HYDROLOGICAL PROCESSES
Hydrol. Process. **28**, 774–783 (2014)
Published online 21 November 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.9592

Initial abstraction and curve numbers for semiarid watersheds in Southeastern Arizona

Yongping Yuan,[1]* Wenming Nie,[1] Steven C. McCutcheon[2] and Encarnación V. Taguas[3]

[1] *USEPA-Office of Research and Development, Environmental Sciences Division, 944 East Harmon Avenue, Las Vegas, Nevada 89119, USA*
[2] *USEPA-Office of Research and Development, Ecosystems Research Division, 960 College Station Road, Athens, Georgia, 30605, USA*
[3] *Department of Rural Engineering, University of Cordoba, Apdo 3048, 14080, Cordoba, Spain*

Abstract:

The Soil Conservation Service (SCS) curve number (CN) estimates of direct runoff from rainfall for semiarid catchments can be inaccurate. Investigation of the Walnut Gulch Experimental Watershed (WGEW) (Southeastern Arizona) and its ten nested catchments determined that the inaccuracy is due to the original SCS ratio (λ) of 0.2 between initial abstraction and maximum potential retention. Sensitivity analyses indicate that runoff estimation can be very sensitive to the initial abstraction ratio, especially for relatively low rainfall amount and for watersheds covered by deep, coarse, and porous soil, conditions that dominate many semiarid watersheds worldwide. Changing the ratio of initial abstraction to the maximum potential retention to optimal values ranging from 0.01 to 0.53 for different Walnut Gulch catchments improved runoff estimates. The greater the channel area and the finer the soil, the smaller the initial abstraction ratio is. The variation of the initial abstraction ratio for the WGEW is due to the variation of maximum potential retention and initial abstraction, which are channel area and soil-dependent parameters. The greater the channel area, the higher the maximum potential retention S is, and the coarser the soil, the larger the initial abstraction I_a is. In addition, the effect of initial abstraction ratio on runoff estimation increases with decreasing CN. Thus, impacts of initial abstraction ratio on runoff estimation should be considered, especially for semiarid watersheds where the CN is usually low. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS curve number; runoff; initial abstraction ratio; maximum potential retention; semiarid watershed

Received 1 September 2011; Accepted 8 October 2012

INTRODUCTION

The Soil Conservation Service (SCS, now the Natural Resources Conservation Service) curve number (CN) method is widely used to estimate direct runoff from a specific or design rainfall (Hawkins *et al*., 2009; SCS, 1985). Reasons for the wide application of this method are (1) the computations are efficient; (2) the required soil type, land use, and management practices are readily available; and (3) it produces satisfactory runoff estimates for many agricultural and urban watersheds (Gassman *et al*., 2007; Hawkins *et al*., 2009; Ponce & Hawkins, 1996; Wang *et al*., 2009; Yuan *et al*., 2001). However, the estimated runoff is inaccurate where watershed retention is a large fraction of the rainfall, as in semiarid watersheds in southeastern Arizona (Hjelmfelt, 1980; Baltas *et al*., 2007; Soulis *et al*., 2009).

The watershed retention concept includes the initial abstraction I_a, the initial rainfall in mm retained before runoff starts; and the maximum potential retention S, the maximum water in mm that a watershed can potentially retain during a rainfall and from which the CN is derived (NRCS, 1997). The SCS originally defined the slope of a log linear approximation to relate the initial abstraction to the maximum potential retention as 0.2 (Figure 10.2 of the National Engineering Handbook-section 4; SCS, 1985), but the source of the original highly uncertain daily rainfall and runoff is no longer known (Hawkins *et al*., 2009). Later, this slope was labeled the initial abstraction ratio λ (Chen, 1982). Because of the uncertainty and unknown origin, several investigators have re-evaluated the selection of 0.2 (Baltas *et al*., 2007; Mishra *et al*., 2006; Mishra & Singh, 2004; Woodward *et al*., 2004; Hawkins *et al*., 2002; Jiang, 2001). For example, Woodward *et al*. (2004) determined the initial abstraction ratio λ to be 0.05 from rainfall and runoff measurements on 327 watersheds in the eastern, mid-western, and southern U.S. In addition, they found that the initial abstraction ratio λ varied from storm to storm and from watershed to watershed (Woodward *et al*., 2004; Jiang, 2001). The maximum potential retention S, from which the CN is derived (NRCS, 1997), was originally defined as a variable of land cover and land treatment, hydrological soil group and condition, and antecedent soil moisture (NRCS, 1997). However, studies in Walnut Gulch Experimental Watershed (WGEW), located in southeastern Arizona, showed that soil moisture had little impact on stream flow in the arid and semi-arid watersheds (Syed *et al*., 2003) because the watershed is almost always dry when it rains and soil moisture 'memory' is relatively short in semiarid conditions. In addition, studies performed by Goodrich *et al*. (1997) and Simanton *et al*. (1996) in the same watershed found that ephemeral

*Correspondence to: Yongping Yuan, USEPA-Office of Research and Development, Environmental Sciences Division, 944 East Harmon Avenue, Las Vegas, NV 89119, USA.
E-mail: yuan.yongping@epa.gov

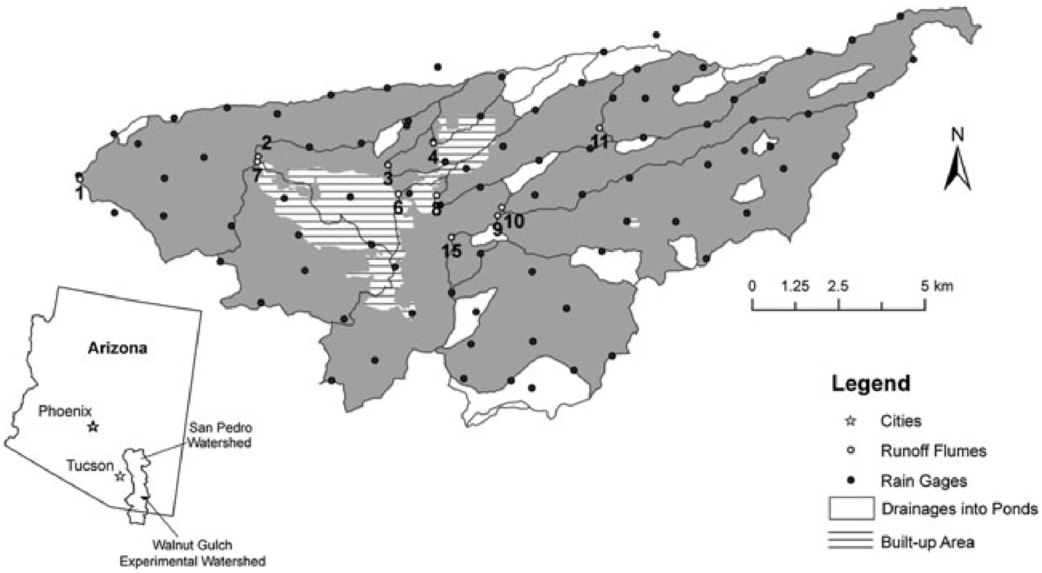

Figure 1. Catchments, rain gages, runoff flumes, drainages into ponds that retain all runoff, and built-up areas of the USDA-ARS Walnut Gulch Experimental Watershed. (Modified from Goodrich *et al.*, 1997)

