Effects of Watershed Subdivision on Peak Discharge in Rainfall-Runoff Modeling in the WinTR-20 Model

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Abstract: The rainfall-runoff model, WinTR-20, uses subdivision to simulate runoff behavior for complex watersheds exhibiting heterogeneous conditions or storage. It has been shown by others that subdivision generally causes the predicted peak discharge to increase, though the underlying processes are often obscured by watershed complexity. This study instead focuses on a simplified, theoretical watershed, systematically comparing the unsubdivided watershed with a two-subbasin model in order to determine the most sensitive factors. Peak discharge sensitivity is evaluated with respect to (1) series subdivision with varying total area, (2) parallel subdivision with varying proportional area, (3) parallel subdivision with varying curve number, and (4) parallel subdivision with simultaneously varying area and curve numbers. Peak discharge is most sensitive to differences in curve number, which controls both the runoff volume and peak timing. Serial subdivision was found to produce a significant high peak discharge, regardless of relative area, while parallel subdivision produced a smaller and more variable effect, either increasing or decreasing peak flow based on the area ratio. Using these subdivision sensitivities, general guidelines are presented for the rational subdivision in rainfall-runoff modeling. For example, subdivision is recommended when subarea curve numbers differ by more than five and the relative sizes of subareas influence the effects of discretization. **DOI: 10.1061/(ASCE)HE .1943-5584.0001188.** *© 2015 American Society of Civil Engineers.*

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Introduction

Rainfall-runoff models are widely used to simulate or predict the hydrologic response of a watershed system to a single storm event. Environmental, conservation, and transportation agencies use these models to compare the hydrologic impact of land development or other watershed changes with existing conditions, particularly when large or complex watersheds are involved. Assessing these effects is important to decision makers and design engineers alike. Unfortunately, stream gauges are rarely located at or near the location where a design is needed. Therefore, design engineers cannot calibrate runoff models to measured data. Thus, designs are often based solely on the experience of the modeler.

Techniques for simulating runoff response for a given watershed involve choosing an appropriate hydrologic model, specifying a representative model structure and set of parameters, and selecting a synthetic or historically observed rainfall event. Generally, the flow of water through a watershed is modeled by dividing the watershed into a series of subbasins that reflect different conditions and routing runoff hydrographs from each subbasin outlet through the stream network to form the runoff hydrograph at the overall basin outlet. One problem with this approach is the same unit hydrograph used for analysis of the total watershed is then used for each subarea even though the unit hydrograph for the smaller subareas would be different than the unit hydrograph for the larger watershed. The Natural Resources Conservation Service (NRCS) WinTR-20 (NRCS 2008) computer model is used for rainfall-runoff modeling and produces simulated estimates of peak discharge rates, runoff volumes, and times to peak, as well as complete runoff hydrographs. Such models are regularly used by design engineers and hydrologists without calibration to measured flood data or to regression equations developed from stream gauge data.

The process of dividing a watershed into smaller subbasins is called subwatershed delineation or subdivision. Generally speaking, a subbasin, subwatershed, or subarea is a fraction of a larger watershed that has unique characteristics producing outputs that differ significantly from adjacent areas. For modeling purposes, the watershed is subdivided if heterogeneity exists among watershed characteristics, such as land use, structures, relief, organization of the drainage network, or storage. In some locations, spatial variation of rainfall may require discretization. Although subdivision is necessary to effectively model differences in runoff behavior observed in a complex watershed, the guidelines describing the degree of difference necessary to divide a watershed are often poorly defined and left to the discretion of modelers. While the effects of subdivision are often weakly examined, subdivision procedures can greatly influence the characteristics of the model-generated runoff hydrograph, especially the peak discharge.

Consider an example of subdivision effects, using the Northwest Branch watershed at Colesville, Maryland. This 55.2-km[2] watershed has at its outlet a USGS stream gauge (No. 01650500) with approximately 70 years of stream gauge record. Using different subdivision criteria, this watershed could be separated into 1, 4,

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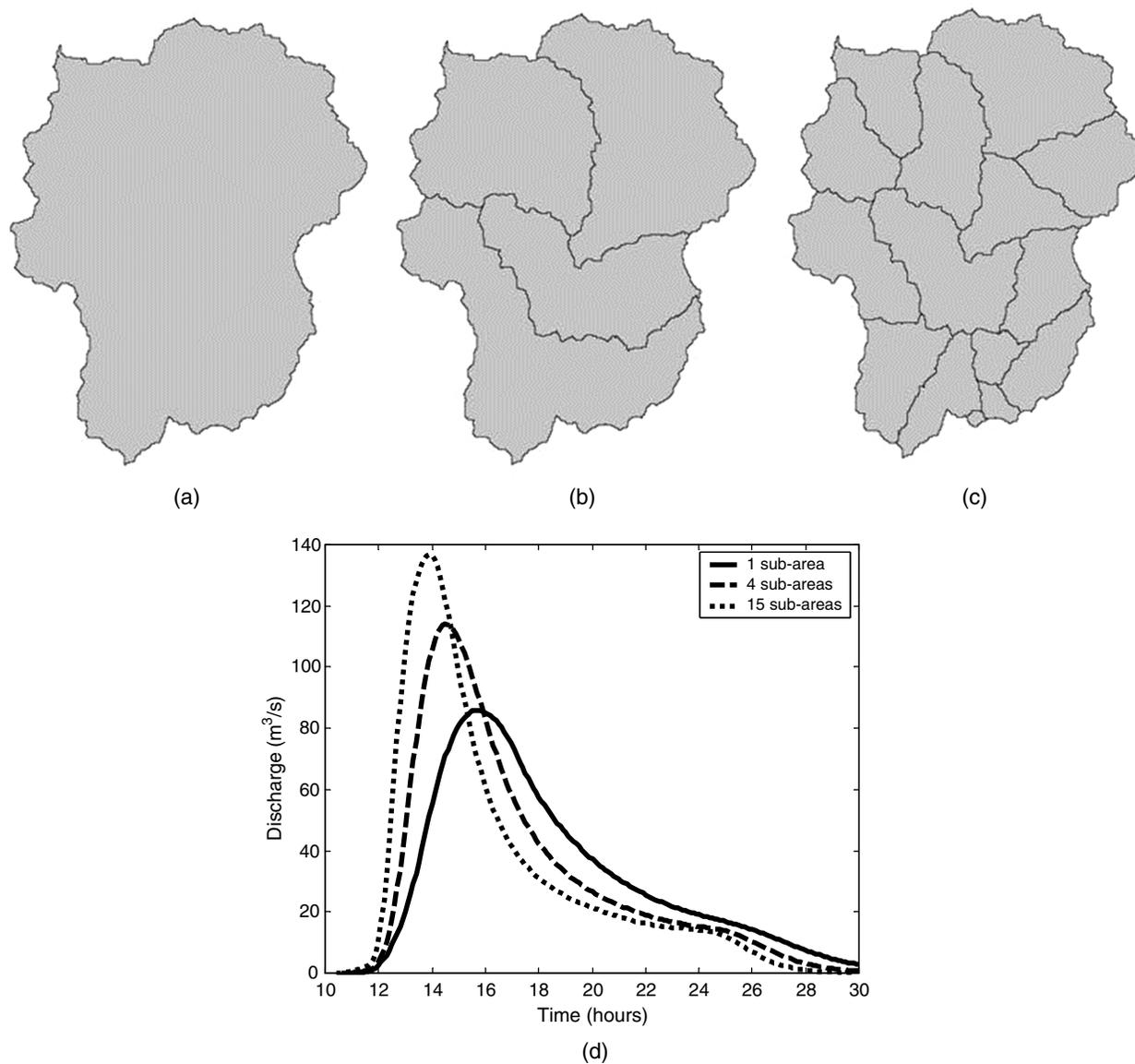
Fig. 1. Northwest Branch watershed with (a) 1 subdivision; (b) 4 subdivisions; (c) 15 subdivisions; (d) predicted runoff hydrographs for the different subdivided systems

