Water Resour Manage (2013) 27:2001–2012
DOI 10.1007/s11269-013-0267-6

SCS-CN Based Quantification of Potential of Rooftop Catchments and Computation of ASRC for Rainwater Harvesting

P. K. Singh · B. K. Yaduvanshi · Swati Patel · Saswati Ray

Received: 21 July 2012 / Accepted: 2 January 2013 /

Abstract Rooftop rainwater harvesting, among other options, play a central role in addressing water security and reducing impacts on the environment. The storm or annual storm runoff coefficient (RC/ASRC) play a significant role in quantification of potential of rooftop catchments for rainwater harvesting, however, these are usually selected from generic lists available in literature. This study explores methodology/procedures based on one of the most popular and versatile hydrological model, Soil Conservation Service Curve Number (SCS-CN) (SCS 1986) and its variants, i.e., Hawkins SCS-CN (HSCS-CN) model (Hawkins et al. 2001), Michel SCS-CN (MSCS-CN) model (Michel et al. Water Resour Res 41:W02011, 2005), and Storm Water Management Model-Annual Storm Runoff Coefficient (SWMM-ASRC) (Heaney et al. 1976) and compares their performance with Central Ground Board (CGWB) (CGWB 2000) approach. It has been found that for the same amount of rainfall and same rooftop catchment area, the MSCS-CN model yields highest rooftop runoff followed by SWMM-ASRC>HSCS-CN>SCS-CN>CGWB. However, the SCS-CN model has close resemblance with CGWB approach followed by HSCS-CN model, SWMM-ASRC, and MSCS-CN model. ASRCs were developed using these models and it was found that MSCS-CN model has the highest value of ASRC (= 0.944) followed by SWMM-ASRC approach (=0.900), HSCS-CN model (=0.830), SCS-CN model (=0.801), and CGWB approach (=0.800). The versatility of these models lies to the fact that CN values (according to rooftop catchment characteristics) would yield rooftop runoff and therefore ASRC values based on sound hydrological perception and not just on the empiricism. The models have inherent capability to incorporate the major factors responsible for runoff production from rooftop/urban, i.e., surface characteristics, initial abstraction, and antecedent dry weather period (ADWP) for the catchments and would be better a tool for quantification rather than just using empirical runoff coefficients for the purpose.

P. K. Singh (✉) · B. K. Yaduvanshi
Polytechnic in Agricultural Engineering, AAU, Dahod 389151, Gujarat, India
e-mail: pushpendras123@gmail.com

S. Patel · S. Ray
CAET, AAU, Godhra 389001, Gujarat, India

Keywords Rooftop rainwater harvesting · SCS-CN method · Runoff coefficient · Rainwater harvesting

1 Introduction

Water shortages are relevant not only to water scarce regions but also to those with an appropriate water supply infrastructure in place, due to the need to secure a stable water supply that allows for rising water demand, rapid urbanization and climate change (Mun and Han 2012). As per UNEP (United Nations Environment Programme), more than 2,000 million people would live under conditions of high water stress by the year 2050, which could be an off-putting factor for development and even existence of a number of regions in the world. The condition would be further worsening with the recent global environmental challenges faced by humanity such as global warming & climate change. This indicates that the issues related to the water resources need to be attended with a great scientific and sustainable approach to have the minimal impacts on the society. Even in those areas of the world that appear to have adequate water supplies, there are constant needs to balance existing supplies with ever growing demands. The collection and storage of rainwater to supplement existing water supplies could alleviate some of these problems. In order to fulfil water demands in future, we will need to rationalize on various technologies for capturing and storing of water. Rainwater harvesting & utilization may be one of the best available methods for recovering natural hydrological cycles and aiding in sustainable urban as well as rural development (Kim et al. 2005).

Rainwater harvesting, among other options, may play a central role in widening water security and reducing impacts on the environment (El-Sayed et al. 2010). Rainwater harvesting (RWH) presents many benefits for urban sustainability and it is emerging as a key strategy in order to cope with water scarcity in cities. Since, roofs represent approximately half of the total sealed surface in cities they contribute to the most important urban storm water runoff flow (Farreny et al. 2011a). With the rapid pace of urbanization and plunging in infrastructural developments, the impervious catchment areas (rooftops particularly) are being increasing tremendously day-by-day, and henceforth greater surface runoffs prospects.

