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Using a topographic index to distribute variable source area runoff predicted with the SCS curve-number equation

Steve W. Lyon, M. Todd Walter, Pierre Gérard-Marchant and Tammo S. Steenhuis*
Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA

Abstract:

Because the traditional Soil Conservation Service curve-number (SCS-CN) approach continues to be used ubiquitously in water quality models, new application methods are needed that are consistent with variable source area (VSA) hydrological processes in the landscape. We developed and tested a distributed approach for applying the traditional SCS-CN equation to watersheds where VSA hydrology is a dominant process. Predicting the location of source areas is important for watershed planning because restricting potentially polluting activities from runoff source areas is fundamental to controlling non-point-source pollution. The method presented here used the traditional SCS-CN approach to predict runoff volume and spatial extent of saturated areas and a topographic index, like that used in TOPMODEL, to distribute runoff source areas through watersheds. The resulting distributed CN–VSA method was applied to two subwatersheds of the Delaware basin in the Catskill Mountains region of New York State and one watershed in south-eastern Australia to produce runoff-probability maps. Observed saturated area locations in the watersheds agreed with the distributed CN–VSA method. Results showed good agreement with those obtained from the previously validated soil moisture routing (SMR) model. When compared with the traditional SCS-CN method, the distributed CN–VSA method predicted a similar total volume of runoff, but vastly different locations of runoff generation. Thus, the distributed CN–VSA approach provides a physically based method that is simple enough to be incorporated into water quality models, and other tools that currently use the traditional SCS–CN method, while still adhering to the principles of VSA hydrology. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS variable source area hydrology; curve number; topographic index; runoff prediction

INTRODUCTION

In humid, well-vegetated areas, such as in the north-eastern USA, most runoff is generated by saturation excess, i.e. via direct precipitation on or exfiltration from saturated areas in the landscape (Ward, 1984). This often occurs near stream channels. As these saturated, runoff source areas vary in size seasonally and during individual storm events, they are often referred to as variable source areas (VSA) or as hydrologically active areas (Dunne and Black, 1970; Frankenberger *et al*., 1999). Few methods can be used to predict saturated-excess areas in a watershed while remaining relatively simple. Boughton's (1987, 1990) method can be cumbersome. The soil moisture routing (SMR) model, a physically based, fully distributed, geographical information system (GIS) integrated code specifically designed for north-eastern USA soils, gives good, representative results (Frankenberger *et al*., 1999; Johnson *et al*., 2003; Mehta *et al*., in press) and has been used in water quality modelling (Kuo *et al*., 1996; Zollweg *et al*., 1996; Walter *et al*., 2001), but it has long computer run-times and may be too complicated for the needs of watershed managers. TOPMODEL and similar models (Beven and Kirkby, 1979; O'Loughlin, 1986) are simple enough, but the models assume that the watershed is underlain by a groundwater table that is not realistic for the north-eastern USA and many

* Correspondence to: Tammo S. Steenhuis, Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA. E-mail: tss1@cornell.edu

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other mountainous areas. The popular 'curve number' method, a much simpler method than either the SMR model or TOPMODEL, was developed in the 1950s and 1960s by the U.S. Department of Agriculture–Soil Conservation Service (USDA–SCS) (USDA–SCS, 1972), now the Natural Resource Conservation Service (NRCS), and is commonly used in water quality models.

The traditional Soil Conservation Service curve-number (SCS-CN) method is a rainfall–runoff model that originally was developed for predicting flood-flow volumes from ungauged watersheds for hydraulic engineering design (Rallison, 1980). Despite this limited scope of intended application and several problems identified with the traditional SCS-CN method (e.g. Freebairn *et al*., 1989; Ritter and Gardner, 1991) it is used ubiquitously in water quality models such as SWAT (Arnold *et al*., 1993), AGNPS (Young *et al*., 1989), CREAMS (USDA, 1980) and GWLF (Haith and Shoemaker, 1987) to predict the fraction of rainfall that runs off. The method also occasionally plays prominent roles in some otherwise well-defined mechanistic models such as CROPSYST (Stockle *et al*., 1994). The original model was justified by Victor Mockus, to whom the traditional SCS-CN method is largely attributed, 'on grounds that it produces rainfall–runoff curves of a type found on natural watersheds' (Rallison, 1980). Subsequently, hydrologists have shown that the basis of the method can be described in ways that are nominally consistent with both the infiltration-excess concept (Hjelmfelt, 1980) and saturation-excess or VSA hydrology (Steenhuis *et al*., 1995). In its most elementary form, the traditional SCS-CN method is conceptually consistent with VSA hydrology; however, current models use the traditional SCS-CN method in a manner that is inconsistent with VSA hydrology. Namely, these models assume runoff amounts are directly controlled by land use and soil type. They do not spatially distribute runoff generation areas in ways that agree with prevailing theories of how or where saturated runoff-source areas develop. Steenhuis *et al*. (1995) gave a spatially varied source area interpretation to the SCS-CN equation. The traditional SCS-CN is used most commonly in a way that implicitly assumes that infiltration excess is the primary runoff mechanism (i.e. using land use or soil class to assign the CN). Saturation-excess, on the other hand, is dependent on landscape factors that are rarely or never used to define CN values. Thus, as long as water quality models continue to adhere to this traditional SCS-CN method, there is a need to develop methods for applying the traditional SCS-CN method to watersheds where saturation-excess is an important process.

The increasingly common application of the traditional SCS-CN method to non-point-source pollution models and related tools for developing land management practices necessitates predicting specific locations of watershed runoff generation (e.g. Heathwaite and Johnes, 1996; Gburek and Sharpley, 1998; Gburek *et al*., 2000, 2002; Walter *et al*., 2000, 2001). Although planners and researchers routinely and successfully calibrate traditional SCS-CN-based models to stream hydrographs, the common infiltration-excess implied approach for assigning CN values to different parts of the landscape results in runoff distributions that do not necessarily give the correct location where runoff is generated. McDowell and Sharpley (2002) demonstrated the importance of manure position in landscape with respect to runoff generation for the transport of phosphorous in a watershed. Clearly, if CN-based models are going to continue to be used to develop management practices for VSA watersheds, we need to develop ways of spatially distributing traditional SCS-CN-predicted runoff that are consistent with the underlying science that describes saturation-excess and VSA hydrology.