and 15 subdivisions [Figs. 1(a–c), respectively]. When the 24-h duration, NRCS Type II storm, for the 5-year return period (approximately 108 mm) is applied to these differently subdivided watersheds using WinTR-20, modeled peak discharge increases by 32 and 59% for the 4 and 15 subdivision models, respectively, relative to the non-subdivided case [Fig. 1(d)]. This difference is of particular concern because, while peak discharge steadily increases with increased subdivision, runoff volume remains approximately constant because the average curve number does not change. This disparity is solely the result of the modeling practice of subdividing and is in opposition to natural watershed observations, which show that peak discharge and flow volumes for a storm of a given return period are generally correlated.

Subdivision decisions have obvious implications on design if a structure is to be placed at the outlet of a modeled watershed. Too little subdivision in the watershed model could result in a structure being designed for an underestimated peak discharge, while too much could result in a design based on an overestimated peak discharge.

It is clear from the example presented using the Northwest Branch watershed and from previous studies (Norris and Haan 1993; Tripathi et al. 2006; Kalin et al. 2003; Rojas et al. 2008) that computed peak discharges are sensitive to subdivision, generally increasing as the degree of subdivision increases. However, past subdivision sensitivity studies have focused on the number of subdivisions using case studies where watershed complexity and local differences may obscure the underlying processes. Rather than using this approach, this study addresses the issue of subdivision by focusing on a simplified, theoretical watershed.

The objective of this study is to systematically compare an unsubdivided watershed with a two-subbasin model in order to isolate and quantify the most sensitive factors. Peak discharge sensitivity is evaluated with respect to (1) series subdivision with varying total area, (2) parallel subdivision with varying proportional area, (3) parallel subdivision with varying curve number, and (4) parallel subdivision with simultaneously varying area and curve numbers. By isolating these processes and evaluating interactions, it is possible to identify situations where subdivision has the greatest effect on modeled peak

discharge. Using these subdivision sensitivities, general guidelines are presented for appropriate watershed subdivision.

Background

Despite the widespread use of rainfall-runoff models such as WinTR-20, and the common practice of watershed subdivision, relatively little research has been done to investigate the effects of subdivision, how it should be applied, and its implications.

Subdivision Effects at Coarse Temporal Resolution (>1 day)

Much of the available research regarding subdivision and the aggregation of watershed parameters has focused on the Soil and Water Assessment Tool model (SWAT, Arnold et al. 1993), which integrates rainfall-runoff modules with sediment, nutrient, and pesticide delivery models. SWAT is a continuous model designed to simulate streamflow and the impact of agricultural management practices at a daily time step. Due to the daily time step, much of the peak flow resolution is lost in the model, particularly in watersheds where the time of concentration is less than 1 day (Cho and Olivera 2009) and studies tend to focus on monthly or annual total streamflow statistics rather than peak discharge (Fitzhugh and Mackay 2000; Chen and Mackay 2004; Han et al. 2013). Hence, the majority of SWAT studies regarding subdivision have concluded that subbasin size does not significantly affect total flow at the watershed outlet (Chen and Mackay 2004; Cho et al. 2010; Fitzhugh and Mackay 2000; Jha et al. 2004), although some studies have shown that subdivision may affect pollutant/sediment loading (Bingner et al. 1997; Migliaccio and Chaubrey 2008). For instance, Bingner et al. (1997) used SWAT to simulate runoff and sediment yield over a 10-year period for the 21.2-km^2 Goodwin Creek watershed in northern Mississippi. Total annual runoff varied by less than 5% between the 14-subbasin model and the 470-subbasin model; however, fine sediment yield increased by approximately 250% from the 14-subbasin model to the 470-subbasin model.

Subdivision Effects at the Sub-Daily Temporal Resolution

The greatest effect of subdivision on model runoff appears at smaller temporal resolutions, i.e., at the timescale of the individual storm event. At the storm event level, the effect of subdivision is not only significant, but is more complex and often nonlinear. For spatial scales typically used in watershed modeling, increased subdivision generally produces higher modeled peak discharge (Norris and Haan 1993; Tripathi et al. 2006; Kalin et al. 2003; Rojas et al. 2008), with increased flashiness but negligible changes in total runoff volume. For example, Norris and Haan (1993) modeled runoff hydrographs in a 151.5-km^2 watershed divided into 2, 5, 10, and 15 subwatersheds using HEC-1 with a NRCS dimensionless unit hydrograph and synthetic rainfall distribution appropriate for the location in central Oklahoma, USA. Peak discharge rates increased as the number of subdivisions increased, with the effect diminishing with a greater number of subdivisions for the same total area. Peak discharge for the watershed divided into 15 subdivisions was 30% higher than the undivided watershed, with times-to-peak flow remaining relatively constant. In this study, time of concentration (t_c) was modified to ensure that total travel time for each subdivision scenario was equal, allowing the researchers to isolate the effect of subdivision on discharge (Norris and Haan 1993). However, the assumption of equivalent peak timing is not made when hydrologic modelers subdivide watersheds in practice and it masks the importance of relative subwatershed peak timing that is investigated herein.