Therefore, keeping in mind the technical and financial limitations of the poor who live in rural or semi-urban areas, search for alternative approaches for development & management of water resources quantitatively and qualitatively both, including the use of decentralized water supply systems and low-cost, low-energy water treatment technologies is inevitable. Given the acute problem of water scarcity that many are likely to face in the near future, the direct exploitation of the natural, simple, and most fundamental source of renewable fresh water—rain—should not be ignored (Postel 1992). Rooftop rainwater harvesting (RTWH) is seen as an alternative source of drinking water, especially in developing countries (Meera and Ahammed 2006). It is one of the most feasible solutions to cope with present conditions, and several countries are reappraising its value (Hatt et al. 2006; Han et al. 2009; Zhang et al. 2009; Rygaard et al. 2011). RTRWH is also expected to contribute to restoring the urban water cycle and alleviating water related disasters, in addition to increasing the water supply (Coombes et al. 2002; Han and Kim 2007; Kim and Han 2008).

The topic has been at the forefront of the research community; and various modelling approaches and methodologies has been developed to quantify the potential of rooftop catchments and criteria for their selection, cost efficiency & reliability and its overall performance (Mun and Han 2012; Farreny et al. 2011a&b; Chiu et al. 2009; Su et al. 2009). Chiu et al. (2009) developed an optimized RTRWHS and provided an energy-saving approach for hilly communities where urbanization is increasing rapidly to save water pumping energy. Su et al. (2009) developed a methodology for establishing the probabilistic relationship between storage capacities and deficit rates of rainwater harvesting (RWH) systems. Mwenge Kahinda et al. (2010) developed a *Roof model* to calculate the optimum size of the RWH tank. Li et al. (2010) explored the efficacy of Rainwater harvesting for domestic application in Ireland. They found that the use of domestic rainwater harvesting systems has the potential to supply nearly 94 % of domestic water in Irish households. Jones and Hunt (2010) evaluated the performance of rainwater harvesting systems in humid and well developed regions North Caroline, USA. Basinger et al. (2010) developed a RWH system reliability model based on nonparametric stochastic rainfall generator. Rygaard et al. (2011) explored the concept of urban water self-sufficiency and discussed new challenges to be encountered and handled successfully. Palla et al. (2011) investigated the optimum performance of the RWH systems using non-dimensional design parameters.

Angrill et al. (2012) identified the most environmentally friendly strategy for rainwater utilization in mediterranean urban environments. Eight different RWH scenarios were defined in terms of diffuse (D) and compact (C) urban models and the tank locations as: (1) underground tank, (2) below-roof tank, (3) distributed-over-roof tank, and (4) block tank. The structural and hydraulic sizing of the catchment, storage, and distribution subsystems was taken into account. The environmental characterization indicated that the best scenario in both urban models is the distributed-over-roof tank (D3, C3). Mun and Han (2012) evaluated RWH system performance and analyzed sensitivity of design parameters on operational parameters and suggested the recommended range of design parameters for improving RWH systems design and operation. Kim and Furumai (2012) assessed the rainwater availability on the basis of building type and water use using GIS. Farreny et al. (2011b) evaluated the cost-efficiency of several strategies for urban RWH in mediterranean weather conditions of Spain. Farreny et al. (2011a) developed a regression based rainfall-runoff model to quantify yields from different rooftop catchments to maximize the availability and quality of rooftop storm water in an urban mediterranean weather environment. A model for estimation of runoff volume and the initial abstraction of each roof was also developed and the physicochemical contamination of roof runoff was analysed. Major differences in the runoff coefficient (RC) were observed, depending mostly on the slope and the roughness of the roof. It was found that sloping smooth roofs ($RC>0.90$) may harvest up to about 50 % more rainwater than flat rough roofs ($RC=0.62$). The RC is a dimensionless value that estimates the portion of rainfall that becomes runoff, taking into account losses due to spillage, leakage, catchment surface wetting and evaporation (Singh 1992). Thus, the RC is one of the most important components for predicting the potential water running off a surface, which can be conveyed to a rainwater storage system. Usually, the values of the RC are selected from generic lists based on the degree of imperviousness and infiltration capacity of the drainage surface. Estimates so far consider that roof RCs are within the range of 0.7–0.95 for relatively frequent storms as shown in Tables 1 and 2.

This broad range is the result of the interaction of many factors, both climatic (size and intensity of the rain event, antecedent moisture, prevailing winds) and architectural (slope, roof material, surface depressions, leaks/infiltration, roughness). For this reason, it seems urgent to develop hydrologically sound models rather than simple empirical models for quantification of the potential of rooftop catchments and develop

Table 1 Review of runoff coefficient (RC) estimates (Farreny et al. 2011b)

Roofs	RC	Reference
Roofs (in general)	0.7–0.9	Pacey and Cullis (1989)
	0.75–0.95	ASCE (1969), McCuen (2004), Singh (1992), TxDOT (2009), Viessman and Lewis (2003)
	0.85	McCuen (2004), Rahman et al. (2010)
	0.8–0.9	Fewkes (2000)
	0.8	Ghisi et al. (2009)
Sloping roofs		
Concrete/asphalt	0.9	Lancaster (2006)
Metal	0.95	Lancaster (2006)
	0.81–0.84	Liaw and Tsai (2004)
Aluminium	0.7	Ward et al. (2010)
Flat roofs		
Bituminous	0.7	Ward et al. (2010)
Gravel	0.8–0.85	Lancaster (2006)
Level	0.81	Liaw and Tsai (2004)

annual storm RC (ASRC) under diverse environmental climatic conditions in the context of RWH.

