تقييم تغير معامل رقم المنحني للجريان السطحي مع تغير رطوبة التربة

Evaluating the Variability of Runoff Curve Number With Soil Moisture Content

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المُلَخَّص

إن طريقة معامل رقم المنحني (CN) والتي تم تطويرها من قبل قسم حفظ التربة في وزارة الزراعة الأمريكية يمكن أن تُستخدم لحساب حجم الجريان السطحي المطلوب عند تصميم المنشآت المائية وفي دراسات تقييم الأثر البيئي . يتم تحديد قيمة هذا المعامل حاليا بالاعتماد على الجداول المنشورة من قبل (USDA-SCS، 1972) و التي يُمكن تعديلها باستخدام كمية الأمطار الهاطلة خلال الأيام الخمسة التي تسبق العاصفة المطرية المدروسة (USDA-SCS، 1985) . تهدف هذه الدراسة إلى تقييم إمكانية استخدام رطوبة التربة قبل حدوث العاصفة المطرية من أجل تعديل قيمة معامل رقم المنحني كبديل لاستعمال كمية الأمطار الهاطلة خلال الأيام الخمسة التي تسبق العاصفة المطرية المدروسة .اُستخدم في هذه الدراسة الأنموذج الرياضي (HYDRUS-1D) من أجل تحديد رطوبة التربة . تمَّ دراسة علاقة الترابط بين قيم معامل رقم المنحني المحددة باستخدام منحنيات التصريف المقاسة و رطوبة التربة قبل حدوث العاصفة المطرية المدروسة ووُجد بأنه هناك علاقة ترابط جيدة بينهما . إن استعمال قيم معامل رقم المنحني المعدلة باستخدام قيمة رطوبة التربة التي تسبق العاصفة المطرية أعطى نتائج أفضل من قيم معامل رقم المنحني المعدلة باستخدام كمية الأمطار الهاطلة خلال الأيام الخمسة التي تسبق العاصفة المطرية المدروسة.

الكلمات المفتاحية: رقم المنحني، الجريان السطحي ، أسبقية الرطوبة.

Abstract

The curve number (CN) method originally developed by USDA soil conservation services (SCS) is widely used in engineering design water structures, and environmental impact assessment for estimating runoff volume. Currently the value of curve number is determined from published tables (USDA-SCS,1972) and modified using 5 day antecedent rainfall published in NEH-4 (USDA-SCS, 1985) . The objective of this study was to investigate the use of antecedent soil moisture content as an alternative to the 5-day antecedent rainfall for curve number adjustment . A dynamic infiltration model (HYDRUS-1D) was used to simulate the temporal variation of soil moisture content. Curve number values estimated from observed hydrograph were correlated to antecedent soil moisture content. A strong correlation (r^2=0.80) was found between CN values and the natural logarithm of antecedent soil moisture content. Using Curve number based on antecedent moisture content value improved the estimation of runoff volume greatly compared to the 5-day antecedent rainfall published in NEH-4 (USDA-SCS, 1985).

Keywords: curve number, surface runoff, antecedent moisture

Introduction

Water scarcity and drought have become major issues in arid and semi arid areas. Alleviating such problems requires more emphasis on planning and management of available water resources. In such areas surface runoff is an important portion of available water resources. Direct measurement of runoff is rarely available and there is a shortage of runoff record which covers sufficient duration of rainy seasons to enable accurate assessment of volume and peak runoff. Therefore, utilizing simulation models which are capable of predicting runoff information based on rainfall record become of great interest to achieve required planning and management of water resources.

The curve number method developed by the U.S. soil conservation (USDA-SCS,1972) perhaps is the most common method for predicting storm runoff (Pathak et al., 1989; Jiang et al., 1998 ; Limbrunner et al., 2004, Fraser and Waters, 2004; Jacobs and Srinivasan, 2005). This method is based on the relationship among rainfall, land use, soil characteristics, and antecedent soil moisture. In this method direct runoff is calculated from rainfall depth as following :

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \text{ for } P > 0.2\,S,\ \ Q = 0 \text{ otherwise} \quad (1)$$

Where:

Q is direct runoff volume (mm)