This paper suggests one way of predicting distributed runoff volumes using a modified version of the traditional SCS-CN method for watersheds where VSA hydrology is important. The objective of this project was to use simple methods to predict the location of VSAs. We merged the traditional SCS-CN method with the spatial distribution of a modified topographic index to evaluate the probability of saturation for a given area. We call this new approach the distributed CN–VSA method and it predicts the probability of saturation for an area of watershed given a rainfall event. The approach is based on hydrological processes observed in the north-eastern USA where the generation of saturated areas is largely the result of accumulated shallow interflow, usually over a hardpan or shallow bedrock and probably is valid in other similar areas throughout the world.

Model theory

The distributed CN–VSA method is a rainfall–runoff model that predicts (i) the fraction of watershed that is saturated and (ii) the location of these areas. Each is discussed separately in the following sections. Predicting rainfall amount and size of the saturated area have been discussed previously by Steenhuis *et al.* (1995) but are briefly reiterated here for completeness.

Predicting the fractional area of watershed that is saturated. A watershed can be divided into two parts, a saturated, runoff generating part and an unsaturated, infiltrating part. The traditional SCS-CN equation, in the typical form (Rallison, 1980), is given as

$$Q = \frac{(P - I_a)^2}{(P + S - I_a)} \quad \text{for } P > I_a$$
$$Q = 0 \quad \text{for } P \leq I_a \tag{1}$$

where Q is the runoff depth (or excess rainfall) (cm), P is the precipitation (cm), S is the amount of water storage available in the soil profile or the maximum storage (cm), and I_a is initial abstraction (cm). Steenhuis *et al.* (1995) showed that Equation (1) can be differentiated to express the saturated fraction contributing runoff, A_f, as

$$A_f = 1 - \frac{S^2}{(P_e + S)^2} \tag{2}$$

where P_e is the effective precipitation (cm) and defined as $P - I_a$ or the amount of water required to initiate runoff. It should be noted that, for this method, P_e is actually 'effective rainfall' but has been termed effective precipitation for consistent terminology with Steenhuis *et al.* (1995). Traditionally, I_a is almost always set equal to $0{\cdot}2S$ in the SCS-CN equation. Hawkins (1979) showed that using $0{\cdot}2S$ for I_a did not result in good runoff prediction unless S was dependent on rainfall amounts. Steenhuis *et al.* (1995) calculated I_a as the amount of water needed to bring the shallowest soil to saturation and calculated moisture content for periods between runoff events using the Thornthwaite–Mather (TM) procedure (Thornthwaite and Mather, 1955, 1957; Steenhuis and van der Molen, 1986). The TM procedure assumes that above field capacity the evapotranspiration is at the potential rate and below field capacity the evapotranspiration decreases linearly with moisture content to zero when the soil is at the wilting point. Based on the VSA concept, Steenhuis *et al.* (1995) showed that S is the potential average storage in the watershed expressed as the ratio of the total volume of water that can be stored in the watershed between conditions where overland flow first occurs and the maximum watershed saturation to the watershed total area. The traditional SCS-CN equation, modified to take into account these new, theoretically defensible, definitions of I_a and S, gave good results for watersheds in the north-eastern USA, especially considering that the method required little extra information relative to the more common application of the method (Steenhuis *et al.*, 1995).

The location of the areas. Equation (2) predicts the fractional area of the watershed contributing to runoff without indicating important information about where that area is located in a watershed. Topographic indices can be used to determine relative propensities for saturation within a watershed and are, in fact, the basis of the popular TOPMODEL (Beven and Kirkby, 1979), a similar model by O'Loughlin (1986), and many derivatives of these two models. These models have been applied successfully on many watersheds with a variety of hydrological processes controlling saturated area development (Hornberger *et al.*, 1985; Ambroise *et al.*, 1996; Moore and Thompson, 1996; Günter *et al.*, 1999; Walter *et al.*, 2002). As discussed by Western *et al.* (2002), there are many instances where topographic indices fail to capture spatial variation in patterns of soil moisture. However, these indices were developed to predict zones of surface saturation and perform well in moderately wet periods when water distributions are strongly driven by topography (Western *et al.*, 1999, 2002) and water quality is most likely to be impacted by VSA runoff. In its most basic form, the topographic index, λ, for any point in a watershed, is defined as the natural log of the area of the upslope watershed per unit contour length, a, divided by the local surface topographic slope (cm), tan (β), from an elevation map. Soil depth and saturated hydraulic conductivity can be included in the index using the following relationship in the case of shallow soils

$$\lambda = \ln\left(\frac{a}{\tan(\beta)D\hat{K}_s}\right) \quad (3)$$

where D is the depth of the soil (cm) and $\hat{K}_s$ is the mean saturated hydraulic conductivity (cm/day). Locations with a large λ are more prone to saturation than locations with a small λ. The authors do not prescribe to any particular form of λ or algorithm for calculation and many different forms of each are available in the literature. At a minimum, a digital elevation model (DEM) is needed to determine a and tan (β). The fractional area of watershed that is saturated for a given storm event, as determined by Equation (2), can be used to determine a critical λ value below which areas are infiltrating and above which areas saturate and runoff is generated. This is done by assuming that areas saturate in order from highest to lowest λ value. The probability of saturation given a rainfall event map is created for the watershed by taking the ratio of the number of times an area saturates over the total number of rainfall events.

MATERIALS AND METHODS

The distributed CN–VSA method was applied to two watersheds located in the Catskill Mountains of New York State and one located in south-eastern Australia. These New York State watersheds are part of the New York City watershed system and are located in the Cannonsville Reservoir basin at 42°21′N and 74°39′W. The distributed CN–VSA method was applied to the Town Brook watershed with an area of 37 km^2 and a forested sub-basin of the Town Brook watershed with an area of 2 km^2. Elevation in the Town Brook watershed ranged from 493 to 989 m and slopes ranged from 0 to 43°. The land use consisted of dairy farming with pasture and rotated corn–hay cropping, forested areas, and small amounts of impervious area and grasses. The forested sub-basin of the Town Brook watershed elevation ranged from 554 to 984 m and slopes ranged from 0 to 40° with the main land use in forest and a small amount of grassed area. The composition of soils in both New York watersheds was typical for the Cannonsville Reservoir basin consisting, primarily, of shallow well-structured silt loam soils on the hilltops and upper slopes and deeper soils on the lower slopes. The region is underlain by a combination of relatively impervious fragipan in upland regions and fractured, well-drained bedrock in lower regions. The majority of soils in the Town Brook watershed are of NRCS hydrological soil groups C and C/D (88 and 8% of soils, respectively). The south-eastern Australian watershed was the Tarrawarra watershed located at 37°39′S and 145°26′E. For complete description and data set availability, see Western and Grayson (1998).