Therefore, this study explores the suitability of one of the most popular and widely used Soil Conservation Service Curve Number (SCS-CN) method and its popular variants to quantify the potential of rooftop catchments for rainwater harvesting with the existing models/approaches. Notably the SCS-CN method has not been previously explored for quantification of potential of rooftop catchments for rainwater harvesting in the recent past. Finally, effort has also been put to develop ASRCs based on the SCS-CN model and existing models/approaches to simplify the quantification of rooftop RWH. The specific objectives of this paper are twofold: (i) to explore the suitability of SCS-CN model and its variants, i.e., Hawkins SCS-CN model (for $\lambda=0.05$), Michel SCS-CN model (Michel et al. 2005) and their comparison with SWMM-ASRC model (Heany et al. 1976), and CGWB approach for rooftop storm water yields and (ii) to develop ASRCs using these models.

Table 2 Quantification of potential of rooftop catchments of CAET campus building for rainwater harvesting on monthly and annual basis using different models

Sl. no	Model for quantification of potential of rooftop catchments	Rooftop runoff potential Q_{RT} (m^3)			
		Monthly			Annual
		July	August	Sept.	
1	SCS-CN Model ($\lambda=0.2$) (SCS 1986)	1549.07	2763.47	448.82	4761.36
2	HSCS-CN Model ($\lambda=0.05$) (Hawkins et al. 2001)	1595.37	2841.63	496.01	4933.01
3	MSCS-CN Model (Michel et al. 2005)	1791.75	3142.2	673.63	5607.58
4	SWMM ASRC Approach (Heany et al. 1976)	1698.53	2974.38	674.27	5347.18
5	CGWB Approach (CGWB 2000)	1509.81	2643.91	599.37	4753.09

2 Materials and Methods

2.1 Soil Conservation Service-Curve Number (SCS-CN) Method

The Soil Conservation Service Curve Number (SCS-CN) method was developed in 1954 and it is documented in Section 4 of the National Engineering Handbook (NEH-4) published by the Soil Conservation Service (now called as Natural Resource Conservation Service), U.S. Department of Agriculture in 1956. It computes the volume of surface runoff for a given rainfall event from small agricultural, forest, and urban watersheds (SCS 1986; Mishra and Singh 2006; Mishra and Singh 2004a, b). The method is widely used by engineers and hydrologists and watershed managers as a simple watershed model, and as a runoff estimating component in more complex computer based watershed models (Mishra and Singh 2003). Recently, Singh and Frevert (2002) edited a book titled 'Mathematical Models of Small Watershed Hydrology and Applications', in which at least 6 of the 22 chapters have mathematical models of watershed hydrology based on SCS-CN approach. This reflects the robustness and everlasting popularity of the SCS-CN technique. Recently, Singh et al. (2010) presented an updated hydrological review of the recent advancements in SCS-CN methodology.

The SCS-CN method is based on the water balance equation along with two fundamental hypotheses. The first hypothesis equates the ratio of actual amount of direct surface runoff (Q) to the total rainfall (P) (or maximum potential surface runoff) to the ratio of actual infiltration (F) to the amount of the potential maximum retention (S). The second hypothesis relates the initial abstraction (I_a) to S, also described as post initial abstraction potential maximum retention (McCuen 2002).

(a) Water balance equation

$$P = Ia + F + Q \tag{1}$$

(b) Proportional equality (first hypothesis)

$$\frac{Q}{P - Ia} = \frac{F}{S} \tag{2}$$

(c) I_a-S relationship (second hypothesis)

$$Ia = \lambda S \tag{3}$$

where, P=total rainfall; I_a=initial abstraction; F=cumulative infiltration excluding I_a; Q= direct runoff; and S=potential maximum retention. The values of P, Q, and S are in mm, while the initial abstraction coefficient (λ) is dimensionless.

Coupling Eqs. (1) and (2), the expression for Q can be written as:

$$\begin{aligned} Q &= \tfrac{(P-Ia)^2}{P-Ia+S} \quad &&; \text{for } P \geq I_a; \\ &= 0 &&; \text{otherwise} \end{aligned} \tag{4}$$

Equation (4) is the general form of the popular SCS-CN method and is valid for $P \geq I_a$; Q=0 otherwise. For λ=0.2, the coupling of Eqs. (3) and (4) results into

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{5}$$

Equation (5) is well recognized as a popular form of the existing SCS-CN method.