Despite the general increase in peak discharge with increasing subdivision, for extremely small urban catchments, peak discharge may decrease with greater subdivision (Zaghloul 1981; Thompson and Cleveland 2009; Stephenson 1989). The urban watersheds where this pattern occurs tend to be very small, as in Zaghloul (1981), which examined a 0.04-km^2 urban tract in Chicago and a 2.2-km^2 urban watershed in Winnipeg, Canada, using the SWMM model. The smaller Chicago watershed showed a slight decrease in the peak flows for an 80-subarea discretization compared to a single watershed model, whereas peak flow in the slightly larger Winnipeg watershed decreased significantly with greater subdivision. The peak flow for the single-watershed model and the 3-subbasin model were 20 and 10% greater than the 41-subbasin model, respectively (Zaghloul 1981). This reversed trend of decreasing peak discharge in small, impervious watersheds highlights the need to understand the competing effects of discharge magnitude and peak timing, which are both affected by watershed subdivision. In this example, the use of highly subdivided impervious areas produces many short, sharp runoff peaks with potentially different travel times, which do not add to create a single large peak, as is the case for fewer subdivisions.

These studies show that subdivision effects on modeled peak discharge are nonlinear and specific to the watershed. Comparing modeled runoff using different subdivision schemes with observed gauge data supports the conclusion that there exists an optimal level of subdivision appropriate for each watershed and that modifying subdivisions may improve model accuracy (Cydzik and Hogue 2009; Warwick and Litchfield 1993). Cydzik and Hogue (2009) considered four discretization configurations (1, 3, 5, and 7 subbasins) while modeling a 50.8-km^2 watershed in the San Bernadino Mountains, east of Los Angeles, California. The authors modeled the watershed using HEC-HMS, incorporating the curve number method as the loss model, the NRCS unit hydrograph, and the Muskingum-Cunge procedure for channel routing. By comparing the various subdivision models to observed hydrographs, the authors found that the five-subbasin model performed the best, with increasing errors resulting from either increases and decreases in subdivision. A similar pattern of increased accuracy with increasing model subdivision, followed by decreases beyond this optimal level was also found by Warwick and Litchfield (1993). In the previously discussed small (0.04–2.2 km^2) urban watershed study by Zaghloul (1981), the optimal discretization scheme was found to be the single watershed model, with no subdivision.

Effect of Storm Size on Subdivision

Goodrich et al. (1988) examined the effect of subdivision on a kinematic wave hydrologic model, KINEROS, in a relatively small, 3.5-km^2, experimental watershed near Tombstone, Arizona. Results of the modeling showed that the effects of subdivision may also be related to storm event size. For a relatively large storm event (approximately the 2-year event), little change was noted through the full range of aggregation from 1 to 30 subdivisions. However, the effect was greater for smaller events, with additional discretization producing larger storm peaks and greater volumes. Ghosh and Hellweger (2012) further supported this relationship, finding that greater subdivision decreased flows for large storm events while increasing flows for smaller storm events.

Methods

Subdivision Scheme

Sensitivity analyses were used to evaluate the degree to which the hydrologic parameters interact when a watershed is subdivided and

the resulting effects on computed peak discharge rates. To simplify the problem of subdivision, a synthetic watershed configuration and set of parameters were used. Knowing the true parameters of the analysis allows for more confidence in the assessment of general findings. As this work is exclusively based on a hypothetical watershed for sensitivity analysis, calibration of the model to observed data was not necessary. The synthetic watershed was derived from the simplest case of subdivision, the separation of a single watershed into two subwatersheds.

Two cases are possible for subdividing a single watershed as shown in Fig. 2. The first case, parallel subdivision, is the separation of the watershed at the confluence of two streams at its outlet. In this case, runoff is generated by the model separately for each subwatershed and combined at the watershed outlet. The second case, series subdivision, is the separation of the watershed at a point in-line with the drainage network. In this case, runoff from the upper subwatershed is generated and then routed in a channel through the lower subwatershed until it is combined with the runoff from the lower subwatershed at the basin outlet.

Using this hypothetical watershed, peak discharge sensitivity is evaluated with respect to (1) series subdivision with varying total area, (2) parallel subdivision with varying proportional area,

(3) parallel subdivision with varying curve number, and (4) parallel subdivision with simultaneously varying area and curve numbers.

Channel, storage, and precipitation parameters were examined in an analogous fashion to the parameters described above. These analyses showed very little sensitivity with respect to peak discharge and are omitted here. Readers wishing more information on sensitivity to these quantities are directed to Casey (1999).

Rainfall-Runoff Model

WinTR-20 was used to simulate peak discharges for the synthetic watershed. By using WinTR-20, appropriate values of model parameters for use with SCS (NRCS) methods were selected. WinTR-20 requires basic information for each subwatershed including drainage area, curve number, and time of concentration, t_c. These parameters are used to develop the unit hydrograph and rainfall excess, which are then convolved to generate the direct runoff hydrograph. In performing the synthetic analyses, assumed values of runoff curve number (CN) and drainage area (A) were used. WinTR-20 uses the curve number as a measure of the runoff potential of a land surface. In this model, values of CN can affect hydrologic response in two ways. First, land use as represented by the curve number is an important indicator of travel times, used an input to the NRCS lag formula (SCS 1973)

$$t_c = 2.27 \times 10^{-4} L^{0.8} \left(\frac{1,000}{CN} - 9 \right) S^{-0.5} \qquad (1)$$

where L = watershed length in m; and S = watershed slope in m/m. Watershed length (L) in m was estimated from the relationship (NRCS 1998)

$$L = 1,740 A^{0.6} \qquad (2)$$

where A = upstream drainage area in km^2. The t_c values are subsequently used to calculate the peak discharge of the unit hydrograph with

$$Q_p = \frac{2.08 AQ}{t_p} = \frac{3.13 AQ}{t_c} \qquad (3)$$

where Q_p = peak discharge in m^3/s; A = drainage area in km^2; Q = runoff in cm; and t_p = time to peak in h. For parallel subdivisions, t_c for the non-subdivided watershed is assumed to be the longer of two subdivided t_c values.

For the series subdivision case, additional information was required about the channel reach for routing of the upstream hydrograph through the lower subwatershed. WinTR-20 uses the Muskingum-Cunge (Cunge 1969) method for hydrograph routing. The method requires a stage-discharge-end area relationship to be specified for each reach. This relationship is based on the channel and floodplain geometry, roughness, and reach length. In this study, a rectangular cross-sectional geometry was assumed with a width determined based on the Dunne and Leopold (1978) bankfull geometry equations

$$W_{bf} = 2.57 A^{0.427} \qquad (4)$$

$$D_{bf} = 0.297 A^{0.31} \qquad (5)$$

where W_{bf} represents bankfull width in m and D_{bf} represents bankful depth in m. Channel roughness and slope were fixed with a Manning's n value of 0.05 and a slope S of 0.01 m/m.