Weather data for both the Town Brook watershed and the forested sub-basin of the Town Brook watershed were collected at the NOAA weather station located in Stamford, NY approximately 1 km north of the watershed from May 1996 to April 2001. Stream-flow data were taken from US Geological Survey (USGS) gauges at outlets for the watersheds. Runoff and rainfall data for the Tarrawarra data set were taken from Western and Grayson (1998). The values of S for the watersheds were found using the method outlined in Steenhuis *et al.* (1995). The TM procedure (Thornthwaite and Mather, 1955, 1957; Steenhuis and van der Molen, 1986) was used to determine the daily water balance given rainfall and potential evapotranspiration. From this daily balance, a dynamic I_a (i.e. not the usual constant value of $0{\cdot}2S$) was calculated for the shallowest soil in the watershed, as the deficit of maximum available storage for this soil, and used to determine P_e. These calculated P_e events were plotted against the observed runoff per event measured from baseflow separated hydrograph data for the New York watersheds and actual measured runoff for the Tarrawarra watershed. Negative P_e values were calculated when rainfall events occur on days where the water balance predicts more available storage than rainfall, but a peak was observed in the stream-flow hydrograph. The peaks may be caused by factors other than overland flow, such as interflow or direct precipitation on the stream channel. Values of S were determined from fitting the curve of the following version of the SCS-CN equation (Steenhuis *et al*., 1995) to the P_e runoff data

$$Q = \frac{P_e^2}{P_e + S} \quad (4)$$

The summer (1 May to 30 November for this study) events were used for the New York watersheds and events from throughout the entire year for the Tarrawarra watershed. For these periods in each watershed, S values

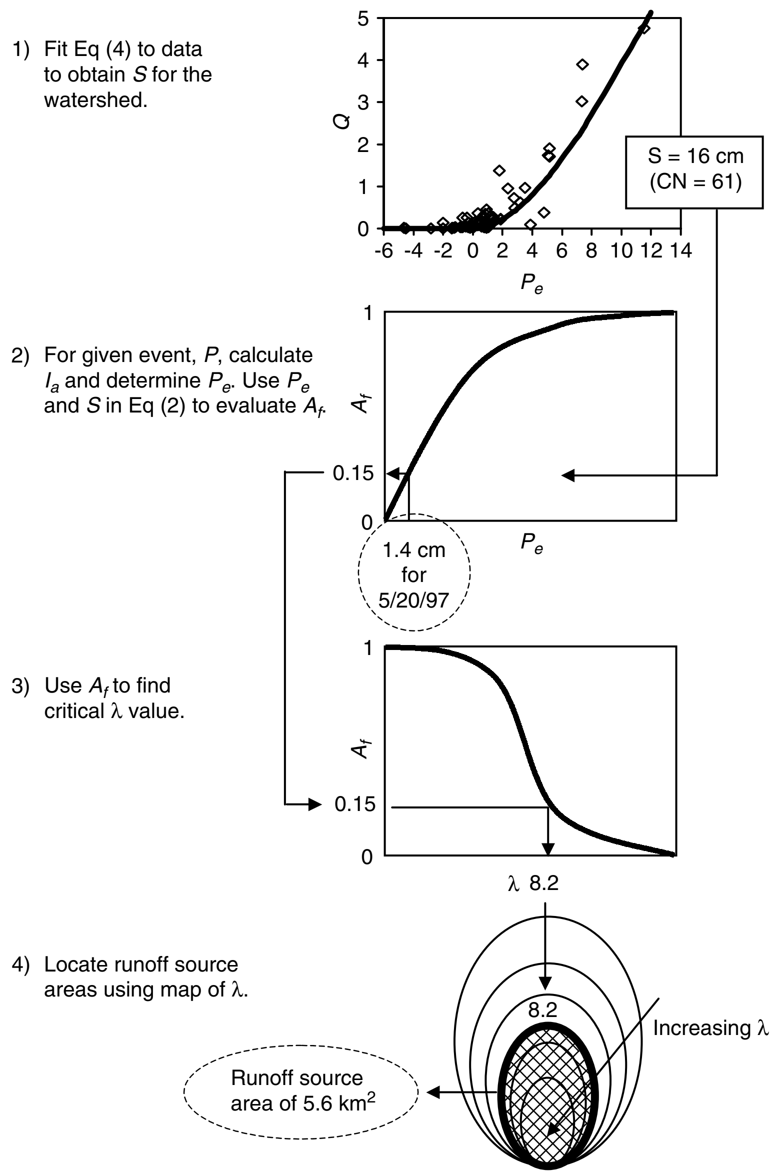

Figure 1. Overview of the distributed CN–VSA method from obtaining S to distributing runoff generation (saturation) showing example calculation for Town Brook watershed on 20 May 1997 described in text

were used to predict A_f during each P_e event using Equation (2). Thus, for each P_e event, a corresponding watershed area producing runoff, A_f, was calculated.

Maps for the distribution of λ defined using Equation (3) for each watershed were created in GRASS v 5·0 GIS (U.S. Army CERL, 1991) using the 10 m USGS DEM to determine contour lengths, slopes and upslope areas using a multidirectional routing approach and using the Soil Survey Geographic Database (SSURGO) soil distribution maps for soil characteristics of the New York watersheds. The soil characteristics were assumed to be in unity for the Tarrawarra watershed. The algorithm for computing the distribution of A_f using λ was performed with the MATLAB v 6·1 software package (The MathWorks, Inc., 2002). The total number of times each area of a watershed saturated for the period of study was calculated. The probability of saturation, given a P_e event, was computed by taking the ratio of the total number of times an area saturated to the total number of P_e events. In addition, runoff-generation distribution maps were created by summing the total P_e depths for these areas for comparison with traditional SCS-CN runoff-generation distribution maps. In this manner, probability of saturation maps given a P_e event and runoff depth distribution maps for each of the three watersheds were created over the period of study.