2.2 Hawkins SCS-CN Model (HSCN Model)

Hawkins et al. (2001) suggested that value of $\lambda=0.05$ would give better fit to data and is more appropriate for use in runoff calculations, and therefore it has been incorporated in the existing SCS-CN method, i.e., Eqs. (3) & (4). For $\lambda=0.05$, the coupling of Eqs. (3) and (4) results into

$$Q = \frac{(P - 0.05S)^2}{P + 0.95S} \tag{6}$$

Since S can vary in the range of $0 \le S \le \infty$, it is mapped on to a dimensionless curve number CN, varying in a more appealing range $0 \le CN \le 100$, as:

$$S = \frac{25400}{CN} - 254 \tag{7}$$

where, S is in mm. The difference between S and CN is that the former is a dimensional quantity (L) whereas the latter is non-dimensional.

The highest possible numerical value of CN (i.e. 100) symbolizes a condition of zero potential maximum retention (S=0), which in a real physical situation represents a fully impermeable rooftop catchment. Many researchers attempted the practical design values validated by experience lying in a realistic range of 40 to 98 (Van-Mullem 1989). All the factors responsible for generation of runoff from rainfall in the watershed actually govern the curve number including hydro-meteorological and watershed characteristics. The major watershed characteristics such as soil type, land use/treatment classes, hydrologic soil group, hydrologic condition, and antecedent moisture condition significantly affect CN (Mishra and Singh 2003).

2.3 Michel Simplified SCS-CN (MSCN) Model

Based on soil moisture accounting procedure (SMA), Michel et al. (2005) introduced a simplified SCS-CN model for runoff computations for a given storm rainfall event. The simplified SCS-CN procedure (hereafter termed as MSCN model) can be expressed as:

$$Q = P\frac{P}{P + S} \quad \text{for AMC I} \tag{8}$$

$$Q = P\frac{(0.48S + 0.72P)}{(S + 0.72P)} \quad \text{for AMC II} \tag{9}$$

$$Q = P\frac{(0.79S + 0.46P)}{(S + 0.46P)} \quad \text{for AMC III} \tag{10}$$

where, Q=direct runoff; P=total rainfall; and S=potential maximum retention or infiltration. In these models, AMC I refers to dry condition (completely pervious) of watershed. AMC II represents normal or average condition of watershed. For AMC III, which refers to completely wet condition of the watershed (or completely impervious such as water body or metallic roads/tiled rooftops).

2.4 Storm Water Management Model (SWMM)-Annual Storm Runoff Coefficient (ASRC) Approach

The annual storm runoff coefficient (ASRC) is defined as the ratio of annual runoff to annual precipitation has been widely used to determine the annual runoff volume (or depth) and annual pollutants loads in storm-water models (Pandit and Gopalakrishnan 1996). The concept of ASRC has also been used in versatile Storm Water Management Model (SWMM) level I by Heany et al. (1976) for urban hydrological studies and investigations. The expression of ASRC can be defined as:

$$\mathrm{ASRC} = 0.15\left(1-\frac{\mathrm{I}}{100}\right)+0.90\left(\frac{\mathrm{I}}{100}\right) \tag{11}$$

where, I represents the percent imperviousness. The constants 0.15 and 0.90 are the assumed ASRC values for completely pervious and impervious watersheds, respectively.

2.5 Central Ground Water Board (CGWB) Approach

Central Ground Water Board (CGWB 2000) has developed and recommended a methodology for computation of availability of rooftop rainwater through rooftop catchments considering the rooftop area and rainfall. In this approach, the runoff coefficient (RC) (defined as the ratio of total runoff (Q) to total rainfall (P), i.e., Q/P) was assumed to be 0.8. The following expression can be used to quantify the rainwater harvesting potential as:

$$\mathrm{RWH\,potential} = \mathrm{P.\,A.\,RC} \tag{12}$$

where A is the rooftop catchment area.

3 Application, Results and Discussion

3.1 Study Area

Five different hydrological models/approaches as discussed above, i.e., SCS-CN method, HSCN model, MSCN model, SWMM- ASRC model, and CGWB approach were applied to the rooftop catchments of newly established College of Agricultural Engineering & Technology (CAET), Anand Agricultural University (AAU) Godhra, for which an effective RTRWH system was to be designed and developed and quantify the potential of rooftop catchments for harvesting rainwater on monthly and annual basis. The total rooftop catchment area of the CAET campus building was approximately found to be 6212.18 m^2. The study area falls under semi arid region and located between 22.30° to 23.23° N latitude and 73.15° to 74.75° E longitude. The climate of the district is characterized by a hot summer and dry in the non- rainy season. The winter season start from December to February followed by the hot season from March to May. The temperature of the area is found to vary from 8 °C (minimum) to 42.0 °C (maximum) with an average annual temperature of 33^0C. For the present study, the daily rainfall data of the previous year, i.e., 2011was collected from Main Maize Research Station (MMRS) Godhra, Panchmahals. The total amount of the rainfall was observed to be 956.40 mm, with a minimum of 120 mm and a maximum of 532.00 mm in the months of September and August, respectively. The ombrothermic diagram of Bagnouls and Gaussen for the study area relating temperature with precipitation emphasizes an aridity period during the year, the month and even the day is shown in Fig. 1.