PARALLEL SUBDIVISION

A_1
CN_1
t_{c1}

A_2
CN_2
t_{c2}

Watershed Outlet

- - - - Watershed Boundary
——— Connector

(a)

SERIES SUBDIVISION

A_1
CN_1
t_{c1}

A_2
CN_2
t_{c2}

Watershed Outlet

- - - - Watershed Boundary
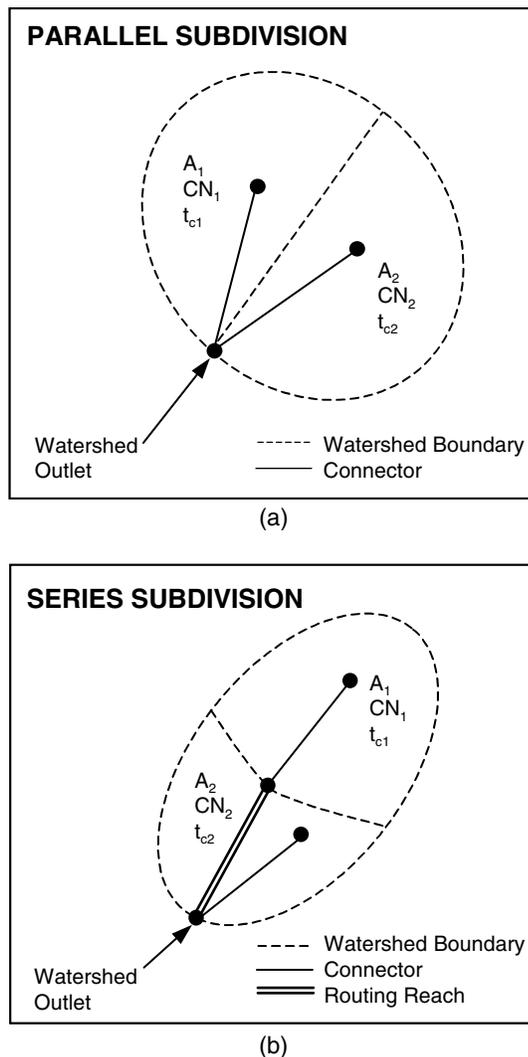——— Connector
════ Routing Reach

(b)

Fig. 2. Watershed schematics for (a) parallel subdivision; (b) series subdivision

In all cases, the NRCS Type II storm distribution was used with a depth of 10.8 cm (4.25 in.), corresponding to roughly a 5-year, 24-h event in the U.S. mid-Atlantic region.

Sensitivity Criteria

Peak discharge was selected as the evaluation criteria because of its important implications to engineering design, such as the sizing of hydraulic structures. In all cases, the predicted peak discharge rates that resulted from subdivision (SUB) were compared with the peak discharge rate for no subdivision (NS). Sensitivity with respect to subdivision were calculated for peak discharge and time to peak as the percent change between the subdivided, $Q_{p,\text{SUB}}$, and non-subdivided, $Q_{P,\text{NS}}$, models with respect to peak discharge

$$\Delta Q_p = \frac{Q_{p,\text{SUB}} - Q_{p,\text{NS}}}{Q_{p,\text{NS}}} \times 100 \qquad (6)$$

Similarly, the relative difference (%) in time to peak discharge was calculated by

$$\Delta t_p = \frac{t_{p,\text{SUB}} - t_{p,\text{NS}}}{t_{p,\text{NS}}} \times 100 \qquad (7)$$

where $t_{p,\text{SUB}}$ and $t_{P,\text{NS}}$ represent the time to peak for the subdivided and non-subdivided models, respectively.

Results

Experiment 1: Effect of Drainage Area on the Effect of Watershed Subdivision

The first experiment examined whether watershed size has an effect on modeled peak discharge when a watershed is subdivided into two equally sized subdivisions using series division [Fig. 2(b)]. Results in Table 1 show that for subwatershed sizes of 0.26 km² (0.1 mi²) to 64.75 km² (25 mi²) the increase in peak discharge (Q_p) caused by subdivision remained fairly constant, between 26.5 and 30.2%. The relative change in time to peak (t_p), however, steadily increased in magnitude with increasing scale from −1.6 to −14.0% over the range of scales examined.

These results show that the act of serial subdivision itself has a greater impact on peak discharge, but is relatively insensitive to total area. Within the TR-20 framework, the act of serial subdivision reduces subbasin area, thereby decreasing overland t_c (Table 1) and producing a more flashy hydrologic response. As is typical in most physical systems, hydrologic travel time within the channel is much shorter than overland runoff travel time, allowing the two more flashy subbasin hydrographs to sum, thereby producing a higher peak discharge. This effect is invariant of total area in this case because the subbasin areas are equal. Time to peak, t_p, increases with area in this case because overland t_c increases with subbasin area, as described by the combination of Eqs. (1) and (2).

Experiment 2: Effect of Proportional Areas of Subwatersheds

The next experiment evaluated how the relative subwatershed drainage areas affect peak discharge for parallel subdivision keeping total watershed area constant. Two parallel subwatersheds were used, with a fixed total area of 2.59 km². The relative area of the two subwatersheds was varied as indicated in Table 2, in increments of 10%. When the drainage area of one subwatershed was less than approximately 25% of the whole area, the peak discharge of the subdivided watershed was 3.2–4.6% lower than the non-subdivided watershed. When the subareas were more equal

Table 1. Results of Experiment 1: Total Drainage Area Experiment with Series Subdivision

Area (km²)	t_c		Q_p			t_p		
	$t_{c,\text{NS}}$ (h)	$t_{c,\text{SUB}}$ (h)	$Q_{p,\text{NS}}$ (m³/s)	$Q_{p,\text{SUB}}$ (m³/s)	ΔQ_p (%)	$t_{p,\text{NS}}$ (h)	$t_{p,\text{SUB}}$ (h)	Δt_p (%)
0.26	1.29	0.93	1.51	1.91	26.5	12.7	12.5	−1.6
0.52	1.80	1.29	2.34	3.01	28.6	13.1	12.7	−3.1
1.29	2.80	2.01	4.17	5.37	28.8	13.7	13.2	−3.6
2.59	3.91	2.80	6.43	8.3	29.1	14.5	13.7	−5.5
5.18	5.45	3.91	9.91	12.8	29.2	15.5	14.5	−6.5
13.0	8.46	6.06	17.4	22.6	29.9	17.3	16.2	−6.4
25.9	11.79	8.46	27.0	34.7	28.5	19.7	17.9	−9.1
38.9	14.33	10.27	34.4	44.8	30.2	22.0	19.0	−13.6
51.8	16.45	11.79	41.6	53.9	29.6	22.8	20.5	−10.1
64.8	18.31	13.13	48.1	61.9	28.7	24.3	20.9	−14.0

Note: NS indicates no subdivision; SUB indicates that the watershed was subdivided.