P is total rainfall (mm), and

$$S = \frac{25400}{CN} - 254 \quad (2)$$

CN is the curve number which is determined based on soil hydrologic group, land use and antecedent moisture condition . CN values are tabulated in chapter 9 of National Engineering Handbook-section 4 (NEH-4) for various land cover and soil hydrologic group (USDA-SCS, 1985). A major disadvantage of CN method is that the temporal variation of curve number with respect to antecedent moisture is not adequately established (Ponce, 1996). Currently, the method used to account for CN variation with antecedent moisture condition (AMC) is based on the amount of rainfall over the previous five days as explained in table 4.2 of NEH-4(USDA-SCS,1985). In this table a curve number values for normal, dry, and wet soil moisture condition is termed CN_{II}, CN_I, and CN_{III}, respectively. The three classes of CN based on 5-day antecedent rainfall are presented in Table 1. Values of CN_{II} are determined based on land cover and soil hydrologic group (USDA-SCS,1985). Values of CN_I and CN_{III} can be obtained from table 4.2 of NEH-4(USDA-SCS,1985) or by using the following equations (Haith et al. 1996):

$$CN_I = \frac{CN_{II}}{(2.334 - 0.01334\,CN_{II})} \quad (3)$$

$$CN_{III} = \frac{CN_{II}}{(0.4036 - 0.0059\,CN_{II})} \quad (4)$$

Table 1. Five-day antecedent rainfall division presented in table 4.2 of NEH-4(USDA-SCS,1985).

Antecedent Moisture Condition	5-day Antecedent Rainfall (mm)
I (dry)	< 36
II (normal)	36 - 53
III (wet)	> 53

Many researchers observed that values of CN exhibit a significant storm to storm variation which can not be explained following the SCS method based on the total rainfall depth observed in 5 days before the storm (Miserocchi and Savi , 2005; Perone and Madramootoo, 1998; Walkers et al., 1998 ; Madramoottoo and Enright, 1988). As an alternative to five-day antecedent rainfall Walkers et al.(1998) used base flow at the watershed outlet prior to storm response as an indicator of watershed moisture condition. They developed a relationship between base flow and curve number. The drawback in this approach is that the base flow measurements are rarely available. Fedora and Beschta (1989) analyzed the influence of antecedent precipitation on curve number. They concluded that long term or seasonal antecedent conditions should be considered.

Borah (1990) performed a study to characterize the temporal variation of curve number. He found that CN follows a clear pattern with respect to seasons; however, Borah (1990) did not establish a correlation between CN values and antecedent soil moisture.

In another study, Jacobs et al. (2003) used remotely sensed soil moisture to adjust curve numbers values. The error in runoff estimate by the SCS method was reduced by nearly 50 percent. More recently, Jacobs and Srinivasan (2005) used high resolution radar rainfall data in Texas watershed to evaluate variation of SCS curve number. The result of their study indicated the need to adjust the curve number value seasonally.

The objective of this study is to investigate using the antecedent soil moisture content to quantify the watershed wetness prior to the runoff event as an alternative to the 5-day antecedent rainfall published in NEH-4 (USDA-SCS, 1985).

Method and materials

Study area

The data used in this study were collected from Syndiane reservoir during the HYDROMED project implemented in cooperation among the Institute of Research for Development (IRD), European Union, and the Arab Center for the Studies of Arid Zones and Dry lands (ACSAD). The Syndiane reservoir, which is, located approximately 30 KM west of the city of Homs, Syria (34.70419°N, 36.44248°E) (Fig. 1) was built in 1967 and has a maximum capacity of 400,000 m^3. The reservoir collects runoff water from a 330 ha catchment. The watershed is characterized by gently rolling terrain with an average basin slope of 7.4 % and a maximum channel slope of 2.3 %. The area attains a maximum elevation of 632 m above mean sea level (MSL) in the north and a minimum of 505 m above MSL near the dam site. The soils of the area have derived from basaltic parent material and are classified in four principle soil type : Loam, sandy clay loam, clay loam, and sandy loam and They belong to the hydrologic group C (USDA-SCS,1985). Land uses and cover are primarily winter wheat (80%) and rangeland (20%). The curve number for this soil-cover complex are 82, 92, and 66 for antecedent moisture condition II , I, and III , respectively (USDA-SCS, 1985). At the end of the year 1997, meteorological station’s equipment were installed next to reservoir. These equipment included a tipping bucket rain gage, an air temperature sensor, and water level sensors.