4 Results and Discussion

In this section, the quantification of potential of rooftop catchment of CAET campus building for rainwater harvesting has been assessed using five different models/approaches, as discussed

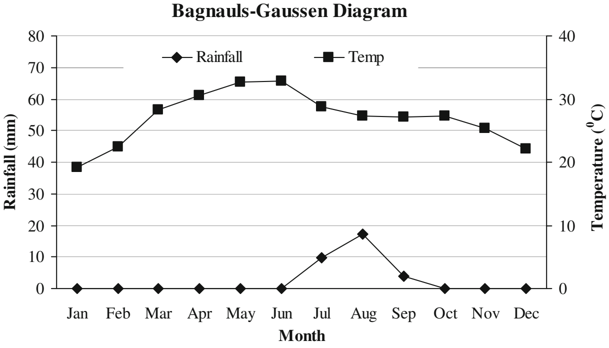

Fig. 1 Ombrothermic diagram of Bagnauls and Gaussen of the study area between average monthly rainfall and temperature

here. In application of the existing SCS-CN model (Eq. 5) and HSCS-CN model (Eq. 6) to assess the rainwater harvesting potential of the rooftop catchment, the value of initial abstraction coefficient (λ) was taken as 0.2 and 0.05, respectively, and the potential maximum retention (S) was computed using Eq. (7) and the curve number (CN) was taken as 98 as per the suggestions given by Van-Mullem (1989). Again for MSCS-CN model Eq. (10), S was computed using Eq. (7) and the curve number (CN) was taken as 98 as per the suggestions given by Van-Mullem (1989). It can be specifically noted here that Eq. (10) corresponds to antecedent moisture condition (AMC) III condition, which refers to completely wet condition or completely impervious (such as metallic roads/tiled rooftops) catchments. As in the present case, the rooftops catchments are entirely tiled and hence resemble to complete impervious in nature. In SWMM- ASRC approach (Eq. 11), the ASRC value was assumed to be 0.90 for completely impervious catchments (Pandit and Gopalakrishnan 1996).

Finally to test the suitability of the proposed models, the results were compared with CGWB approach (Eq. 12), which is the standard method used in India for quantification of potential of rooftop catchments. Using these models the potential of the CAET campus rooftop catchment was quantified on daily, monthly and annual basis. Figure 2a-c show the distribution of daily potential of rooftop rainwater with rainfall events using MSCS-CN model. A similar analysis was performed for all the remaining four models (not shown here). Table 3 shows monthly as well as annual potential of CAET campus rooftop catchment for rainwater harvesting using all the five models.

Notably, it can be observed from Tables 1 and 2 that for the same amount of rainfall and same rooftop catchment area, the MSCS-CN model yields highest rooftop runoff followed by SWMM-ASRC, HSCS-CN, and SCS-CN model. However, as discussed above, the performance of all the four models was statistically evaluated in comparison to the standard and recommended method of CGWB (CGWB 2000) in terms of potential error of estimate (PE) (Gundekar et al. 2008).

Potential error of estimate (PE): The expression for PE can be expressed as:

$$Q = \frac{(Q_{RTM} - Q_{RTCGWB})}{Q_{RTCGWB}} \times 100 \tag{13}$$

where, Q_{RTM} and Q_{RTCGWB} represents computed rooftop runoff water using the models at Sl. No. 1-4 and CGWB approach, respectively. Using Eq. (13) the values of PE (annual basis) were computed as −0.002; −0.038; −0.180; and −0.125, respectively for SCS-CN Model (λ=0.2) (SCS 1986); HSCS-CN Model (λ=0.05) (Hawkins et al. 2001); MSCS-CN Model (Michel et al. 2005); SWMM ASRC Approach (Heany et al. 1976). On the basis of PE values, the SCS-CN model has close resemblance with CGWB approach followed by