Table 2. Results of Experiment 2: Results of Fractional Drainage Area Experiment with Parallel Subdivision

Area			Q_p					t_p				
A_1 (km²)	A_2 (km²)	Ratio (%)	$Q_{p,1}$ (m³/s)	$Q_{p,2}$ (m³/s)	$Q_{p,\text{SUB}}$ (m³/s)	$Q_{p,\text{NS}}$ (m³/s)	ΔQ_p (%)	$t_{p,1}$ (h)	$t_{p,2}$ (h)	$t_{p,\text{SUB}}$ (h)	$t_{p,\text{NS}}$ (h)	Δt_p (%)
0.26	2.33	10–90	1.50	6.14	6.51	6.82	−4.55	12.7	14.3	14.3	14.3	−0.5
0.52	2.07	20–80	2.35	5.69	6.91	7.14	−3.22	13.1	14.2	13.9	14.2	−2.3
0.78	1.81	30–70	3.06	5.24	7.76	7.48	3.74	13.3	14.1	13.7	14.1	−2.4
1.04	1.55	40–60	3.65	4.76	8.27	7.90	4.68	13.5	13.9	13.7	13.9	−1.3
1.29	1.29	50–50	4.16	4.16	8.32	8.32	0	13.8	13.8	13.8	13.8	0.0

Note: Heading key = drainage area (A); peak discharge (Q_p); time to peak (t_p); without subdivision (NS); with subdivision (SUB).

in size, subdivision produced a larger peak discharge (3.7–4.7% increase).

The effect of relative size in two parallel subbasins is related to differences in peak timing weighted by runoff, which in turn is controlled by relative area. As the relative size difference between subbasin 1 and 2 grows, the difference between $t_{p,1}$ and $t_{p,2}$ increases (Table 2). However, simultaneously, the contribution and thereby relative importance of the smaller subbasin diminishes as its area decreases. This explains why the largest difference in time to peak occurs when the area ratio is 40 to 60%, between the extremes of equal areas (50–50%) and a non-subdivided watershed (100–0%), and with the relative size of both subbasins comparable so the contribution of each is important.

Peak discharges are lessened when subbasin areas are most different, for example when the area ratio is 90–10%, because the subbasin peaks are not coincident, separated by 1.63 h. In addition, because of its longer travel time, the larger subbasin, which contributes the majority of runoff, produces a lower peak discharge. When the area ratio is nearly equal (60–40%), the subbasin peaks occur at nearly the same time and are more pronounced.

Experiment 3: Effect of Difference in CN for Subwatersheds

The third experiment evaluated the role of CN in peak discharge rates when a theoretical watershed is subdivided in parallel. Both subwatersheds had a fixed drainage area of 1.29 km², resulting in a total drainage area of 2.59 km² as in Experiment 2. The curve number values for the two subwatersheds were varied so as to achieve incremental differences of 5, over the range of 60 to 90. Because of the variation scheme used, the average CN of the overall watershed remained fixed at 75 for all configurations. Results are shown in Table 3.

Peak discharge for the subdivided case ($Q_{p,\mathrm{SUB}}$) was always greater than the non-subdivided watershed and increased nonlinearly with increasing curve number difference (ΔCN). As such, the maximum increase in peak discharge (almost 81%) corresponds to the largest difference in curve number (ΔCN = 30, $CN_1 = 90$, $CN_2 = 60$). When ΔCN is less than 5, the increase in peak discharge is relatively small (<5.2%), though this difference remains larger than the most extreme area subdivision case (Table 4). The increasing effect of CN differences on a parallel subdivided watershed is related to the nonlinearity of the SCS rainfall-runoff equation, which produces ever-increasing runoff depth and flashier behavior (lower t_c) from highly urbanized (high CN) areas.

Differences in time to peak, $t_{p,1}$ and $t_{p,2}$, increased linearly with differences in CN, from 0 to 2.0 h (Table 3). However, unlike the relative area comparison (Experiment 2), this difference in peak timing makes little difference relative to the additional runoff

produced by the more impervious (higher CN) area. Runoff from the urban subwatershed far exceeds runoff from the rural subwatershed, which is why time to peak for the entire subdivided watershed, $t_{p,\mathrm{SUB}}$, is nearly identical to the urban watershed, $t_{p,1}$.

The high sensitivity to CN differences and relatively insensitivity to peak timing can be shown graphically by comparing the hydrographs produced by the urban and rural subwatersheds. Fig. 3 shows runoff hydrographs for four cases: (a) ΔCN = 30; (b) ΔCN = 20; (c) ΔCN = 10; and (d) ΔCN = 0. For the most extreme CN differences [Figs. 3(a and b)], the urban watershed produces a large, flashy hydrograph and as such, dominates the resulting total watershed discharge. The low CN subbasin produces very little runoff, with the peak occurring significantly later, and as such only contributes to the falling limb of the hydrograph. When CN differences are smaller [Figs. 3(c and d)], the urban and rural hydrographs are more similar, but are smoother with lower peak discharge. This creates an increase in peak discharge relative to non-subdivided watershed, but only to a minor degree.

Experiment 4: Effect of Differences in Subwatershed Area and CN

As a final experiment, the relative proportion of the two parallel subdivisions was allowed to vary in conjunction with the CN difference. The area fraction and CN difference were evaluated separately in Experiments 2 and 3, respectively; however, it is important to quantify the effects of their interaction. For this analysis, the fraction of subwatershed area and the CN difference (ΔCN) were simultaneously varied for the subdivision and no subdivision cases. Peak discharge without subdivision was calculated based on the appropriate area-weighted average CN as a baseline for each case.

Fig. 4(a) shows the case where the urban (high CN) subwatershed represents the larger area fraction and Fig. 4(b) shows the case where the rural (low CN) subwatershed has greater area. As in Experiment 3, the difference in CN appears to be the most important factor with respect to peak discharge and this effect increases nonlinearly with increasing differences. Following the results in Experiment 2, the area ratio affects the peak discharge by changing the overland travel time. For the majority of cases, the highest difference in peak discharge occurs when the subdivided areas are nearly equal (50%), allowing the discharge peaks to coincide and add.