Figure 1 provides an illustration of the distributed CN–VSA method. As an example, on 20 May 1997 in the Town Brook watershed, 1·6 cm of rain fell on a day with an I_a of 0·2 cm (from TM water balance on shallowest soil) to produce a P_e of 1·4 cm for the watershed. For the Town Brook watershed, a S value of 16 cm (CN value of 61) was determined by fitting Equation (4) to plots of all observed runoff events against their respective P_e events (see Figure 2a). Using Equation (2), a P_e value of 1·4 cm, and a S value of 16 cm, this gives an A_f of 0·15 (or 15% of the watershed). From the generated λ map for the watershed, this A_f corresponded to a critical λ value of 8·2 (i.e. 15% of the watershed has a λ value higher than 8·2). Thus, all areas in the watershed with λ values of 8·2 or higher were saturated by the event on 20 May 1997. This corresponds to a predicted saturated area of 5·6 km^2. Using P_e, the saturated areas generated a runoff depth of 1·4 cm for this event and, by multiplying this by the saturated area, this leads to a runoff volume of 78 400 m^3. It should be noted that using the traditional SCS-CN method, the I_a would be 0·2S or 3·2 cm for this and all events in the Town Brook watershed.

RESULTS AND DISCUSSION

Evaluation of maximum storage

In order to calculate A_f during a rainfall event, values of S were first obtained for each watershed using the method outlined by Steenhuis *et al*. (1995). In Figure 2a, the S value of 16 cm (CN value of 61) was obtained for the Town Brook watershed. For the forested sub-basin of the Town Brook watershed, the analysis in Figure 2b gives an S value of 24 cm (CN value of 51). These values are similar to results seen by Steenhuis *et al*. (1995) for two different watersheds located in the Catskill Mountains with S values of 16 and 30 cm. Figure 2c shows a S value of 8 cm (CN value of 76) for the Tarrawarra watershed. Points of $Q > P_e$ are the result of runoff events occurring on days when, based on the TM water balance, it is predicted that there is a large amount of storage in the soil and, thus, a low P_e. Observed runoff events are the result of rainfall directly on stream and impervious areas that quickly produce runoff and are not influenced by initial abstraction.

Distributed CN–VSA comparison with observed data

Figure 3a shows the resulting probability of saturation map predicted using the distributed CN–VSA method for the forested sub-basin of the Town Brook watershed. Figure 3a also shows GPS-located saturated areas for a sampling date in April 1999 within the forested sub-basin of the Town Brook watershed. The observed saturated areas coincide with the high probability of saturation areas predicted using the distributed CN–VSA method. This is seen in Table I where the average probability of saturation per each saturated area is given. Thus, the distributed CN–VSA method gives good representation of the observed saturated areas. The distributed CN–VSA method misrepresented some of the observed saturated areas by predicting these

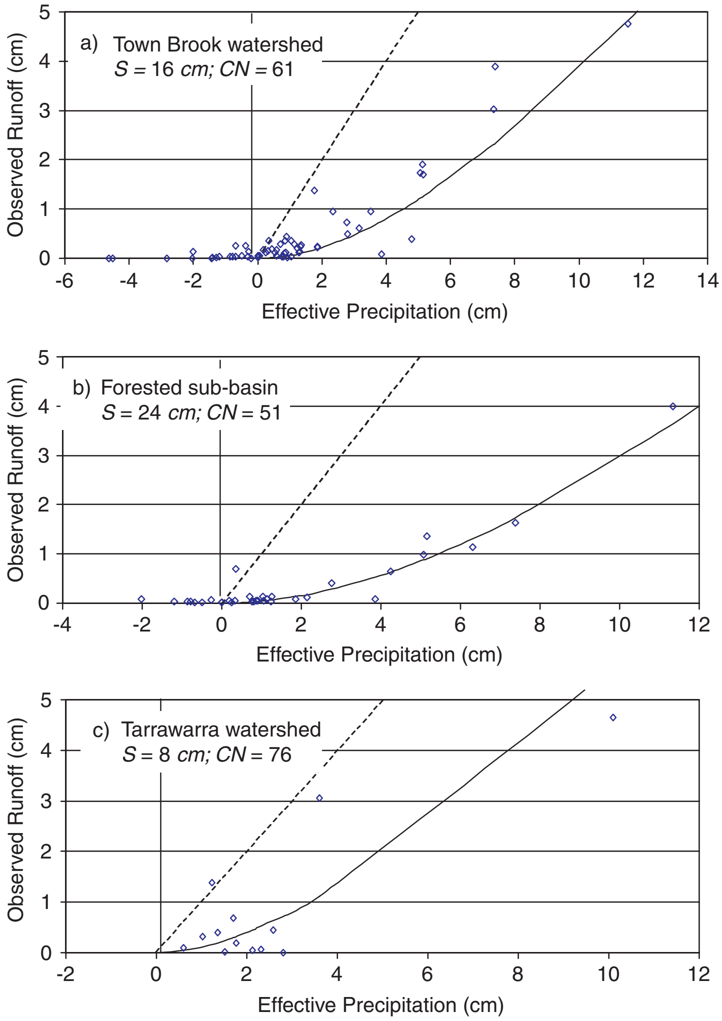

Figure 2. Calculation of S from observed runoff and effective precipitation using the method outlined by Steenhuis *et al*. (1995) for (a) Town Brook watershed, (b) forested sub-basin of Town Brook watershed and (c) Tarrawarra watershed

Table I. Average probability of saturation predictions for the forested sub-basin of the Town Brook watershed for the observed saturated areas for an April 1999 sampling

Saturated area	Average probability of saturation (%)
A	1
B	1
C	40
D	47
E	51
F	51
G	51
H	73