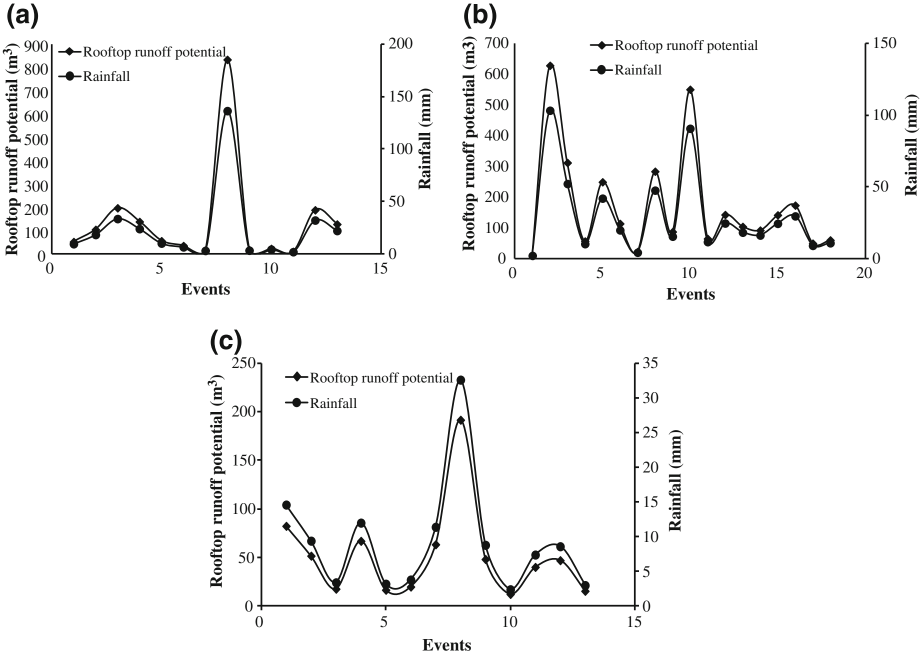

Fig. 2 **a**-**c**: Daily potential of rooftop catchment for rainwater harvesting using MSCS-CN model for the months of July, August and September, respectively

HSCS-CN model, SWMM-ASRC, and MSCS-CN model. Hence, SCS-CN model can be used in place of CGWB approach for Indian conditions.

4.1 Estimation of Annual Storm Runoff Coefficient (ASRC)

It is essential to consider the RC in the selection of roofs in order to maximise their RWH potential. For this reason, it seems urgent to solve the lack of specific RC for different roof types under diverse environmental climatic conditions in the context of RWH (Farreny et al. 2011a). Therefore, an attempt has been made to compute the ASRCs for the models/approaches which were used in this study to assess the potential of rooftop catchments for rainwater harvesting. The developed values of ASRCs are given in Table 3. The developed values of ASRCs are explicit functions of curve number (CN) and model specific. The highest possible numerical value of CN (i.e. 100) symbolizes a condition of zero potential maximum retention (S=0), which in a real physical situation represents an impermeable watershed. On the contrary the lowest possible numerical value of CN indicates a situation

Table 3 Computed values of ASRC for different models/approaches

Sl. no.	Model/Approach	ASRC
1	SCS-CN Model (λ=0.2) (SCS 1986)	0.801
2	HSCS-CN Model (λ=0.05) (Hawkins et al. 2001)	0.830
3	MSCS-CN Model (Michel et al. 2005)	0.944
4	SWMM-ASRC Approach (Heany et al. 1976)	0.900
5	CGWB Approach (CGWB 2000)	0.800

of highest potential maximum retention ($S=\infty$), reflecting a physical situation of an infinitely abstracting watershed. Therefore, in principle, the ASRC values will also vary on 0-100 scale based on the major runoff producing characteristics of the rooftop catchments. Therefore, the versatility of these models lies to the fact that CN values (according to rooftop catchment characteristics) would yield rooftop runoff and therefore ASRC, which would be based on sound hydrological perception and not just on the empiricism.

However, particularly, for the present study, the develop ASRCs can be directly applied in place of their corresponding models, i.e., SCS-CN Model, HSCS-CN Model, and MSCS-CN Model, and SWMM-ASRC approach for assessing the runoff potential of the rooftop catchments in a similar way to that of CGWB approach and other approaches. It can be observed from the Table 3 that MSCS-CN model has the highest value of ASRC (= 0.944) followed by SWMM-ASRC approach (= 0.900), HSCS-CN model (= 0.830), SCS-CN model (=0.801), and CGWB approach (= 0.800). The SCS-CN model has a close resemblance to CGWB approach, as for as ASRC is concern.

The practical relevance of this study can be attributed to the fact that on one side it explores and paves the applicability of versatile SCS-CN based models for rooftop rainwater harvesting/urban hydrological studies and on the other side, these models can be applied for different rooftop catchments having different rooftop materials such as clay, clay tiles, flat gravel, and green roofs, etc. The models have capability to incorporate the major factors responsible for runoff production from rooftop/urban catchments and would be better a tool for quantification rather than just using empirical runoff coefficients for the purpose. On the other hand, the study also provides a sound hydrological foundation to rainwater harvesting related studies. In a nutshell, the study entice to hydrological scientists and water managers to explore for improved urban hydrological models rather empirical coefficients for rooftop runoff quantification. The concepts of initial abstraction and antecedent dry weather period (ADWP) (Farreny et al. 2011b), which play an important role in rooftop runoff quantification, are an integral part of the SCS-CN methodology, and therefore, the proposed models can be used for the purpose rather than to develop regression models for the purpose.