When the urban subdivision has a larger area [Fig. 4(a)], peak discharge is increased relative to the non-subdivided watershed for nearly all cases and increases with increasing differences in CN. The increase is detectable (5–10%) for ΔCN > 10 ($CN_1 = 80$, $CN_2 = 70$) when area ratios are nearly equal. The effects of subdivision on peak discharge decrease as the watershed becomes

Table 3. Results of Experiment 3: Results of Curve Number Difference Experiment with Parallel Subdivision

			Q_p					t_p				
ΔCN	CN_1	CN_2	$Q_{p,1}$ (m³/s)	$Q_{p,2}$ (m³/s)	$Q_{p,\mathrm{SUB}}$ (m³/s)	$Q_{p,\mathrm{NS}}$ (m³/s)	ΔQ_p (%)	$t_{p,1}$ (h)	$t_{p,2}$ (h)	$t_{p,\mathrm{SUB}}$ (h)	$t_{p,\mathrm{NS}}$ (h)	Δt_p (%)
0	75	75	4.16	4.16	8.32	8.32	0	13.8	13.8	13.8	13.8	0
5	77.5	72.5	4.92	3.49	8.29	7.88	5.2	13.6	13.9	13.8	13.9	−0.7
10	80	70	5.79	2.90	8.35	7.47	11.8	13.4	14.1	13.6	14.0	−3.1
15	82.5	67.5	6.78	2.38	8.54	7.07	20.8	13.2	14.2	13.4	14.1	−5.1
20	85	65	7.93	1.95	9.01	6.71	34.3	13.2	14.5	13.3	14.4	−7.8
25	87.5	62.5	9.22	1.57	9.85	6.41	53.6	13.1	14.7	13.1	14.5	−10.1
30	90	60	10.69	1.25	11.00	6.08	80.9	12.9	15.1	12.9	14.6	−11.7

Note: Heading key = curve number (CN); peak discharge (Q_p); time to peak (t_p); without subdivision (NS); with subdivision (SUB).

Table 4. Summary of Subdivision Effects on Time to Peak (t_p) and Peak Discharge (Q_p)

Experiment	Δt_p		ΔQ_p	
	Min (%)	Max (%)	Min (%)	Max (%)
Ex. 1: series subdivision	−14.0	−1.6	26.5	30.2
Ex. 2: parallel—varying area	−2.4	0	−4.5	4.7
Ex. 3: parallel—varying CN	−11.7	0	0	80.9
Ex. 4: parallel—varying area and CN	−22.1	0	−14.0	91.0

more impervious, eventually tending towards zero when urban area represents 90% of the watershed [Fig. 4(a)]. This is expected, as both the subdivided and non-subdivided watersheds have average CNs corresponding to near zero infiltration, which in turn leaves little difference between the two.

When the rural subdivision has a larger area, an interesting result occurs. For values of ΔCN below 20, when the urban fraction is less than or equal to 20%, subdivision decreases the peak discharge [Fig. 4(b)]. This decrease is caused by significant differences in peak timing for the urban and rural subdivisions, which minimizes the effect of the normally important urban subwatershed. When the urban portion becomes significant (>30% by area), this timing issue is minimized and peak discharge follows the expected pattern of increasing peak discharge, shown in Fig. 4(a).

Discussion

These results show that, for a simplified two-subbasin case, peak discharge is most sensitive to differences in curve number between the subbasins (Table 4). For differences in CN as little as 10 ($CN_1 = 80$, $CN_2 = 70$), peak discharge can be increased by 11.8%. For the most extreme case tested, if a watershed with an area weighted CN of 75 were to be separated into its constituent parts, with subbasin CN values of 60 and 90, respectively, modeled peak discharge would increase by 80.9% (Tables 3 and 4). It is important to note that, in this case, subdividing a watershed into a near impervious industrial area (CN = 90) and agricultural land with well-drained soil (CN = 60) is reasonable and is likely nearer to real-life conditions, with the non-subdivided model significantly underestimating peak discharge. This example highlights the high sensitivity to CN differences and the need for appropriate subdivision, avoiding unnecessary subdivision of similar CNs and allowing for subdivision of areas with significantly different CNs.

The problem of unnecessary subdivision is highlighted in Experiments 1 and 2, where a watershed with consistent land surface is unnecessarily subdivided first in series (Experiment 1) and then in parallel (Experiment 2). Peak discharge was most sensitive to series subdivision, which produced greater than 25% increase in peak flow by act of subdivision alone, regardless of the area ratio (Table 4). Parallel subdivision was the least sensitive parameter examined, producing a much smaller effect (−4.5 to 4.7%) related to times to peak from the two subwatersheds. When the times to peak
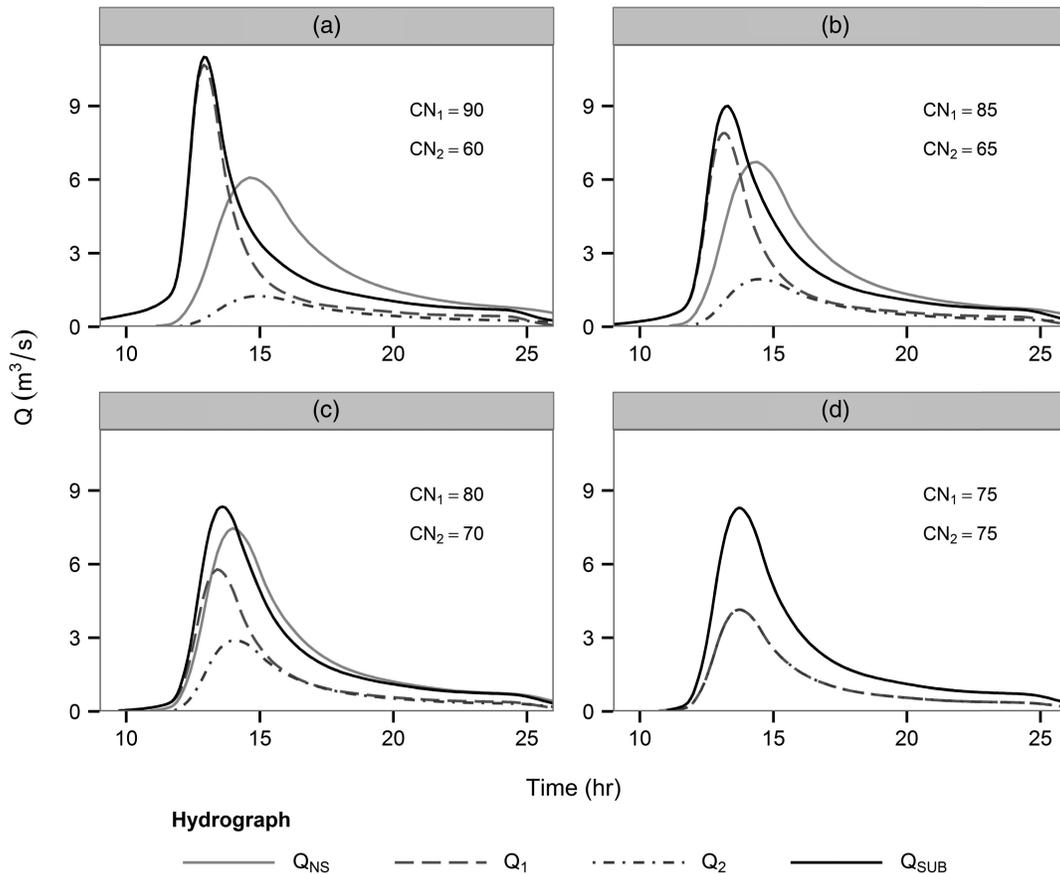