Annual precipitation occurs from October to May. During the five seasons 1997/1998, 1998/1999, 1999/2000, 2000/2001, 2001/2002, the annual rainfall depths were 737, 575, 556, 703, 586 mm, respectively.

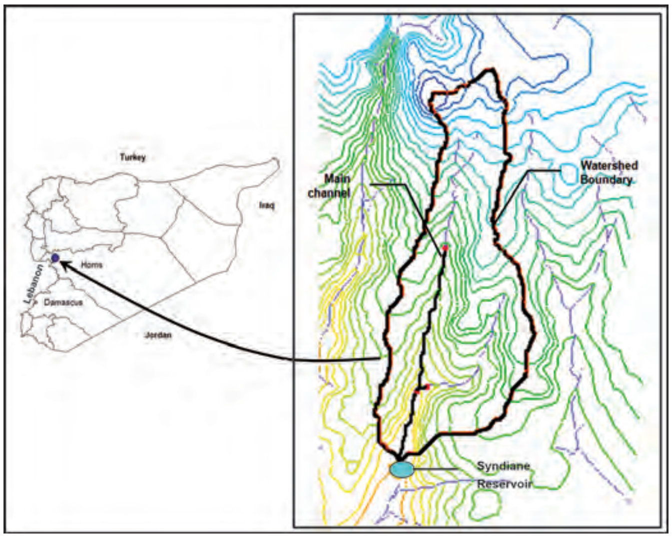

Figure 1. Syndiane watershed and its location on Syria map.

Curve number calibration

The calibration of curve number was performed using the HEC1 (USACE-HEC,1985) model. HEC1 is a hydrological model to simulate runoff hydrograph. The HEC1 model is based on unit hydrograph method to transform direct runoff to runoff hydrograph. HEC1 has several options for unit hydrograph for estimating direct runoff. In this study direct runoff was calculated using SCS curve number method (USDA-SCS, 1972). The standard SCS unit hydrograph was used to produce the runoff hydrograph. The lag time was determined using the SCS lag equation.

Table 2 lists the 15 rainfall events used as rainfall input in this study. The events were selected at different times between 1997 and 2002. The events rainfall depth varied between 21.5 mm to 181 mm. Measured runoff hydrograph were obtained from the change in the water volume in the reservoir based on water level measurement. The starting time of a runoff event was the same as the start time of the associated rainfall event. The ending time of event is the time storm flow had returned to normal level similar to the level observed before the rainfall event began.

Table 2. The 15 rainfall events used to calibrate curve numbers and the calculated soil moisture condition prior to each event.

No.	Date of event	storm depth (mm)	Antecedent soil moisture content m^3/m^3
1	29 /12/ 1997	50.0	0.29
2	7/ 1/ 1998	21.5	0.32
3	25 /1/ 1998	101.0	0.39
4	30 /3 / 1998	182.0	0.36
5	29 /11 / 1998	107.5	0.17
6	19 /1 / 1999	43.0	0.39
7	4 /2/ 1999	56.5	0.25
8	24 /12/ 2000	39.0	0.33
9	24 /1/ 2001	38.5	0.27
10	5 /2/ 2001	54.5	0.31
11	17 /2/ 2001	23.5	0.33
12	25 /11/ 2001	26.5	0.22
13	21 / 1/ 2002	46.0	0.34
14	24 /11/ 2002	181.0	0.22
15	19 /12/ 2002	35.0	0.34

Calibrated CN values were obtained through adjusting CN values to match the simulated and observed hydrographs of all 15 rainfall events.