Lastly, the SCS-CN based models can also be used for qualitative assessment of rooftop runoff water. In this reference, an interesting study was conducted by Mishra et al. (2004) for Partitioning of metal elements in Urban Rainfall-Runoff Overland. However, as for as slope factor is concerned, which plays an important role in runoff generation process can be considered in development of improved SCS-CN based models and could be further explored for urban hydrological studies.

5 Conclusions

The quantification of potential of rooftop catchments for rainwater harvesting is one of the most important key factors for sustainable rainwater management in urban as well as rural areas. This study attempted to explore the applicability of popular and widely used SCS-CN model and its advanced versions i.e., Hawkins SCS-CN model (HSCS-CN) (Hawkins et al. 2001), Michel SCS-CN model (MSCS-CN) (Michel et al. 2005), and Storm Water Management Model-Annual Storm Runoff Coefficient (SWMM-ASRC) (Heany et al. 1976) and their performance was compared with well established and widely used Central Ground Board (CGWB) approach (CGWB 2000) in India. It was found that for the same amount of rainfall and same rooftop catchment area, the MSCS-CN model yields highest rooftop runoff followed by SWMM-ASRC>HSCS-CN>SCS-CN>CGWB. Finally, the ASRCs values for these models were also computed and it was found that MSCS-CN model has the highest value of ASRC (= 0.944) followed by SWMM-ASRC approach (= 0.900), HSCS-CN model (= 0.830), and SCS-CN model (= 0.801) as compared to the CGWB approach (= 0.800). The models used in this study incorporates major runoff producing characteristics of the rooftop catchments such as surface roughness and vegetation and various hydro-meteorological characteristics such as initial abstraction and antecedent dry weather period (ADWP) and therefore provides a sound hydrological alternative to empirical models for quantification of potential of rooftop catchments for rainwater harvesting. These results have an important significance for local governments and urban as well as rural settlements from the perspective of sustainable rainwater management. The findings and the explored models could be a benchmark for an accurate estimation of potential of rooftop catchments and therefore design of storage tanks and sewerage systems, respectively to prevent water scarcity and flooding, during monsoon periods for an effective and efficient management of rainwater.

References

Angrill S, Farreny R, Gasol CM, Gabarrell X, Viñolas B, Josa A, Rieradevall J (2012) Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate. Int J Life Cycle Assess 17(1):25–42

ASCE (1969) Design and construction of sanitary storm sewers. In: ASCE manuals and reports on engineering practice, 37. ASCE, New York

Basinger M, Montalto F, Lall U (2010) A rainwater harvesting system reliability model based on nonparametric stochastic rainfall generator. J Hydrology 392:105–118

Central Ground Water Board (2000) Guide on artificial recharge to ground water prepared by central ground water board. Ministry of Water Resources, Government of India, New Delhi

Chiu Y-R, Liaw C-H, Chen L-C (2009) Optimizing rainwater harvesting systems as an innovative approach to saving energy in hilly communities. Renew Energy 34:92–498

Coombes PJ, Kuczera G, Kalma JD, Argue JR (2002) An evaluation of the benefits of source control measures at the regional scale. Urban Water 4:307–320

El-Sayed M, Mahgoub M, van der Steen NP, Abu-Zeid K, Vairavamoorthy K (2010) Towards sustainability in urban water: a life cycle analysis of the urban water system of Alexandria City, Egypt. J Clean Prod 18 (10–11):1100–1106

Farreny R, Gabarrell X, Rieradevall J (2011a) Cost-efficiency of rainwater harvesting strategies in dense Mediterranean neighbourhoods. Resour Conserv Recycl 55:686–694

Farreny R, Morales-Pinzón T, Guisasola A, Taya C, Rieradevall J, Gabarrell X (2011b) Roof selection for rainwater harvesting: quantity and quality assessments in Spain. Water Res 45:3245–3254

Fewkes A (2000) Modelling the performance of rainwater collection systems: towards a generalised approach. Urban Water 1:323–333

Ghisi E, Tavares DF, Rocha VL (2009) Rainwater harvesting in petrol stations in Brasília: potential for potable water savings and investment feasibility analysis. Resour Conserv Recycl 54:79–85

Gundekar HG, Khodke UM, Sarkar S, Rai RK (2008) Evaluation of pan coefficient for reference crop evapotranspiration for semi-arid region. Irrig Sci 26:169–175

Han MY, Kim SR (2007) Local water independency ratio (LWIR) as an index to define the sustainability of major cities in Asia. Water Sci Technol Water Supply 7(4):1–8