channel losses and partial storm area coverage became increasingly important to rainfall-runoff relationship as watershed scale increases, with a critical transition threshold area of around the range of 37–60 ha. They concluded that runoff modeling in WGEW and similar semiarid areas requires explicit treatment of transmission losses from channel infiltration. For these reasons, the controlling factors for the initial abstraction ratio must be re-evaluated before assigning a universal value for this parameter. In this study, the sensitivity of initial abstraction ratio on runoff estimation was analyzed first to illustrate the importance of this study. Then, the initial abstraction I_a, maximum potential retention S, and initial abstraction ratio λ were determined and correlated to drainage area, channel area, and soil characteristics for the WGEW and its ten nested catchments in southeastern Arizona. Finally, relationships between CN with λ of 0.2 and CN with λ of different values were explored to extend findings from this study to other types of land use. The objectives of this study are to (1) determine the optimized I_a, S, and λ for the 11 catchments; (2) compare runoff estimations with measurements using the optimized λ from this study and a fixed λ of 0.2; (3) re-evaluate the controlling factors for I_a, S, and λ; and (4) develop relationships between CN with λ of 0.2 and CN with different λ.

RESEARCH METHODS

Study catchments

This study investigated the WGEW operated by the U. S. Department of Agriculture, Agricultural Research Service, and ten catchments nested within the watershed in Southeastern Arizona (Figure 1). The experimental watershed has an area of 148 km^2 and lies between latitude 31° 63′ N and 32° 81′ N and longitude 110° 15′ W and 109° 89′ W. Elevations in the watershed range from 1217 m to 1929 m. The average annual rainfall is approximately 324 mm, but varies seasonally and annually (Goodrich *et al.*, 1997). Seventy five percent of the annual total precipitation occurs from July to mid-September as intense, brief, localized thunderstorms (Simanton *et al.*, 1996). Detailed land cover information in the WGEW can be found in Skirvin *et al.* (2008). In summary, the dominant vegetation on the watershed is shrubs with grass. Other vegetation includes shrubs with scattered grass, grass and scattered shrubs, grass, oak woodland, and trees and shrubs along channels (Skirvin *et al.*, 2008). Built-up or disturbed land use occupied about 8% of the watershed (Skirvin *et al.*, 2008). As shown in Figure 2, the watershed (ponds excluded) is mainly covered by well-drained sandy loam (71.7%) and loamy sand (3.3%), and by relatively fine loam (20.8%), undefined riparian soil (2.7%), and clay loam (1.6%) (Heilman *et al.*, 2008). The WGEW contains 17 ponds (man-made terminal basins) that do not contribute runoff and that have an area of 1700 ha. Because the ponds do not contribute runoff, pond area was excluded from runoff calculation. The drainage area excluding pond area is defined as active drainage area in this study. For example, the watershed has an active drainage area of 13 100 ha (Table I).

Data analysis

Sensitivity analysis. The sensitivity analysis includes two steps: (1) evaluating the effect of the initial abstraction ratio λ on runoff estimation; and (2) examining impacts of the CN and rainfall on the relative sensitivity of λ on runoff.

To evaluate the impact of λ on runoff estimation, relative changes of runoff with progressive changes of λ were examined. Decreased from 0.2 to 0.02, the λ was reduced 10% in each step. The relative changes of runoff were estimated using equation:

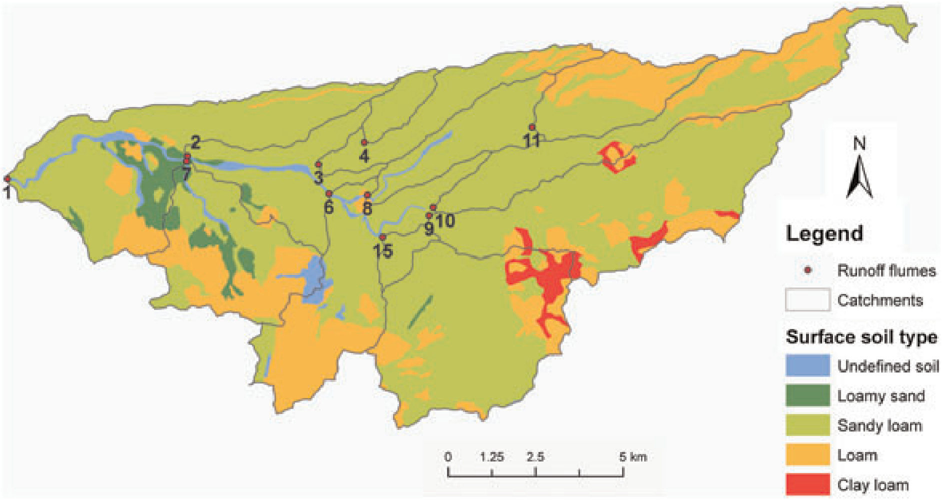

Figure 2. Surface soil type of the USDA-ARS Walnut Gulch Experimental Watershed

Table I. Parameters derived using the least square method from rainfall-runoff pairs measured between 1967 and 1989 for the USDA-ARS Walnut Gulch Experimental Watershed and ten nested catchments

Runoff gage	Number of data pairs	Number of $Q>0$	Active drainage area (ha)	Optimized λ				$\lambda=0.2$	
				S (mm)	CN	I_a (mm)	λ	S (mm)	CN
1	1590	101	13 100	386.8	39.6	7.5	0.02	93.5	73.1
2	1555	140	9561	244.9	50.9	7.5	0.03	79.5	76.2
3	1027	133	546	33.0	88.5	17.5	0.53	66.1	79.3
4	911	82	229	109.2	69.9	11.1	0.10	70.9	78.2
6	1486	140	8147	273.3	48.2	5.0	0.02	76.5	76.8
7	1136	116	1363	108.5	70.1	17.7	0.16	95.5	72.7
8	1186	127	1330	50.0	83.6	11.4	0.23	54.3	82.4
9	1282	111	2076	149.9	62.9	6.4	0.04	69.5	78.5
10	1242	101	1478	328.4	43.6	3.3	0.01	85.7	74.8
11	1030	141	635	54.8	82.2	10.9	0.20	54.6	82.3
15	1167	102	1640	265.3	48.9	4.0	0.02	78.8	76.3

$$\nabla Q_i = \frac{Q_i - Q_0}{Q_0} \times 100 \tag{1}$$

where ∇Q_i is the relative change of runoff at step i, Q_i and Q_0 are calculated runoff at step i and step 0, respectively. The λ declines from 0.2 to 0.02 from step 0 to step 9, with 10% decrease for each step. Corresponding runoff used in Equation (1) was calculated using the following equations:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad \text{when } P > I_a$$

$$Q = 0 \quad \text{when } P \leq I_a \tag{2}$$

$$\text{and } I_a = S \times \lambda \tag{3}$$

where Q is runoff, P is rainfall depth, I_a initial abstraction, S the maximum potential retention, and λ the initial abstraction ratio. The P used in Equations (2) and (3) is 1 inch (25.4 mm) to represent typical rainfall in the semiarid southwestern US (1 inch to 4 inches in the WGEW). A CN of 80, the median estimated from Simanton *et al.* (1996) for the WGEW, was used to estimate S used in the above equations.