Soil moisture calculation

The HYDRUS-1D model (Simunek et al., 1998) was used to estimate soil moisture content. HYDRUS-1D is a software package for simulating water movement in one-dimensional variably saturated media. The program, which numerically solves Richared equation, is capable of simulating daily soil moisture content based on daily precipitation, evapotranspiration (ET), and soil characteristics. Daily evapotranspiration was determined using Penman Montith equation (Allen et al. 1998) utilizing climatic data obtained from Homs weather station. The soil hydraulic function of Van-Genuchten (1980) was used to describe soil and water retention and unsaturated hydraulic conductivity functions. Soil physical properties were obtained from soil datadbase provided within HYDRUS-1D model and the soil map of Syndiane catchment. HYDRUS 1 is used here to get a good indicator of the soil moisture variation and of a water soil content before each event. Values of calculated soil moisture content prior to each rainfall event are presented in Table 2.

Results and discussion

Evaluating the Five-day antecedent rainfall AMC of NEH-4(USDA-SCS,1985)

With exception to rainfall event of 24/12/2000, the five-day cumulative rainfall prior to each of the rainfall event was less than 36 mm (Table 3) ; therefore, according to 5-day antecedent rainfall published in NEH-4 (USDA-SCS, 1985), CN values for these events are associated with dry condition (condition I) and is equal to 56. However, the soil moisture content prior to those events varies greatly between 0.17 for 29/11/1998 rainfall event to 0.39 for 25/1/1998 and 19/1/1999 events.

The calibrated curve number values (CN_{cal}) varied between 48 and 92 . Figure 2 shows example of observed and calibrated hydrograph for 4-2-1999 storm. The relative error between CN_I and CN_{cal} ranged between 4 % for 24/12/2000 rainfall event and 39% for 5/2/2001 rainfall event.

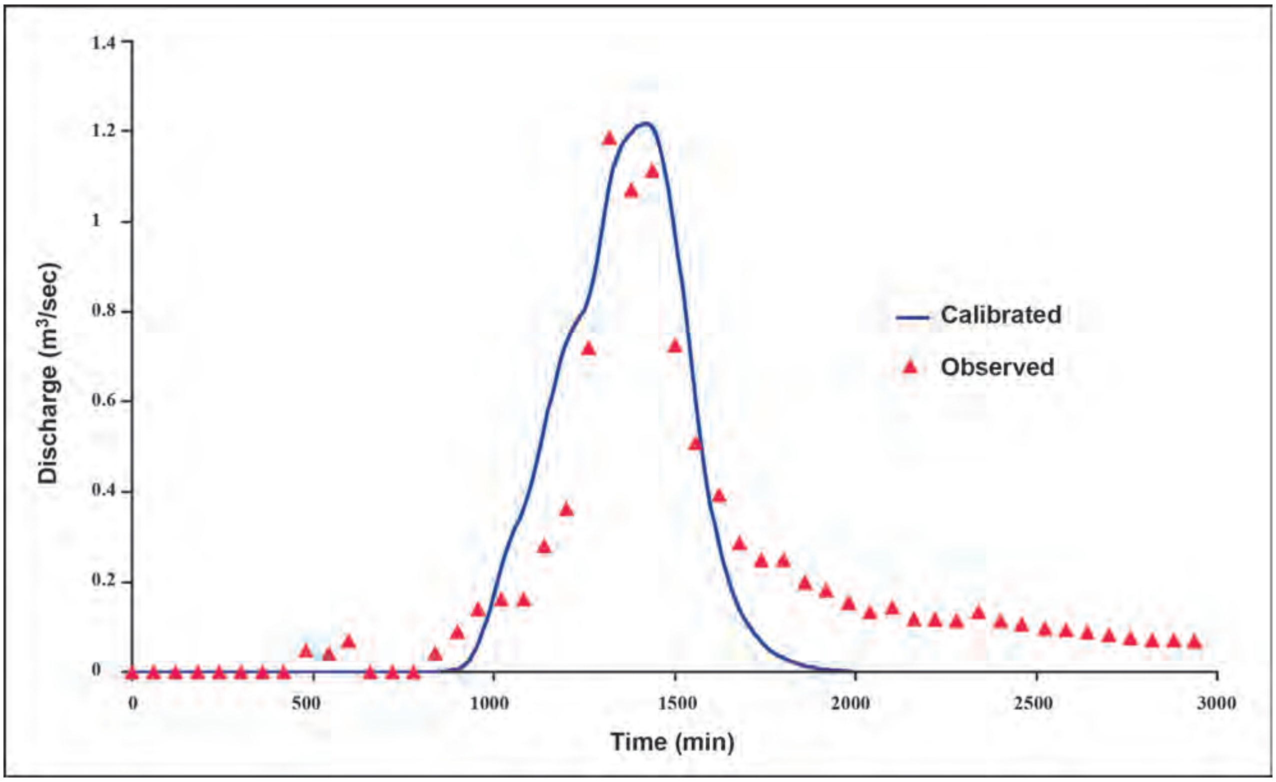

Figure 2. Observed and calibrated hydrograph for 4-2-1999 storm.