Fig. 3. Effect of CN variation on runoff hydrographs for parallel subdivision with equal size subwatersheds for (a) ΔCN = 30; (b) ΔCN = 20; (c) ΔCN = 10; (d) ΔCN = 0
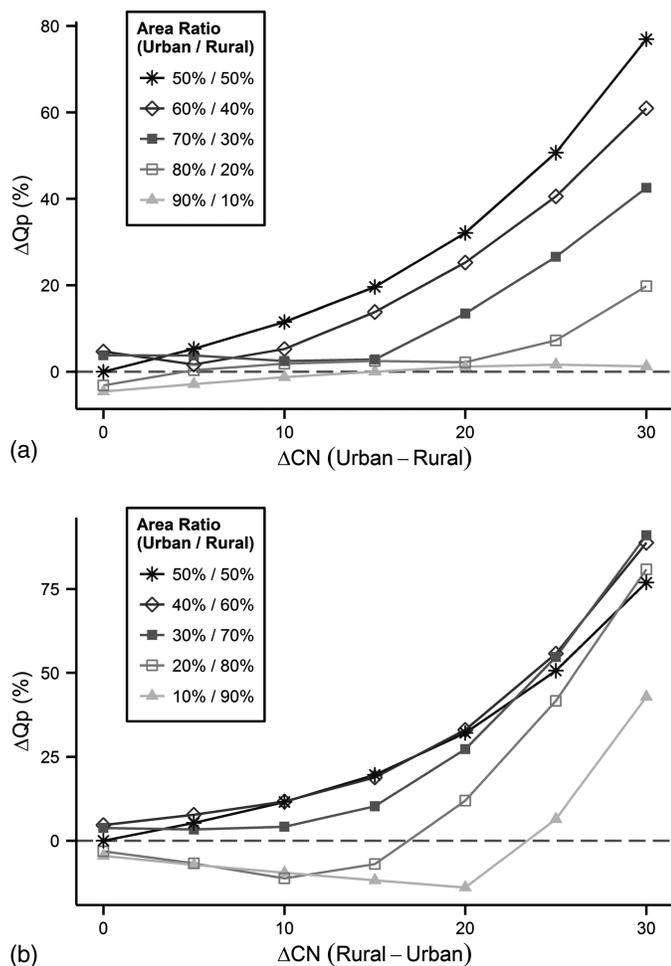
Fig. 4. Percent change in peak flow versus ΔCN for (a) larger urban area; (b) larger rural area

coincide, peak discharge increased when compared to the non-subdivided watershed. However, when area ratios differed significantly, the time to peak differed significantly, decreasing resultant peak discharge.

Findings presented here disagree with previous research (Norris and Haan 1993; Tripathi et al. 2006; Kalin et al. 2003; Rojas et al. 2008) that suggests that greater subdivision results in increased peak discharge. While this is the case for the majority of hypothetical watersheds tested, decreases in peak discharge were noted when watersheds were subdivided in parallel with greatly different area ratios (Table 2) or for subdivided watersheds with a significant portion of low CN area [Fig. 4(b)].

It is also important to note that even within this simplified, hypothetical model when multiple parameters were allowed to vary, as in Experiment 4, the effect of subdivision quickly becomes complex. This reinforces the conclusion that although these *unit subdivision* results provide insight into how a subdivided rainfall-runoff model will behave, it is important for modelers to test this sensitivity within their own models, as the effects may be complex and unexpected.

Guidance for the Application of Subdivision

The analysis presented herein showed that parallel subdivision can increase the peak discharge by up to 80.9% when the difference in CN between two parallel subwatersheds is large. This shows the

importance of modeling CN as accurately as possible and separating subbasins based on differences in CN. Additionally, unnecessary subdivision should be avoided when modeling a watershed with relatively homogenous features, as this can greatly increase peak discharge when divided in series and produce mixed effects when modeled in parallel.

This paper can now present guidelines to aid the engineer in the rational application of subdivision. The guidelines presented here are based on local effects of subdivision since the global effects cannot be identified without knowledge of other hydrographs flowing to the design point. They are based on the knowledge of parameter values so that heterogeneities can be identified and compared to support a subdivision decision. Since the correctness of subdivision is not addressed, the language of these guidelines is intended to support decisions based on the effects of subdivision. That is, if the guidelines state that subdivision is not necessary given certain conditions, it is implied that subdivision has a minimal effect. The following guidelines are proposed:

1. As long as the watershed is homogeneous with respect to CN, it is not necessary to subdivide based on area alone (i.e., making watershed areas equal). Focus instead on the most accurate depiction of land surface (Rule 2) and overland/channel flow (Rule 3).
2. If the difference in curve number between two potential subwatersheds is greater than 5 to 10, subdivision should be considered. This is the most sensitive modeling parameter.
3. Make sure there is a physical basis for series subdivision, as this produces an immediate effect on peak discharge.
4. Understand that complex hydrologic models may have complex interactions. If possible, test several subdivision scenarios to determine the model's sensitivity to this parameter.

Conclusions

Ideally, the magnitude of a computed peak discharge for a heterogeneous watershed should not differ significantly based on modeler decisions. Unfortunately, commonly used watershed models yield significantly different peak discharge estimates for different subdivision layouts. In addition, watershed subdivision can lead to unrealistic peak discharge rates without a corresponding change in runoff volume.

It has been shown by others and is demonstrated in this work that subdivision generally causes predicted peak discharge to increase, though in very specific cases may also produce decreases. This behavior has important implications in design depending on how subdivision is applied. Subdivision is necessary to reflect heterogeneities in watershed conditions, but improper or excessive subdivision could produce artificially high modeled flows, leading to over-designed hydraulic structures. Subdivision sensitivity also affects the accuracy of flood risk estimates. Inflated estimates of flood magnitudes due to subdivision will adversely influence flood risk estimates whether for an annual exceedence probability or for binomial flood risk. Therefore, it may be good design practice to test several subdivision scenarios to test model sensitivity before selecting a final design flow. For any one case, understanding the effects of alternate subdivision scenarios can reduce the risk of overdesign or underdesign.