To examine impacts of CN or rainfall on relative sensitivity of λ on runoff, changes of relative sensitivity with a progressive change of CN or rainfall depth was evaluated. Relative sensitivity, S_r, was calculated using the following equation:

$$S_r = \left(\frac{x}{y}\right)\left(\frac{y_2 - y_1}{x_2 - x_1}\right) \tag{4}$$

where x is the initial abstraction fraction (λ), y is the estimated runoff, x_1, x_2, and y_1, y_2 are $\pm$10% of the initial value of λ and associated runoff values, respectively (White & Chaubey, 2005). The initial λ was set as 0.2; hence, the x_1 and x_2 was 0.18 and 0.22, respectively.

More specifically, S_r values were first calculated with progressively increased rainfall (15 – 75 mm), while the CN remained unchanged ($CN = 80$), and then S_r values were calculated with a progressively increased CN (70 – 100), while the rainfall depth remained unchanged ($P = 25.4$ mm).

Representative catchment rainfall. This study compiled rainfall and runoff for the WGEW and ten of the nested catchments larger than 229 ha (Table I). Catchments with relatively larger active drainage area were selected for the following two reasons: (1) to reduce the impacts of scale on runoff or CN (Goodrich *et al*., 1997; Simanton *et al*., 1996); and (2) to examine impacts of soil on runoff estimation, as the WGEW and ten catchments were covered by different types of soil.

For each catchment, representative rainfall occurring during 1967 to 1989 was estimated using Thiessen polygon weighting (NRCS, 1997). Only rainfall-runoff from July 1st to Sept. 14th were consistently available for this study because during 1980 to 1989, most rain gages were not operated for the remainder of the year (Goodrich *et al*., 2008; Stone *et al*., 2008). This study defined a new event if at least 1 h lapsed with no rainfall at any gages for a catchment (Syed *et al*., 2003). The estimated representative rainfall was matched with runoff. Runoff was matched to a rainfall, if that runoff started after the rainfall but no later than 2.5 h after that rainfall ended. Runoff in cubic feet was converted to mm based on active drainage area.

Parameter estimation and testing. Least square fit method was used for parameter estimation for each catchment. Based on observed rainfall P (independent variable) and runoff Q (dependent variable) during 1967 to 1989, two independent parameters of I_a and S in Equation (2) were first estimated using the least-square method to minimize the sum of the square of the residuals. Then, again, the least square fit method was used to estimate the only parameter S (because $I_a = 0.2S$) in Equation (5) (NRCS, 1997) using the same observed rainfall and runoff data including rainfall events without generation of runoff. The MATLAB (http://www.mathworks.com/help/techdoc/) software was used to perform this analysis and results are shown in Tables I and II.

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad P > 0.2S$$

$$Q = 0 \quad P \leq 0.2S \tag{5}$$

The CN was estimated from the maximum potential retention S as:

$$CN = \frac{25400}{254 + S} \tag{6}$$

Three statistics were used to evaluate goodness of fit and bias for Equation (5) and Equation (2). These include the Nash–Sutcliff coefficient (*NSE*), the coefficient of determination (R^2), and the percent of bias (*PBIAS*). The Nash–Sutcliff coefficient is (Gupta *et al*., 1999; Nash & Sutcliffe, 1970)

$$NSE = 1 - \left[\frac{\sum_i^n (Q_{esti} - Q_{obsi})^2}{\sum_i^n (Q_{obsi} - Q_{avg})^2}\right] \tag{7}$$

Table II. Evaluation of runoff estimation for the USDA-ARS Walnut Gulch Experimental Watershed and ten nested catchments during 1967 to 1989 using estimated S and I_a as listed in Table I

Runoff gage	Optimized λ			λ = 0.2		
	NS	PBIAS	R^2	NS	PBIAS	R^2
1	0.39	12.0	0.39	0.25	64.9	0.26
2	0.41	16.7	0.41	0.35	50.9	0.36
3	0.62	24.5	0.62	0.60	9.4	0.61
4	0.51	6.0	0.51	0.50	15.9	0.50
6	0.44	4.2	0.44	0.34	51.4	0.36
7	0.74	26.5	0.74	0.74	31.0	0.74
8	0.57	17.9	0.57	0.57	15.6	0.57
9	0.65	4.6	0.65	0.61	33.3	0.61
10	0.34	1.5	0.34	0.23	61.1	0.25
11	0.64	13.9	0.64	0.64	14.0	0.64
15	0.48	−5.8	0.48	0.34	46.7	0.37

where n is the number of matched pairs of rainfall and runoff, Q_{esti} and Q_{obsi} the estimated and observed runoff for pair i, and Q_{avg} the average observed runoff over the optimization period. The coefficient of determination R^2 is

$$R^2 = \left\{ \frac{\sum_{i=1}^{n} (Q_{obsi} - Q_{obsave})(Q_{esti} - Q_{estave})}{\left[\sum_{i=1}^{n} (Q_{obsi} - Q_{obsave})^2 \sum_{i=1}^{n} (Q_{esti} - Q_{estave})^2\right]^{0.5}} \right\}^2 \tag{8}$$

where Q_{estavg} and Q_{obsavg} are the average estimated and observed runoff over the optimization period. The *PBIAS* is

$$PBIAS = \left[\frac{\sum_{i=1}^{n} (Q_{obsi} - Q_{esti}) \times 100}{\sum_{i=1}^{n} (Q_{obsi})}\right] \tag{9}$$

The goodness of fit is the best when R^2 and *NSE* approach to one and the closer *PBIAS* is to zero the less bias (Walvoord *et al*., 2003). These statistics were only used to evaluate the relative performance of Equation (5) and Equation (2), to prevent any uncertainty derived from a heuristic criterion when evaluating satisfactoriness of runoff estimates (McCuen *et al*., 2006).

Multiple regression. Multiple regression analysis was performed to further explore any other factors affecting runoff that might not be completely incorporated into the CN method. Particularly, multiple regression analysis was performed to explore any correlations of the maximum potential retention, initial abstraction, and initial abstraction ratio with surface soil type, active drainage area, and channel area for the WGEW and ten nested catchments.

Multiple regressions were performed to determine the contribution of active drainage area, channel area, and soil type to estimated I_a, S, and λ. The independent variables were proportional extent of four soils (clay loam, loam, sandy loam, and loamy sand) in active drainage area, and the logarithmic transformation of active drainage area and channel area for each catchment. The dependent variables were I_a, and logarithmic transformation of I_a, S, and λ. The proportional extents of surface soil type were estimated from the SSURGO database (NRCS, 2010). In this study, multiple regression (Proc Reg, SAS® 9.2) was conducted for the logarithmic transformation, because a power law relationship was identified between watershed active drainage area and *CN* (Simanton *et al*., 1973). Residuals from each model were tested for normality (Shapiro Wilk test, $p > 0.25$).