Table 3. Comparison of the calibrated curve number (CN_{cal}) and the curve number based on 5-Day Antecedent Rainfall (mm)(USDA-SCS,1985).

No.	Date of event	5-Day Antecedent Rainfall (mm)	AMC based on NEH-4 (USDA-SCS, 1985)	Curve number based on 5-Day Antecedent Rainfall (mm)(USDA-SCS, 1985)	Calibrated curve number ($CN_{ca}l$)	Percent error (%)
1	29 /12/ 1997	6	I	56	72.5	23
2	7/ 1/ 1998	1.5	I	56	86	35
3	25 /1/ 1998	15	I	56	91	38
4	30 /3 / 1998	19	I	56	88	36
5	29 /11 / 1998	0.5	I	56	51	-10
6	19 /1 / 1999	25	I	56	85	34
7	4 /2/ 1999	0	I	56	76	26
8	24 /12/ 2000	84.5	III	89	85.5	-4
9	24 /1/ 2001	23.5	I	56	79	29
10	5 /2/ 2001	1.5	I	56	92	39
11	17 /2/ 2001	30	I	56	91	38
12	25 /11/ 2001	18	I	56	48	-17
13	21 / 1/ 2002	13.5	I	56	90	38
14	24 /11/ 2002	0	I	56	59	5
15	19 /12/ 2002	28.9	I	56	87	36

It is evident from this result that USDA-SCS antecedent moisture condition does not characterize the soil moisture preceding a rainfall event and does not explain the storm to storm variation of CN values.

Correlation between Antecedent soil moisture content and curve number

Soil moisture prior to each of the 15 rainfall event was plotted against the calibrated values of curve number (CN_{cal}) . A linear relationship between the natural logarithm of soil moisture content and curve number were deduced (Figure 3)

$$CN_{\Theta} = 55.593 \ln(\Theta) + 1.79 CN_{II} \quad (r^2=0.80) \qquad (5)$$

Where:

Θ is the volumetric soil moisture content prior to rainfall event (m^3/m^3).

CN_{II} is the curve number for normal moisture condition.

CN_{Θ} is the adjusted curve number based on the antecedent moisture content. The strong correlation between the curve number and the soil moisture content indicate that antecedent moisture content has major influence on curve number. Similar result was obtained by (Jacobs et al., 2003) when they correlated remotely sensed soil moisture data to curve number values.

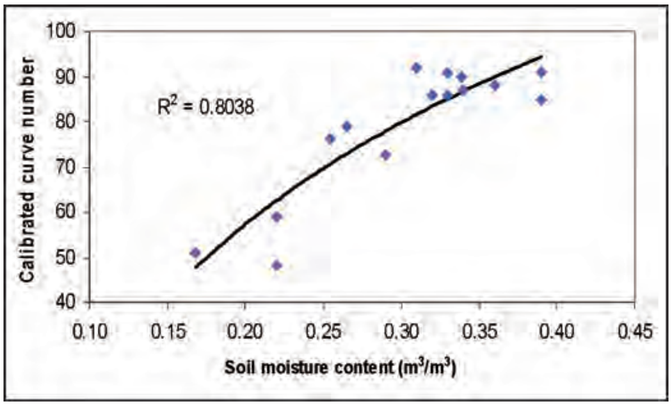

Figure 3. The relation between calibrated curve number and soil moisture content prior to each of the investigated 15 rainfall events.

Evaluation of the developed relationship between curve number and soil moisture content

Six events (Table 4) were used to evaluate curve number obtained from Eq. 5. The rainfall events were selected to represent different rainfall depths, different antecedent soil moisture contents and different years.