By simulating the hydrologic response of a simple, theoretical watershed over a range of subdivision scenarios, the sensitivity of peak discharge to subdivision was analyzed. Simulated peak discharges produced by WinTR-20 were compared for watersheds featuring series and parallel subdivision with discharges from the same watersheds without subdivision. It was shown that subdivision

based on variation in watershed parameters, especially CN differences, produced the greatest changes in peak discharge, up to 80.9% over the undivided cases. Peak discharge was also found to be highly sensitive to serial subdivision and less sensitive to parallel subdivision. Effects from this type of subdivision are explained by their relative effects on peak timing. In the case of the fractional watershed area analysis, when the peaks of the hydrographs arriving at the outlet differed significantly in time, a decrease in peak discharge was apparent when compared to the case when the watershed was not subdivided. When the times to peak coincided, peak discharge increased. The effect of CN amplified this result because it was used both in estimating the time of concentration and in determining the runoff volume generated from a subwatershed.

Based on these reported findings, guidance for the rational application of watershed subdivision to an actual watershed modeling exercise was provided. Where observations are available, the degree of subdivision may be calibrated, similar to other hydrologic parameters. For the majority of watersheds where this is not possible, the proposed guidelines should be followed and sensitivity analyses performed to determine the potential error related to the subdivision scheme.

References

Arnold, J. G., Engel, B. A., and Srinivasan, R. (1993). "A continuous time, grid cell watershed model." *Proc., Application of Advanced Information Technologies: Effective Management Natural Resources Conf.*, ASAE, St. Joseph, MI, 267–278.

Bingner, R. L., Garbrecht, J., Arnold, J. G., and Srinivasan, R. (1997). "Effect of watershed subdivision on simulation runoff and fine sediment yield." *Trans. ASAE*, 40(5), 1329–1335.

Casey, M. J. (1999). "The effect of watershed sudivision on simulated hydrologic response using the NRCS TR-20 model." Master's thesis, Dept. of Civil and Environmental Engineering, Univ. of Maryland, College Park, MD.

Chen, E., and Mackay, D. S. (2004). "Effects of distribution-based parameter aggregation on a spatially distributed agricultural nonpoint source pollution model." *J. Hydrol.*, 295(1–4), 211–224.

Cho, H., and Olivera, F. (2009). "Effect of the spatial variability of land use, soil type, and precipitation on streamflows in small watersheds." *J. Am. Water Resour. Assoc.*, 45(3), 673–686.

Cho, J., Lowrance, R. R., Bosch, D. D., Strickland, T. C., Her, Y., and Vellidis, G. (2010). "Effect of watershed subdivision and filter width on SWAT simulation of a coastal plain watershed." *J. Am. Water Resour. Assoc.*, 46(3), 586–602.

Cunge, J. A. (1969). "On the subject of a flood propagation computation method (Muskingum method)." *J. Hydraul. Res.*, 7(2), 205–230.

Cydzik, K., and Hogue, T. S. (2009). "Modeling postfire response and recovery using the hydrologic engineering center hydrologic modeling system (HEC-HMS)." *J. Am. Water Resour. Assoc.*, 45(3), 702–714.

Dunne, T., and Leopold, L. B. (1978). *Water in environmental planning*, W.H. Freeman, New York, 818.

Fitzhugh, T. W., and Mackay, D. S. (2000). "Impacts of input parameter spatial aggregation on an agricultural nonpoint source pollution model." *J. Hydrol.*, 236(1–2), 35–53.

Ghosh, I., and Hellweger, F. L. (2012). "Effects of spatial resolution in urban hydrologic simulations." *J. Hydrol. Eng.*, 10.1061/(ASCE)HE .1943-5584.0000405, 129–137.

Goodrich, D. C., Woolhiser, D. A., and Sorooshian, S. (1988). "Model complexity required to maintain hydrologic response." *Hydraulic engineering*, S. A. Abt and J. Gessler, eds., ASCE, New York, 431–436.

Han, J.-C., Huang, G.-H., Zhang, H., Li, Z., and Li, Y.-P. (2013). "Effects of watershed subdivision level on semi-distributed hydrological simulations: Case study of the SLURP model applied to the Xiangxi River watershed, China." *Hydrol. Sci. J.*, 59(1), 108–125.

Jha, M., Gassman, P. W., Secchi, S., Gu, R., and Arnold, J. (2004). "Effect of watershed subdivision on SWAT flow, sediment, and nutrient predictions." *J. Am. Water Resour. Assoc.*, 40(3), 811–825.

Kalin, L., Govindaraju, R. S., and Hantush, M. M. (2003). "Effect of geomorphologic resolution on modeling of runoff hydrograph and sedimentograph over small watersheds." *J. Hydrol.*, 276(1–4), 89–111.

Migliaccio, K. W., and Chaubrey, I. (2008). "Spatial distributions and stochastic parameter influences on SWAT flow and sediment predictions." *J. Hydrol. Eng.*, 10.1061/(ASCE)1084-0699(2008)13:4(258), 258–269.

Norris, G., and Haan, C. T. (1993). "Impact of subdividing watersheds on estimated hydrographs." *Appl. Eng. Agric.*, 9(5), 443–445.

NRCS (Natural Resources Conservation Service). (1998). *National engineering handbook. Part 630—Hydrology*, Washington, DC.

NRCS (Natural Resources Conservation Service) (2008). "Win TR-20 tutorial." ⟨www.wsi.nrcs.usda.gov/products/w2q/H . . ./WinTR20/ WinTR20Tutorial.ppt⟩ (Jul. 3, 2011).

Rojas, R., Velleux, M., Julien, P. Y., and Johnson, B. E. (2008). "Grid scale effects on watershed soil erosion models." *J. Hydrol. Eng.*, 10.1061/ (ASCE)1084-0699(2008)13:9(793), 793–802.

SCS (Soil Conservation Service). (1973). "A method for estimating volume and rate of runoff in small watersheds." *TP-149*, U.S. Dept. of Agriculture, Washington, DC.

Stephenson, D. (1989). "Selection of stormwater model parameters." *J. Environ. Eng.*, 10.1061/(ASCE)0733-9372(1989)115:1(210), 210–220.

Thompson, D. B., and Cleveland, T. G. (2009). "Subdivision of Texas watersheds for hydrologic modeling." *0-5822*, Texas Dept. of Transportation Research and Technology, Texas Tech Univ., Lubbock, TX.

Tripathi, M. P., Raghuwanshi, N. S., and Rao, G. P. (2006). "Effect of watershed subdivision on simulation of water balance components." *Hydrol. Process.*, 20(5), 1137–1156.

Warwick, J. J., and Litchfield, J. (1993). "Impact of spatial and temporal data limitations on the modeling of runoff quantity and quality." *Water management in the '90's: A time for innovation*, K. Hon, ed., ASCE, New York, 862–865.

Zaghloul, N. A. (1981). "Sensitivity analysis of the SWMM runoff-transport parameters and the effects of catchment discretisation." *Adv. Water Resour.*, 6(4), 214–223.