Equivalent CN

In order to use existing CN tables, this study developed theoretical relationships between CN for SCS selected initial abstraction ratio 0.2 ($CN_{0.2}$) and *CN* for initial abstraction ratios of 0.01, 0.05, and 0.1 (CN_λ). Relationships between $CN_{0.2}$ and CN_λ were estimated by (1) using $CN = 30$, runoff was calculated for 55 rainfall events (1 mm to 55 mm) using Equation (2), where $I_a = 0.01S$; (2) using the same least square method as described in section 2.2.3, fitted S for rainfall-runoff pairs obtained in step 1 using Equation (5) ($I_a = 0.2S$); (3) from S, calculated $CN_{0.2}$ using Equation (6); (4) using *CN* values from 35 to 95 (with interval of 5) and repeating steps 1 to 3, a series pair of $CN_{0.01}$ and $CN_{0.2}$ were obtained; (5) repeating steps 1–4 (where $I_a = 0.05S$ and $0.1S$ in Equation (2), respectively), a series pair of $CN_{0.05}$ and $CN_{0.2}$ and a series pair of $CN_{0.1}$ and $CN_{0.2}$ were obtained.

To evaluate discrepancies between theoretical runoff for CN_λ (λ is 0.01, 0.05, and 0.1) and $CN_{0.2}$, the residual sum of squares (*RSS*) and the sum of squares of residuals were calculated. In addition, the residual sum of the squares for normalized runoff (*NRSS*), runoff with a unit mean and standard deviation, was also estimated to compensate for the effects of absolute values of runoff.

RESULTS AND DISCUSSION

Sensitivity of runoff to initial abstraction ratio

For a given CN and rainfall depth, estimated runoff increased as the initial abstraction ratio λ decreased (Figure 3), and the estimated runoff was increased by 214% when the initial abstraction ratio λ was decreased 90% from 0.2 to 0.02.

For a given CN ($CN = 80$), the relative sensitivity of initial abstraction ratio λ (absolute value of S_r) was increased with the decrease of rainfall (Figure 4), consistent with findings by Woodward *et al*. (2004). Over the WGEW, the majority of rainfall from 1967 to 1989 was less than 25 mm. The relative sensitivity of the initial abstraction ratio λ was from −10.80 to −1.90 corresponding to a range of rainfall from 15 mm to 25 mm

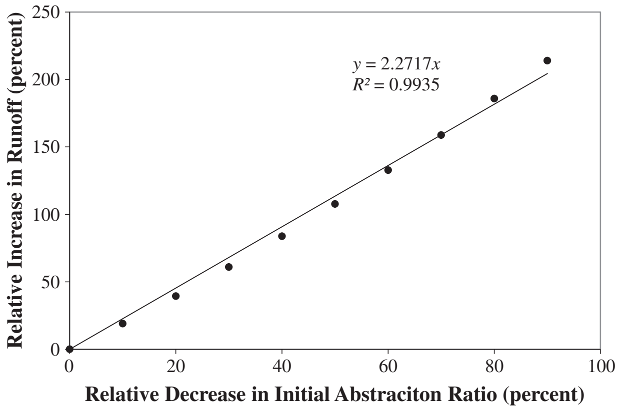

Figure 3. Relative increase in percent [calculated from Equation (1)] of estimated runoff [from Equation (2)] *versus* relative decrease in percent of initial abstraction ratio λ (from 0.2 to 0.02, decreasing 0 percent to 90%) for a curve number of 80 and a rainfall depth of 25.4 mm

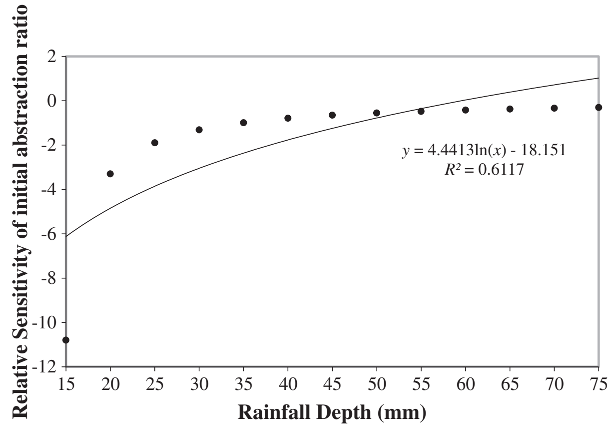

Figure 4. Relative sensitivity of initial abstraction ratio to rainfall when curve number remains unchanged at 80

(Figure 4), suggesting that runoff estimates from the WGEW are very sensitive to the initial abstraction ratio λ.

For a given rainfall depth of 1 inch (25.4 mm), the relative sensitivity of initial abstraction ratio λ (absolute value of S_r) increased with the decrease of CN (Figure 5). The majority of CNs in the WGEW are less than 85 (Simanton *et al*., 1996), corresponding to a large sensitivity (−0.94 to −11.74 corresponding to CNs of 85 to 70) of runoff estimates to the initial abstraction ratio λ. Small CNs are calculated from large maximum potential retention also indicating that runoff estimation is sensitive to the initial abstraction ratio for watersheds with high maximum potential retention. The maximum potential retention is largely but not exclusively related to soil porosity and moisture (NRCS, 1997). In watersheds covered by deep, porous soils, soil moisture has little impact on maximum potential retention (Syed *et al*., 2003), thus the largest maximum potential retention occurs due to the large infiltration rate and soil storage.

Initial abstraction ratio and runoff estimation

Fits of Equation (5) ($\lambda = 0.2$, solid line) and Equation (2) (optimized λ, dashed line) to observed rainfall and runoff are shown in Figure 6. The optimized parameters for each

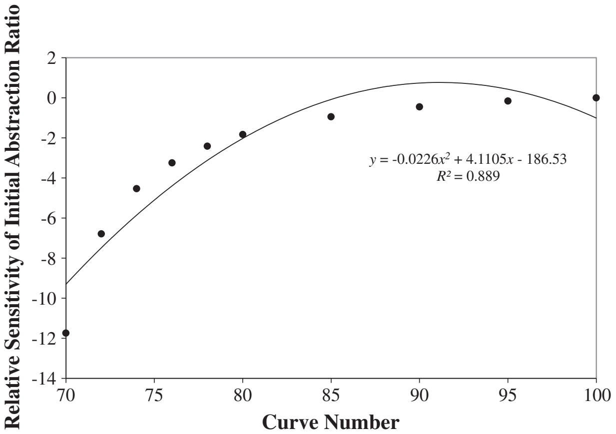

Figure 5. Relative sensitivity of initial abstraction ratio to curve number when rainfall remains unchanged at 25.4 mm