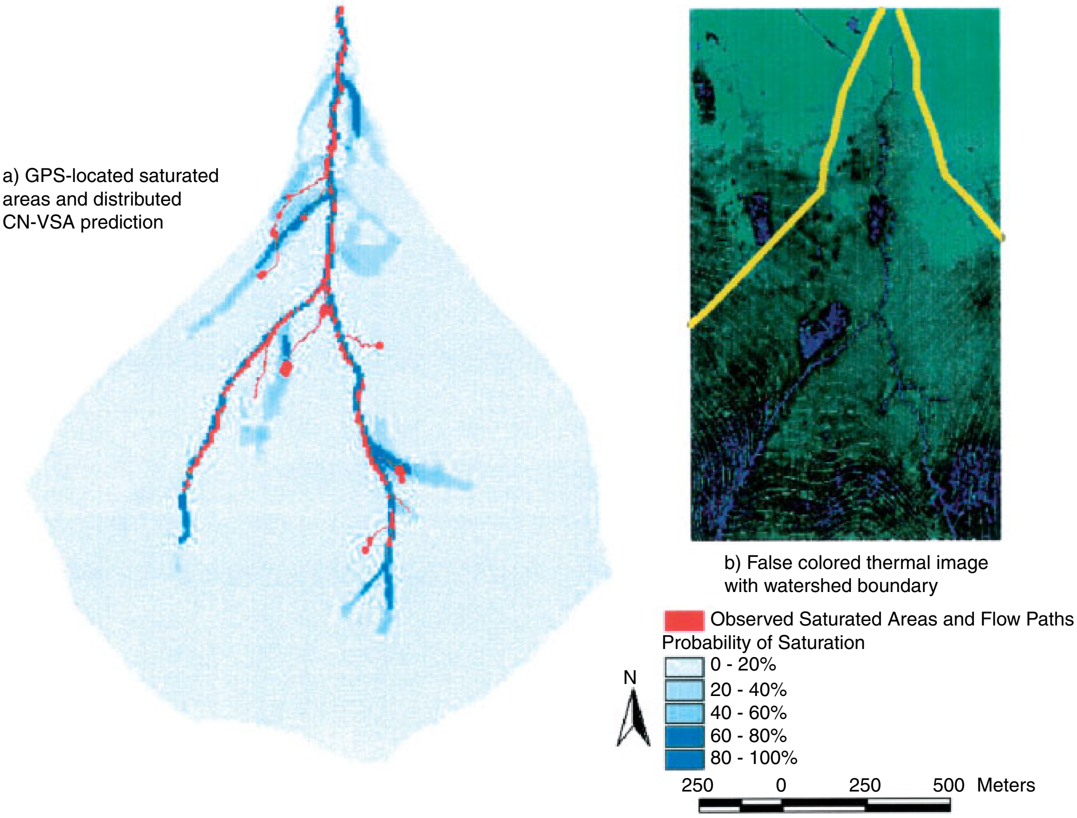

Figure 3. (a) Observed saturated areas and flow paths for April 1999 sampling using GPS over laying predicted probability of saturation using the distributed CN–VSA method and (b) false coloured thermal imaging for November 2000 of the forested sub-basin of the Town Brook watershed

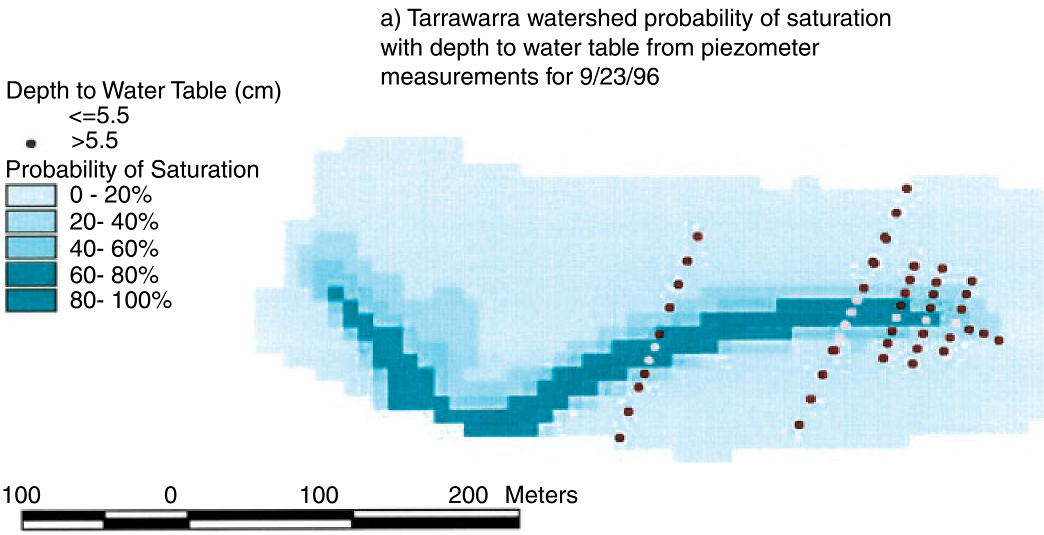

Figure 4. (a) Probability of saturation prediction using the distributed CN–VSA method with depth to water table measurements

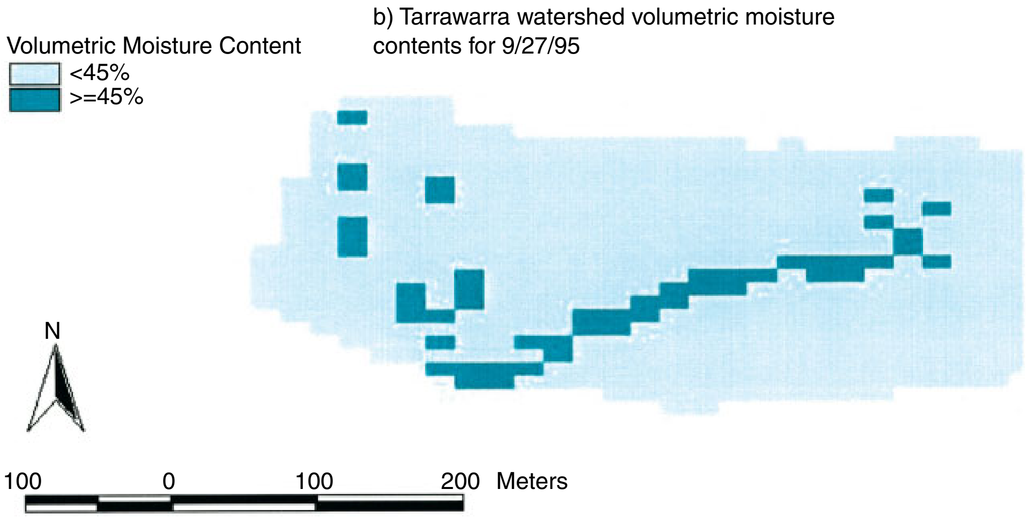

Figure 4. (b) Volumetric moisture content distribution using a TDR probe for the Tarrawarra watershed

areas in the low probability of saturation; however, these occurrences are few (2 of 8) and can be attributed to microscale topographic factors (Mehta *et al*., in press). As these observations were made slightly outside of the calibration range of this analysis, they demonstrate the need of a minimal amount of calibration data in order to represent probability of saturation for the distributed CN–VSA method.

