theory would only affect the headwaters of streams and would not coincide with agricultural lands. If BMP selection was based on saturation excess theory, however, efforts to protect water quality would be focused on near stream areas containing agricultural land. Using saturation excess theory, the stream buffer zones could be located on agricultural land to reduce manure spreading near streams and transport from agricultural land to streams. This is important for developing TMDLs across the United States, which uses land use and management changes as a tool to improve water quality, but is based heavily on runoff modeling (Bosch *et al.,* 2004). These two runoff methods identify vastly different CSAs, although they predict similar total runoff; this demonstrates that calibration of a hydrologic model to streamflow is only the first step in selecting an appropriate model.

Identification of CSAs with hydrological models requires knowledge of the runoff processes occurring within the watershed. Methods are available to determine dominant runoff mechanisms before model selection. Field observations made during runoff generating events are crucial to locating areas where water runs off. Srinivasan *et al.* (2002) were able to use a network of water level loggers and runoff detectors to determine saturation excess and infiltration excess generated runoff. Knowledge of historical weather data and watershed characteristics also aids in defining runoff processes. By comparing long term rainfall intensities and watershed characteristics, Walter *et al.* (2004) were able to estimate dominant hydrological processes generating runoff for the New York City watersheds. Remote sensing has also been used to identify runoff processes, usually through VSA identification, at the watershed scale (Verhoest *et al.,* 1998; Guntenspergen *et al.,* 2002; Toyra *et al.,* 2002). These are just some methods currently being used to determine runoff processes. Regardless of how the process is determined, the most important aspect of runoff model selection is knowledge of what runoff process is actually occurring and matching the appropriate model. Identifying the actual runoff process is especially important as the next generation of biogeochemical transport models evolve from the current suite of hydrological models. Future models will need to be consistent with prevailing hydrological theories on where and how runoff is generated in the quantification of CSAs for locating areas in which BMPs will be most effective.

CONCLUSION

A thorough and accurate understanding of hydrologic mechanisms in a watershed is essential for reliable prediction of stream water quality and, thus, effective land use management to protect water quality. Results from the 10 study sites indicate a positive correlation between TP and SRP concentrations and the amount of agricultural land use, as do similar studies of P concentration in relation to land use. Two runoff generation mechanisms (infiltration excess and saturation excess) were modeled, and resulting TP and SRP concentrations compared. The estimations of stream TP and SRP concentration were directly influenced by the spatial position of runoff source areas. These two mechanisms differ in their spatial distributions of runoff generation; therefore, sharply differing nutrient management scenarios could result depending on which runoff model was selected. Given that funds available to watershed managers tend to be limited, the correct runoff generation mechanisms need to be identified to ensure optimal placement and implementation of BMPs to protect water quality.

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