equation are shown in Table I. The initial abstraction ratios, which are calculated from the optimized S and I_a in Equation (2), range from 0.01 to 0.53. Various values of initial abstraction ratio ranging from 0.0 to 0.3 were reported in other studies (Hawkins *et al*., 2010; Baltas *et al*., 2007; Woodward *et al*., 2004; Hawkins *et al*., 2002; Jiang, 2001). The average of initial abstraction ratio for the 11 catchments is 0.12, which is 38% less than the NRCS (1997) definition of 0.2. For catchments with the initial abstraction ratio close to 0.2, such as 7, 8, and 11 (λ from 0.16 to 0.23), the fitted lines for the two equations are very similar (Figure 6). Whereas, for catchments 1, 2, 4, 6, 9, 10, and 15 with an initial abstraction ratio smaller than 0.2 (λ from 0.01 to 0.10), the estimated runoff using Equation (5) ($\lambda = 0.2$) is smaller than that from Equation (2) (optimized λ) for small rainfall events (less than approximately 30 mm) and are larger than estimates of Equation (2) for large rainfall events (larger than approximately 30 mm). For catchment 3, where the initial abstraction ratio is larger than 0.2 (λ is 0.53), the estimated runoff using Equation (5) ($\lambda = 0.2$) is smaller than the estimates of Equation (2) (optimized λ) for relatively larger rainfall events (greater than approximately 30 mm).

Table II shows the *NSE*, R^2, and *PBIAS* that were calculated from observed runoff and calculated runoff using Equation (5) and Equation (2) with estimated I_a and S (Table I) for each catchment. Except for catchments 7, 8, and 11, the *NSE* and R^2 associated with the optimized initial abstraction ratio λ are closer to 1 than those associated with a fixed initial abstraction ratio λ of 0.2, indicating a better fit when the initial abstraction ratio λ is optimized. Similarly, for catchments 1, 2, 4, 6, 7, 9, 10, 11, and 15, the *PBIAS* values for Equation (2) are closer to 0 than those for Equation (5). The *NSE*, R^2, and *PBIAS* are similar for Equation (5) and Equation (2) at catchments 7, 8, and 11. Thus, in the WGEW, runoff estimates using Equation (2) are more accurate than estimates using Equation (5), especially when the initial abstraction ratio λ is much smaller than 0.2.

Results of multiple regression analysis

Table III shows the proportional extent of surface soil types, active drainage area, and channel area for the WGEW and ten of the nested catchments. These catchments were mainly covered by sandy loam (41% to 100%). Relatively fine soils include clay loam and loam, the proportional extent of which was from 0.0% to 4.8% and from 0.0% to 43.3%, respectively. In addition, the extent of loamy sand and undefined soil (mainly in the channels, Figure 2) ranges from 0.0% to 12.8% and from 0.0% to 5.7%, respectively. The riparian soils and stream channel sediments were mainly distributed in the catchments draining into flumes 1, 2, and 6 (Figure 2).

The maximum potential retention S is determined as a channel area-dependent parameter. As shown in Table IV, the logarithm of channel area is the most significant estimator of the logarithm of the maximum potential retention S, with a partial R^2 (partial coefficient of determination, which shows the contribution of an estimator to the variation of a response in multiple regression) of 0.502 (positive). The positive or negative followed with the partial R^2 signifies the influence direction. The CN varied inversely with active drainage area (a power law relationship) (Simanton *et al*., 1973), thus a positive relationship between the maximum potential retention S and the active drainage area should be expected ($S = 25\,400/(254 + CN)$). In this study, the logarithm of the channel area, instead of the logarithm of the active drainage area, was identified as the strongest estimator of the logarithm of the maximum potential retention. This finding is supported by Simanton *et al*. (1996) in that the general nature of declining CN with active drainage area was due to channel transmission losses in southwestern ephemeral streams. A strong correlation between active drainage area and channel area is observed for the WGEW, with a correlation coefficient of 0.948. Thus, although not the strongest estimator, active drainage area could also partially explain the variation of the maximum potential retention S (R^2 is 0.503 for linear regression). In addition, a linear regression model could better explain the maximum potential retention–channel area relationship, because the R^2 (0.593) is higher than that of the power law model (0.502). This finding is supported by a linear regression model proposed by Simanton *et al*. (1996) to describe the CN–area relationship.

Clay loam, loam, and loamy sand were determined as three significant estimators for the logarithm of initial abstraction $\log(I_a)$, suggesting that the initial abstraction I_a was a soil-dependent parameter. The partial R^2 of clay loam, loam, and loamy sand for $\log(I_a)$ is 0.465 (negative), 0.078 (negative), and 0.072 (positive), respectively, and the total R^2 for the $\log(I_a)$ is 0.615 (Table IV). The R^2 for I_a is higher than that of $\log(I_a)$, indicating initial abstraction can be better estimated by soil type using a linear relationship. Three determined significant estimators for I_a are clay loam, loamy sand, and sandy loam, with a partial R^2 of 0.480 (negative), 0.122 (positive), and 0.098 (positive), respectively, and the total R^2 is 0.700. Sandy loam is a soil with high infiltration. Soulis *et al*. (2009) used HYDRUS 1D (Simunek *et al*., 2008) to simulate runoff for 30 rainfall