Additional corroboration of the method by observed data is given in Figure 3b by thermal imaging data collected over a region of the forest sub-basin of the Town Brook watershed from a November 2000 sampling. Thermal imaging can be used to qualitatively approximate locations of surface water. This method of comparison was limited to this region owing to data availability. When the thermal data are compared with the distributed CN–VSA prediction for the same region, the corresponding extent of areas of high probability of saturation visually show good relation to actual areas containing high soil water. Flow paths and saturated areas were false coloured so the cooler temperature areas (i.e. surface waters) are indicated in the thermal image by blue colouring and warmer temperature areas (i.e. dry regions) are indicated by green colouring. It can be seen that the major flow paths lay in regions predicted as high probability of saturation by the distributed CN–VSA method. This imaging, along with the GPS-located saturated areas, provide observed data to corroborate the results obtained with the distributed CN–VSA method.

The probability of saturation for the Tarrawarra watershed is given in Figure 4a. Figure 4a also shows the depth to water table for the 23 September 1996 sampling using piezometers. It can be seen that the water table was within 5·5 cm of the surface in the regions of high probability of saturation, and it is deeper in regions where there was a lower probability of saturation. Figure 4b shows the time-domain reflectometry (TDR) probe sampling of volumetric soil moisture for the 27 September 1995 sampling. Again, areas with volumetric soil moisture higher than 45% spatially coincided with predicted areas of high probability of saturation. Note that this trend is observed primarily during the wet season when topography drives spatial distribution of soil moisture and may not be valid during the entire year. Western *et al*. (1999) provided a complete analysis of spatial variability of the soil moisture distribution of the Tarrawarra watershed. These measures of field moisture contents and water tables demonstrate the predictive ability of the distributed CN–VSA method during wet seasons.

Distributed CN–VSA comparison with the SMR model

The distributed CN–VSA method was also compared with the predictions made using the more robust SMR model for the Town Brook watershed. The distributed CN–VSA probability of saturation map for the

Town Brook watershed is given in Figure 5a. The distribution follows what is typically expected from a map derived using a λ distribution. Higher probability of saturation occurs in the downslope regions and the upslope regions have small probability of saturation. To gauge the relative extent of these predictions, a similar analysis was performed using the more computationally rigorous and extensively validated SMR model. This result is shown in Figure 5b and, as expected upon visual inspection, the maps show similar extent of high probability of saturation areas. Also, the regions of extremely low saturation coincide in the upslope areas for the prediction methods. Differences can be seen for the comparisons with the two watersheds in the discontinuous distribution given by the SMR probability of saturation prediction. The SMR prediction shows bands of slightly higher probability of saturation in the upslope regions of the watershed. These regions are attributable to transient conditions simulated by the SMR model. The slopes saturate more readily when the watershed has high moisture levels from previous storm events for a given storm event. As the distributed CN–VSA method assumes steady-state conditions, these regions start each day with average moisture content and, thus, show a slightly lower probability of saturation given a storm event.

The fractional area of saturation predicted using the distributed CN–VSA method was compared with the fractional area predicted using the SMR model for the Town Brook watershed in Figure 6. For the Town Brook watershed, the calculated standard error between the two predictions of fractional area is 0·086; that is, 67% of the predicted fractional areas for the two methods are within ±8·6% of the watershed area in agreement. Figure 6 shows that there is more disagreement between the two methods at lower A_f (i.e. smaller P_e events). This can be attributed to the evapotranspiration (ET) control on runoff generation at lower P_e events (i.e. storms occurring during high ET). For larger events, the topography controls runoff generation and there is better agreement between the two models. These results follow those observed in the literature in which, during the summer, the topographic index does not represent the moisture distribution, but it does well in the remainder of the year (Western *et al*., 1999, 2002; Grayson *et al*., 2002). To further compare the predictions of probability of saturation given a P_e event, Table II gives the distributions of probability of saturation maps produced using both the distributed CN–VSA method and the SMR model for the watershed. This table shows that the sizes of area predicted by both models are in agreement over all the P_e events.

Distributed CN–VSA comparison with traditional SCS-CN method

The distributed CN–VSA method was used to generate a map showing the distribution of cumulative runoff generation for the Town Brook watershed over the entire simulation period (summer from 1 May 1996 to 30 November 2000). This map was created for comparison with the distribution of runoff generation given by the traditional SCS–CN method for the same period. Figure 7a shows the distribution of runoff generation for the Town Brook watershed using the distributed CN–VSA method and Figure 7b shows the distribution of runoff generation predicted using the traditional SCS-CN method. The CN values used to generate the runoff depth map in Figure 7b were calibrated and validated with stream-flow data. This comparison was restricted to the Town Brook watershed owing to a lack of validated CN values for other sites. As expected, the distribution created from the traditional SCS-CN method resembles the land use map for the watershed. This spatial distribution of runoff generation is not consistent with the fundamentals that describe saturation-excess and VSA hydrology that dominates in this region. The spatial runoff distribution given by the distributed CN–VSA method is in agreement with the VSA hydrology concept. These distributions show regions of runoff source areas varying in size seasonally and during individual storm events. Thus, regions near the stream generate the majority of runoff for the modelled period. This result directly affects the management practices implemented in these watersheds.

To further demonstrate the differences in runoff generation using the two methods, Table III gives the breakdown of location of runoff generation divided into land use types. Table III also gives the percentage of total runoff volume generated from each land use type. The table shows good agreement (0·8% difference) in the prediction of total runoff volume between the traditional SCS-CN method and the distributed CN–VSA method. This demonstrates the ability to calibrate the traditional SCS-CN method with stream hydrographs