The 5-day antecedent rainfall for the six rainfall events were less than 36 mm (Table 4). Therefore, the curve number based on the 5-day antecedent rainfall according to (USDA-SCS,1985) is 66 .

The antecedent soil moisture content calculated using HYDRUS-1D model varied between 0.20 for the 9/12/2002 rainfall event and 0.40 for the 2/1/2003 rainfall event. The curve number calculated from Eq. 5 based on soil moisture content varied among the studied storms and ranged between 58.3 and 95.8 .

Using the curve number (CN_I) based on 5-day antecedent rainfall produced runoff volume greatly less than the observed ones (Table 5). The error in estimating the runoff volume based on CN_I ranged between 38 % and 148 %. As mentioned earlier, many researchers (Miserocchi and F. Savi, 2005; Perone and. Madramootoo, 1998; Walkers et al., 1998 ; Madramoottoo and Enright, 1988) observed that using curve number based on the 5-day antecedent rainfall could result in large errors in the estimated runoff volume.

By using the curve number calculated from Eq. 5 based on antecedent soil moisture content (CN_Θ), the errors in estimated runoff volume was reduced greatly (Table 5). The difference between the observed runoff volume and the estimated one using

Table 4. Comparison of curve number calculated based on 5-Day Antecedent Rainfall and that calculated from Eq. 5 moisture content.

Date of event	Rainfall depth (mm)	5-Day Antecedent Rainfall (mm)	Curve number based on 5-Day Antecedent Rainfall (CN_I) (mm)	Volumetric moisture content m^3/m^3	Curve number based on antecedent moisture content (CN_Θ)
7/2/1998	55	2	66	0.34	86.7
30/3/1998	43.0	19.0	66	0.36	89.9
27/1/1999	44.5	6.5	66	0.28	74.9
19/12/2001	89.0	22.0	66	0.25	70.5
9/12/2002	55.5	4.0	66	0.20	58.3
2/1/2003	48.5	32.0	66	0.40	95.8

Table 5. Comparison of observed runoff volume, estimated runoff volume using CN_I^a, and estimated volume using CN_Θ^a.

Date of event	Observed Rrunoff volume (m^3)	Simulated runoff volume using CN_I (m^3)	Error (%)	Simulated runoff volume using CN_Θ (m^3)	Error (%)
7/2/1998	69021	16917	75.5	83045.7	-20.3
30/3/1998	48816	6233	87.2	57195.0	-17.2
27/1/1999	21251	7320	65.6	21572.0	-1.5
19/12/2001	106207	66243	37.6	98323.0	7.4
9/12/2002	6826	16917	-147.8	5983.0	12.3
2/1/2003	107000	10580	-99.7	121216.0	-13.3

[a] CN_I is the curve number based on 5-day antecedent rainfall, and CN_Θ is the curve number calculated from Eq. 5 based on antecedent soil moisture content.

CN_Θ ranged from -1.5% to 20.3%. Having an error of 20.3% in runoff volume is due to the fact that in addition to antecedent moisture content, there are other factors such as rainfall depth and intensity may effects runoff volume (Hjelmfelt, 1991).

This result shows that quantifying pre-runoff conditions using soil moisture content is more adequate than using the rainfall observed in 5 days before the storm .

Summary and Conclusion

This study investigated the use of soil moisture content, rather than antecedent rainfall, as a mean for quantifying the watershed wetness prior to a rainfall event of interest. Good correlation (r^2=0.80) was found between CN values and the natural logarithm of antecedent soil moisture content. Using Curve number based on antecedent moisture content values improved estimation of the runoff volume greatly compared to the 5-day antecedent rainfall published in NEH-4 (USDA-SCS, 1985). The suggested method requires knowledge of soil moisture content prior to runoff event. Since such measurement is not readily available, dynamic infiltration model such as HYDRUS-1D could be used to estimate soil moisture content. This model requires daily evapotranspiration, daily precipitation, and general soil characteristic. These data usually are easily available. One of the advantages of the proposed method to adjust curve number is that it allows continues simulation of CN which is required by many hydrological simulation model such as EPIC (Williams, 1995), and AGNPS. (Young, 1987).

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