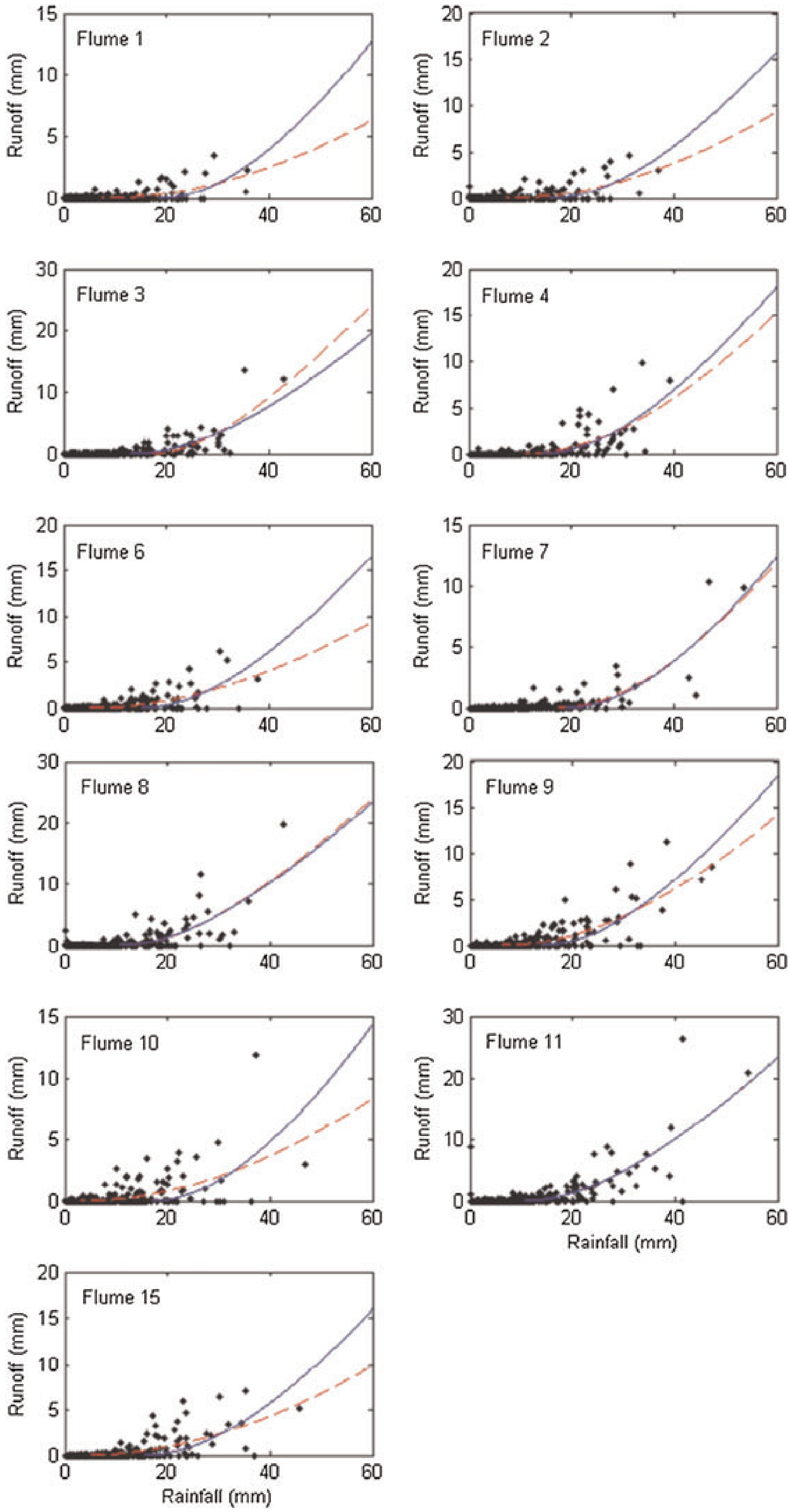

Figure 6. Rainfall-runoff relationships and non-linear fits of the curve number runoff equations. Solid line: Equation (5) ($\lambda = 0.2$); dashed line: Equation (2) with optimized λ

Table III. Area, channel area, and proportional extent of soil type for the USDA-ARS Walnut Gulch Experimental Watershed and ten nested catchments

Runoff gage	Active drainage area (Ha)	Channel area (Ha)	Channel area/ drainage area	Clay loam (%)	Loam (%)	Sandy loam (%)	Loamy sand (%)	Undefined soil (%)
1	13 100	491	0.037	1.5	20.8	71.7	3.3	2.7
2	9561	350	0.037	2.1	20.1	75.7	0.4	1.7
3	546	27	0.049	0.0	0.0	100.0	0.0	0.0
4	229	15	0.066	0.0	0.0	100.0	0.0	0.0
6	8147	280	0.034	2.5	23.4	72.7	0.1	1.3
7	1363	28	0.021	0.0	40.5	41.0	12.8	5.7
8	1330	70	0.053	0.0	22.3	75.7	0.0	1.9
9	2076	70	0.034	4.9	15.3	79.8	0.0	0.0
10	1478	61	0.041	1.2	26.8	72.0	0.0	0.0
11	635	39	0.062	0.0	43.3	56.7	0.0	0.0
15	1640	231	0.141	4.5	16.3	78.5	0.6	0.0

Note: Channel area is from (Goodrich *et al*., 1997).

Table IV. Multiple regression of soil type and logarithm of drainage area and channel area (estimators) with initial abstraction I_a and logarithm of the maximum potential retention S, initial abstraction I_a, and initial abstraction ratio λ (responses), partial R^2 are listed with direction of influence (negative or positive). Bold numbers are for the strongest estimator

	Estimators						
Responses*	Clay loam	Loam	Sandy loam	Loamy sand	Log(Drainage area)	Log(Channel area)	R^2
Log(S)						**0.502**(+)	0.502
Log(I_a)	**0.465**(−)	0.078(−)		0.072(+)			0.615
I_a	**0.480**(−)		0.098(+)	0.122(+)			0.700
Log(λ)	0.102(−)					**0.478**(−)	0.581

Note: probability $p < 0.3$ for all F tests.
The multiple regression equations are:
$\log(S) = 1.166 + 0.507 \log(\text{Channel area})$.
$\log(Ia) = 1.112 - 0.083$ Clay loam $- 0.006$ Loam $+ 0.027$ Loamy sand.
$Ia = 0.744 - 1.551$ Clay loam $+ 0.128$ Sandy loam $+ 0.855$ Loamy sand.
$\text{Log}(\lambda) = -0.017 - 0.122$ Clay loam $- 0.534 \log(\text{Channel area})$.

events ranging from 8.9 mm to 114.1 mm falling on some of the sandy loam and sandy clay loam covering a Greek experimental watershed, and they found that the Greek sandy loam contributed no runoff for any of the 30 rainfall events, whereas sandy clay loam contributed to runoff generation for large rainfall events ($P > 40$ mm) (Soulis *et al*., 2009). Thus, the increasing catchment coverage of sandy loam and decreasing coverage of sandy clay loam should lead to the decrease of runoff and increase of initial abstraction I_a. In addition, this study found that coverage with clay loam negatively impacted initial abstraction I_a.

The initial abstraction ratio λ is a channel area and a soil-dependent parameter. Two estimators were examined in this study for log(λ): log(channel area) and clay loam, with a partial R^2 of 0.478 (negative) and 0.102 (negative), respectively, and a total R^2 of 0.581. Clay loam, the strongest negative estimator for initial abstraction also has a negative impact on λ, and log(channel area) should impact λ the opposite way as the affect on the maximum potential retention S.

Although variations of the maximum potential retention S, initial abstraction I_a, and initial abstraction ratio λ can be mainly explained by variations of channel area and surface soil type (total R^2 from 0.502 to 0.700, Table IV), other possible factors are not considered in this study. As an example, the initial abstraction of catchment 3 is much higher than that of catchment 4 (17.5 mm *versus* 11.1 mm, Table I), although these two catchments are characterized by the same surface soil type (100.0% of sandy loam, Table III). The difference in initial abstraction for these two catchments could be due to other factors, such as the differences in land slope. Future studies may be needed to investigate impacts of slope, and probably other factors influencing S, I_a, and λ.