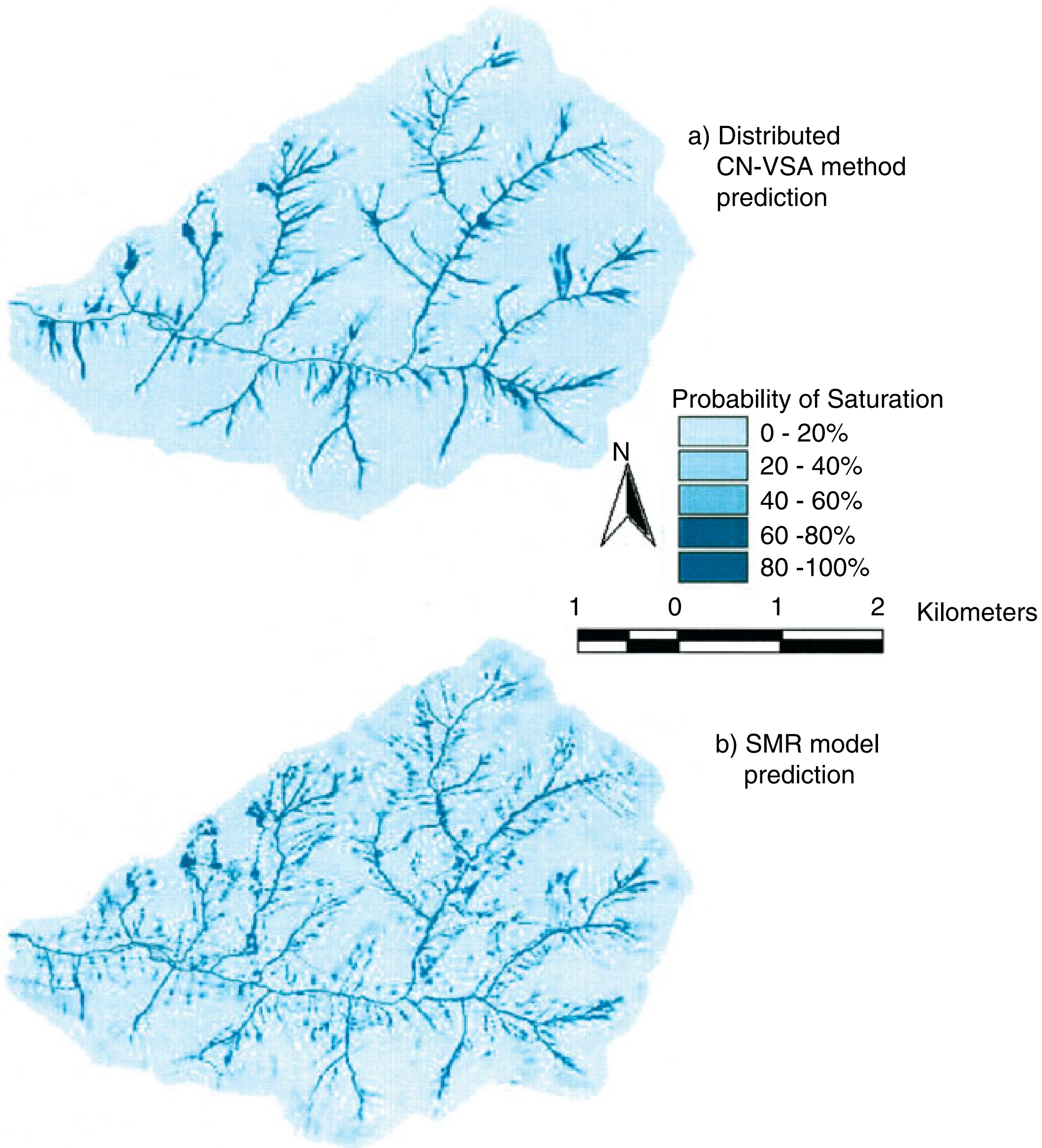

Figure 5. Probability of saturation for a given P_e event prediction for Town Brook watershed using (a) the distributed CN–VSA method and (b) SMR model

alone. However, the disagreement between the two methods becomes clear when the location of runoff generation is considered. The traditional SCS-CN method, which is heavily influenced by land use, shows the majority of runoff being generated by the forest (deciduous) (40·4%) followed by the grass (shrub) (21·4%) for the watershed. The distributed CN–VSA method gives the majority of runoff generation from the grass (shrub) (45·3%) followed by forest (deciduous) (23·5%). When the agricultural land use of corn is considered, the traditional SCS-CN method predicts that 4·3% of runoff volume is generated in this land use whereas the distributed CN–VSA method predicts only 2·5% of runoff volume being generated.

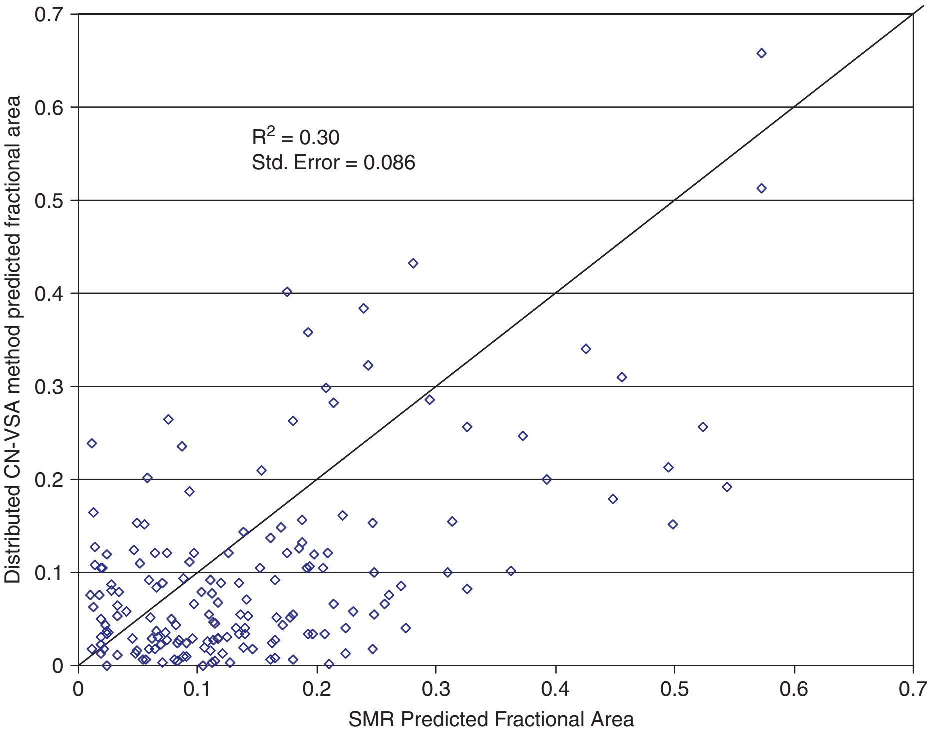

Figure 6. Fractional area of watershed saturating for summer P_e events predicted by the distributed CN–VSA compared with the SMR model prediction of fractional area of watershed for Town Brook watershed

Table II. Distribution of probability of saturation predictions for the Town Brook watershed for the modelled period (summer from 1 May 1996 to 30 November 2000) using the SMR model and the distributed CN–VSA method

Probability of saturation (%)	Town Brook watershed			
	SMR model		Distributed CN–VSA method	
	Area (ha)	Percentage of total (%)	Area (ha)	Percentage of total (%)
0 to 20	2811	75·8	3217	86·8
20 to 40	490	13·2	189	5·1
40 to 60	206	5·6	155	4·2
60 to 80	127	3·4	66	1·8
80 to 100	72	1·9	79	2·1
Total	3706	100·0	3706	100·0

These differences in runoff generation location play a crucial role in land management at the watershed scale.