Equivalent CN

Table V shows the estimated equivalent CNs associated with initial abstraction ratio of 0.2 ($CN_{0.2}$) to CNs for initial abstraction ratios of 0.01, 0.05, and 0.1. The values of CN_λ are always smaller than the equivalent $CN_{0.2}$ and deviations between CN_λ and $CN_{0.2}$ decrease with increasing λ. In addition, as the CN increases, the deviations between CN_λ and $CN_{0.2}$ decrease. As shown in Table V, the residual sum of the squares RSS increases with increasing $CN_{0.2}$ until $CN_{0.2}$ is at 82 to 84 (bold values in Table V), and then decreases with the increase

Table V. Equivalent curve numbers associated with initial abstraction ratio of 0.2 to curve numbers for three initial abstraction ratios (0.01, 0.05, and 0.1) with rainfall ranging from 1 mm to 55 mm, residual sum of squares (*RSS*), and residual sum of squares of normalized data (*NRSS*). n.a.: data not available. Bold numbers are curve number pairs (CN_λ and $CN_{0.2}$) when the residual sum of the squares *RSS* reaches the maximum value and the maximum *RSS* value

$CN_{0.01}$	$CN_{0.2}$	RSS	NRSS	$CN_{0.05}$	$CN_{0.2}$	RSS	NRSS	$CN_{0.1}$	$CN_{0.2}$	RSS	NRSS
30	65	16.45	5.80	30	57	0.44	3.96	30	48	n.a.	n.a.
35	67	22.81	4.56	35	60	1.54	3.22	35	51	0.00	1.36
40	70	29.52	3.57	40	63	3.56	2.58	40	55	0.04	1.16
45	72	36.26	2.77	45	66	6.48	2.04	45	59	0.28	0.95
50	74	42.74	2.13	50	69	10.18	1.58	50	63	0.87	0.76
55	76	48.57	1.60	55	72	14.37	1.20	55	66	1.94	0.59
60	78	53.31	1.17	60	74	18.70	0.88	60	70	3.46	0.44
65	80	56.43	0.83	65	77	22.68	0.62	65	73	5.29	0.32
70	**82**	**57.28**	0.55	70	80	25.72	0.42	70	77	7.16	0.22
75	85	55.09	0.34	**75**	**83**	**27.09**	0.26	75	80	8.66	0.14
80	87	49.05	0.19	80	86	26.00	0.14	**80**	**84**	**9.26**	0.08
85	90	38.53	0.09	85	89	21.71	0.07	85	88	8.43	0.03
90	93	23.72	0.03	90	92	14.05	0.02	90	92	5.83	0.01
95	96	7.62	0.00	95	96	4.69	0.00	95	96	2.05	0.00

Their relationships are:
1) $CN(\lambda=0.2)=55.026e^{0.0058\ CN(\lambda=0.01)}$ $R^2=0.998$.
2) $CN(\lambda=0.2)=46.139e^{0.0078\ CN(\lambda=0.05)}$ $R^2=0.996$.
3) $CN(\lambda=0.2)=36.303e^{0.0105\ CN(\lambda=0.1)}$ $R^2=0.991$.

of $CN_{0.2}$. Higher residual sum of the squares *RSS* signifies a larger discrepancy between runoff associated with CN_λ and $CN_{0.2}$. Hence, impacts of λ will be maximized when $CN_{0.2}$ is approximately 82 associated with λ of 0.01, 83 associated with λ of 0.05 and 84 associated with λ of 0.1. In comparison, the residual sum of the squares for normalized runoff *NRSS* decreases with increasing $CN_{0.2}$, suggesting that the initial abstraction ratio λ has less effect on runoff estimates as CN increases which is consistent with the sensitivity analysis (Figure 5).

Comparisons for three pairs between runoff for $CN_{0.01}$ and $CN_{0.2}$ are shown in Figure 7. A threshold rainfall can be observed for each CN pair, above which runoff for $CN_{0.2}$ is greater than those for $CN_{0.01}$, and below which runoff for $CN_{0.2}$ is smaller than those for $CN_{0.01}$. Runoff estimated using $CN_{0.2}$ is similar to those from $CN_{0.01}$ when $CN_{0.2}$ is 93, while apparent discrepancies in runoff

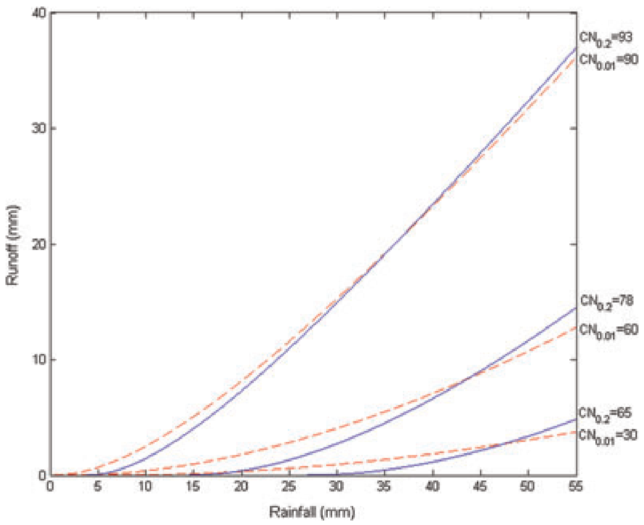

Figure 7. Rainfall and runoff for three curve number pairs associated with initial abstraction ratios of 0.01 and 0.2

can be observed between $CN_{0.01}$ and $CN_{0.2}$ for smaller $CN_{0.2}$ (78 and 65). Figure 7 is consistent with observations by Woodward *et al*. (2004) that distinct differences in runoff are associated with lower CNs.

In summary, runoff estimation in the WGEW is very sensitive to initial abstraction ratio λ because the watershed has relatively low rainfall amount during rainfall events (majority of rainfall events less that 25 mm) and high maximum potential retention due to the large infiltration rate and soil storage. Thus, the initial abstraction ratio λ was re-evaluated using rainfall runoff data collected in the watershed in order to improve runoff estimation. The initial abstraction ratios range from 0.01 to 0.53 for the WGEW and the nested catchments. The wide range of initial abstraction ratio λ (the ratio between initial abstraction and maximum potential retention) is due to variations of channel area and surface soil type of the watershed and the nested catchments, and possible other factors which need further investigation. Runoff estimation is improved for the WGEW and ten nested catchments by using the optimized λ from this study. Finally, theoretical relationships were established between the CNs for initial abstraction ratio 0.2 ($CN_{0.2}$) and the CNs for initial abstraction ratios of 0.01, 0.05, and 0.1 (CN_λ) so that existing CNs developed by the SCS for various land uses can be used for different initial abstraction ratios from 0.2.

CONCLUSIONS

Runoff estimation can be very sensitive to the initial abstraction ratio, especially for relatively low rainfall amount and for watersheds covered by deep, coarse, and porous soil that dominate many semiarid watersheds worldwide. This study improved runoff estimation for the

WGEW and ten nested catchments by changing the initial abstraction ratio λ from 0.2 to optimized values (0.01 to 0.53). For the WGEW and the nested catchments, initial abstraction ratios λ are related to catchment channel area and coverage of surface soil type: the larger the channel area and the finer the soil, the smaller the initial abstraction ratio is. The effect of initial abstraction ratio on runoff estimation increases with decreasing CNs. Thus, impacts of the initial abstraction ratio on runoff estimation should be considered, especially for semiarid watersheds where the CN is usually low.

ACKNOWLEDGEMENTS

We gratefully acknowledge the dedication of ARS staff in establishing and maintaining the WGEW and their diligent long-term collection of high quality hydrologic and watershed data. The authors are grateful for the valuable comments and suggestions provided by Dr. Richard H. Hawkins, Dr. David C. Goodwich, and anonymous reviewers.

NOTICE

Although this work was reviewed by the USEPA and approved for publication, this scientific paper may not necessarily reflect official Agency policy. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

REFERENCES

Baltas EA, Dervos NA, Mimikou MA. 2007. Determination of the SCS initial abstraction ratio in an experimental watershed in Greece. *Hydrology and Earth System Sciences* **11**: 1825–1829.

Chen CL. 1982. An evaluation of the mathematics and physical significance of the soil conservation service curve number procedure for estimating runoff volume In *Proc., Int. Symp. on Rainfall-Runoff Modeling*. Water Resources Publ.: Littleton, Colo.; 387–418.

Gassman PW, Reyes MR, Green CH, Arnold JG. 2007. The soil and water assessment tool: Historical development, applications, and future research directions. *Transactions of the ASABE* **50**: 1211–1250.

Goodrich DC, Keefer TO, Unkrich CL, Nichols MH, Osborn HB, Stone JJ, Smith JR. 2008. Long-term precipitation database, Walnut Gulch Experimental Watershed, Arizona, United States. *Water Resources Research* **44**: W05–SO04. DOI:10.01 029/2006WR005782.

Goodrich DC, Lane LJ, Shillito RM, Miller SN, Syed KH, Woolhiser DA. 1997. Linearity of basin response as a function of scale in a semiarid watershed. *Water Resources Research* **33**: 2951–2965.

Gupta HV, Sorooshian S, Yapo PO. 1999. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of Hydrologic Engineering* **4**: 135–143.

Hawkins RH, Jiang R, Woodward DE, Hjelmfelt AT, van Mullem JA, Quan QD. 2002. *Runoff curve number method: Examination of the initial abstraction ratio, in Proceedings of the Second Federal Interagency Hydrologic Modeling Conference*, ASCE Publications: Las Vegas, Nevada. DOI:10.1061/40685(2003)308, 2002.

Hawkins RH, Ward TJ, Woodward DE, van Mullem JA (eds). 2009. *Curve Number Hydrology*: *State of the Practice*. ASCE: Reston, VA.

Hawkins RH, Ward TJ, Woodward DE, van Mullem JA. 2010. Continuing evolution of rainfall-runoff and the curve number precedent. in P*roceedings of the* 2^{nd} *Joint Federal Interagency Conference*, June 27-July 1, 2010. Las Vegas, Nevada,

Heilman P, Nichols MH, Goodrich DC, Miller S, Guertin P. 2008. Geographic information systems database, Walnut Gulch Experimental Watershed, Arizona, United States. *Water Resources Research*. DOI:10.1029/2006WR005777.

Hjelmfelt AT. 1980. Empirical-investigation of curve number technique. *Journal of the Hydraulics Division* **106**: 1471–1476.

Jiang R. 2001. Investigation of runoff curve number initial abstraction ratio. MS thesis, Watershed Management, University of Arizona, Tucson, AZ. 120 pp.

McCuen RH, Knight Z, Cutter AG. 2006. Evaluation of the Nash-Sutcliffe efficiency index. *Journal of Hydrologic Engineering* **11**: 597–602.

Mishra SK, Sahu RK, Eldho TI, Jain MK. 2006. An improved I_a-S relation incorporating antecedent moisture in SCS-CN methodology. *Water Resources Management* **20**: 643–660.

Mishra SK, Singh VP. 2004. Long-term hydrological simulation based on the Soil Conservation Service curve number. *Hydrological Processes* **18**: 1291–1313.

Nash JE, Sutcliffe JV. 1970. River flow forecasting through conceptual models. Part I: a discussion of principles. *Journal of Hydrology* **10**: 282–290.

NRCS. 1997. *Part 630 - Hydrology, National Engineering Handbook*. Washington D.C.

NRCS. 2010. Soil Survey Geographic (SSURGO) Database for [Walnut Gulch Experimental Watershed, AZ]. Available online at http://soildatamart.nrcs.usda.gov. Accessed [12/13/2010].

Ponce VM, Hawkins RH. 1996. Runoff curve number: has It reached maturity? *Journal of Hydrologic Engineering* **1**: 11–19.

SCS. 1985. *National Engineering Handbook. Section 4: Hydrology*. U.S. Department of Agriculture: Washington D.C.

Simanton JR, Hawkins RH, Mohseni-Saravi M, Renard KG. 1996. Runoff curve number variation with drainage area, Walnut Gulch, Arizona. *Transactions of ASAE* **39**: 1391–1394.

Simanton JR, Renard KG, Sutter NG. 1973. *Procedures for identifying parameters affecting storm runoff volumes in a semiarid environment. USDA-ARS Agricultural Reviews and Manuals ARM-W-1*. USDA-ARS: Washington, D.C.

Simunek J, van Genuchten MT, Sejna M. 2008. Development and applications of the HYDRUS and STANMOD software packages and related codes. *Vadose Zone Journal* **7**: 587–600.

Skirvin S, Kidwell M, Biedenbender S, Henley JP, King D, Collins CH, Moran S, Weltz M. 2008. Vegetation data, Walnut Gulch Experimental Watershed, Arizona, United States. *Water Resources Research* **44**: W05S08. DOI:10.1029/2006WR005724

Soulis KX, Valiantzas JD, Dercas N, Londra PA. 2009. Investigation of the direct runoff generation mechanism for the analysis of the SCS-CN method applicability to a partial area experimental watershed. *Hydrology and Earth System Sciences* **13**: 605–615.

Stone JJ, Nichols MH, Goodrich DC, Buono J. 2008. *Long-term runoff database*, Walnut Gulch Experimental Watershed, Arizona, United States. Water Resources Research 44.

Syed KH, Goodrich DC, Myers DE, Sorooshian S. 2003. Spatial characteristics of thunderstorm rainfall fields and their relation to runoff. *Journal of Hydrology* **271**: 1–21.

Walvoord MA, Phillips FM, Stonestrom DA, Evans RD, Hartsough PC, Newman BD, Striegl RG. 2003. A reservoir of nitrate beneath desert soils. *Science* **302**: 1021–1024.

Wang X, Hoffman DW, Wolfe JE, Williams JR, Fox WE. 2009. Modeling the Eeffectiveness of conservation pactices at Shoal Creek watershed, Texas, using APEX. *Transactions of the ASABE* **52**: 1181–1192.

White KL, Chaubey I. 2005. Sensitivity analysis, calibration, and validations for a multisite and multivariable SWAT model. *Journal of the American Water Resources Association* **41**: 1077–1089.

Woodward DE, Hawkins RH, Jiang R, Hjelmfelt AT, Van Mullem JA, Quan QD. 2004. *Runoff Curve Number Method: Examination of the Initial Abstraction Ratio In Proceedings of the World Water and Environmental Resources Congress and Related Symposis*. ASCE Publications: Philadelphia, PA. DOI:10.1061/40685(2003)308

Yuan YP, Bingner RL, Rebich RA. 2001. Evaluation of AnnAGNPS on Mississippi Delta MSEA watersheds. *Transactions of ASAE* **44**: 1183–1190.