CONCLUSION

We derived a distributed CN–VSA method and demonstrated its application to three watersheds. The method provides a simple way to predict the fraction of a watershed producing saturation-excess runoff and a manner

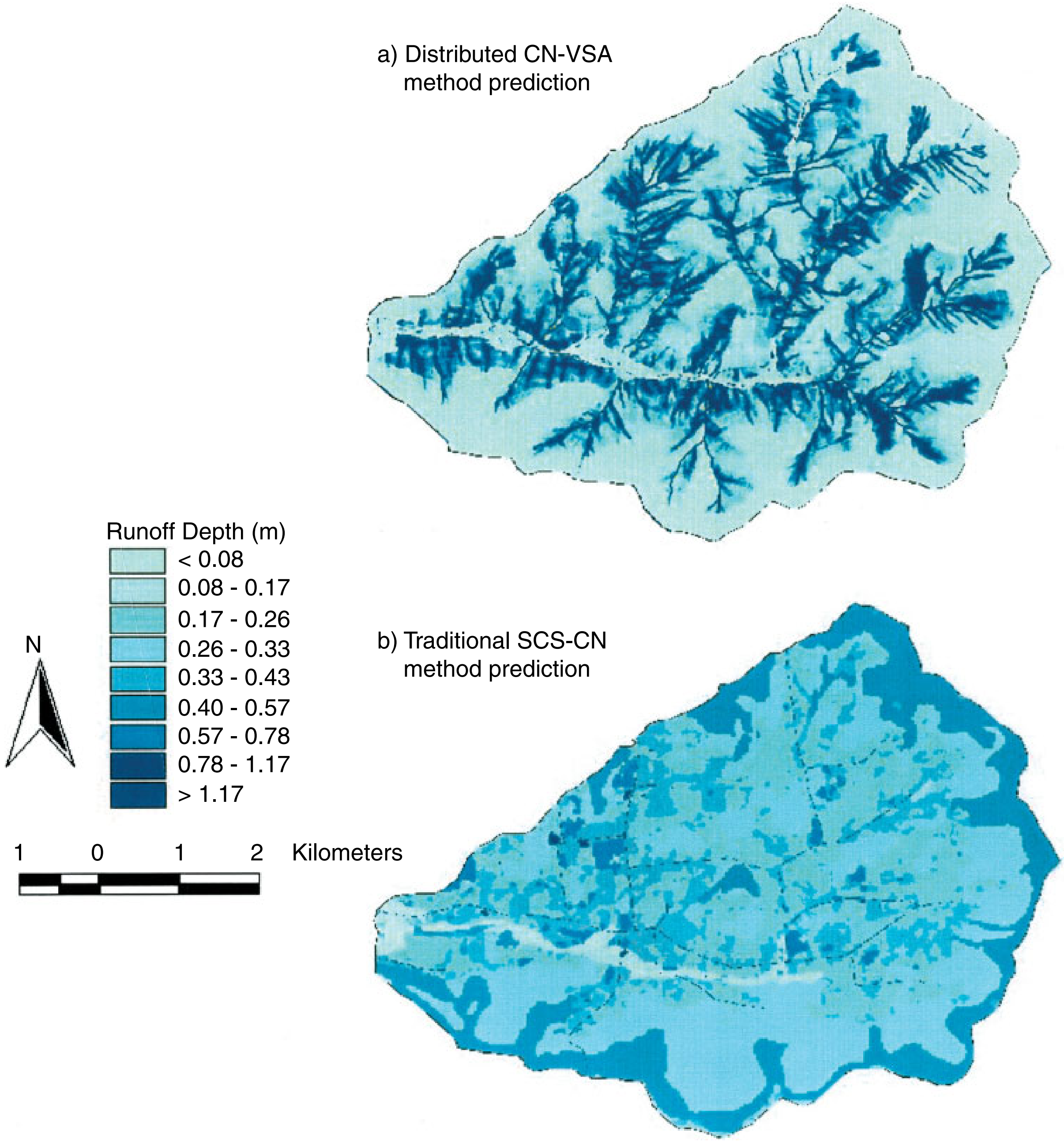

Figure 7. Total runoff depths for all summer events for Town Brook watershed using (a) the distributed CN–VSA method and (b) the traditional SCS-CN method

in which to locate these saturated areas. The distributed CN–VSA method showed good agreement with both measured and modelled saturated areas. The procedure tested with several independent 'measures' for the extent of saturated areas: (i) observed saturation located using GPS, (ii) remotely sensed thermal data, (iii) measured water table heights, (iv) distributed TDR volumetric soil moisture and (v) a more extensively

Table III. Comparison of runoff generation volumes divided among land use types for the Town Brook watershed using the traditional SCS-CN method and the distributed CN–VSA method

Land use	Traditional SCS-CN method		Distributed CN–VSA method	
	Runoff generation (m^3)	Percentage of total (%)	Runoff generation (m^3)	Percentage of total (%)
Forest (deciduous)	5 310 000	40·4	3 120 000	23·5
Forest (coniferous)	1 810 000	13·8	853 000	6·4
Grass (shrub)	2 820 000	21·4	6 010 000	45·3
Grass	2 250 000	17·1	2 810 000	21·2
Corn	569 000	4·3	328 000	2·5
Alfalfa	17 700	0·1	4670	0·0
Impervious (built up)	11 500	0·1	1360	0·0
Water	106 000	0·8	13 100	0·1
Road (rural)	260 000	2·0	122 000	0·9
Road (built up)	273	0·0	248	0·0
Total	13 200 000	100·0	13 300 000	100·0

validated model. This distributed CN–VSA approach is one way to meaningfully apply the traditional SCS-CN method to areas where saturation excess is an important runoff process and, thus, improve the reliability of the widely used suite of water quality models based on the traditional SCS-CN method. The new distributed CN–VSA method retains the basic form of the traditional SCS-CN method but does not use the tabulated land use and soil class approach to determine S. The only additional data needed are topography and perhaps soil information, which is widely available throughout most of the USA and essential to many hydrological models. The distributed CN–VSA method provides a tool simple enough to be implemented in managing nutrients in the NYC watersheds and most current non-point-source pollution models or water quality models.

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