Han MY, Mun JS, Kim TI (2009) Climate change adaptation strategy by multipurpose, proactive rainwater management and case studies in Korea. J Korean Soc Water Wastewater 23(2):223–230

Hatt BE, Deletic A, Fletcher TD (2006) Integrated treatment and recycling of stormwater: a review of Australian practice. J Environ Manag 79(1):102–113

Hawkins RH, Woodward DE, Jiang R (2001) Investigation of the runoff curve number abstraction ratio. Paper presented at USDA-NRCS Hydraulic Engineering Workshop, Tucson, Arizona

Heany JP, Huber WC, Nix SJ (1976) Storm water management model: level I-preliminary screening procedures, EPA Rep. No. 66/2-76-275. U.S. Environ. Protection Agency (U.S. EPA), Cincinnati, Ohio

Jones MP, Hunt WF (2010) Performance of rainwater harvesting systems in the southeastern United States. Resour Conserv Recycl 54:623–629

Kim J, Furumai H (2012) Assessment of rainwater availability by building type and water use through GIS-based scenario analysis. Water Resour Manag 26(6):1499–1511

Kim YJ, Han MY (2008) Rainwater storage tank as a remedy for a local urban flood control. Water Sci Technol Water Supply 8(1):31–36

Kim R-H, Lee S, Kim YM, Lee JH, Kim SK, Kim JG (2005) Pollutants in rainwater runoff in Korea: their impacts on rainwater utilization. Environ Technol 26:411–420

Lancaster B (2006) Guiding principles to welcome rain into your life and landscape. In: Rainwater harvesting for drylands and beyond, 1. Rainsource Press, Tucson, Arizona

Li Z, Boyle F, Reynold A (2010) Rainwater harvesting and greywater treatment systems for domestic application in Ireland. Desalination 260:1–8

Liaw CH, Tsai YL (2004) Optimum storage volume of rooftop rain water harvesting systems for domestic use. J Am Water Resour Assoc 40:901–912

McCuen RH (2002) Approach to confidence interval estimation for curve numbers. J Hydrol Eng 7(1):43–48

McCuen R (2004) Hydrologic analysis and design, 3rd edn. Pearson Education Inc, Upper Saddle River

Meera V, Ahammed MM (2006) Water quality of rooftop rainwater harvesting systems: a review. J Water Supply Res Technol Aqua 55:257–268

Michel C, Andreassian V, Perrin C (2005) Soil conservation service curve number method: how to mend a wrong soil moisture accounting procedure. Water Resour Res 41:W02011. doi:10.1029/2004WR003191

Mishra SK, Singh VP (2003) Soil conservation service curve number (SCS-CN) methodology. Kluwer Academic Publishers, P. O. Box 17, 3300 AA Dordrecht, The Netherlands

Mishra SK, Singh VP (2004a) Long-term hydrologic simulation based on the Soil Conservation Service curve number. Hydrol Process 18:1291–1313

Mishra SK, Singh VP (2004b) Validity and extension of the SCS-CN method for computing infiltration and rainfall-excess rates. Hydrol Process 18:3323–3345

Mishra SK, Singh VP (2006) A re-look at NEH-4 curve number data and antecedent moisture condition criteria. Hydrol Process 20:2755–2768

Mishra SK, Sansalone JJ, Singh VP (2004) Partitioning analog for metal elements in urban rainfall-runoff overland flow using the soil conservation service curve number concept. J Environ Eng 130(2):145–154

Mun JS, Han MY (2012) Design and operational parameters of a rooftop rainwater harvesting system: definition, sensitivity and verification. J Environ Manag 93:147–153

Mwenge Kahinda J, Taigbenu AE, Boroto RJ (2010) Domestic rainwater harvesting to improve water supply in rural South Africa. J Phys Chem Earth 35:742–751

Pacey A, Cullis A (1989) Rainwater harvesting: the collection of rainfall and runoff in rural areas. Intermediate Technology Publications, London

Palla A, Gnecco I, Lanza LG (2011) Non-dimensional design parameters and performance assessment of rainwater harvesting systems. J Hydrology 401:65–76

Pandit A, Gopalakrishnan G (1996) Estimation of annual storm runoff coefficients by continuous simulation. J Irrig Drain Eng 122(40):211–220

Postel S (1992) Last oasis: facing water scarcity. W.W. Norton and Company, New York

Rahman A, Dbais J, Imteaz M (2010) Sustainability of rainwater harvesting systems in multistorey residential buildings. Am J Eng Appl Sci 3:889–898

Rygaard M, Binning PJ, Albrechtsen H (2011) Increasing urban water self-sufficiency: new era, new challenges. J Environ Manag 92(1):185–194

SCS (1986) Urban hydrology for small watersheds, Technical Release No. 55. Soil Conservation Service, USDA, Washington, D. C

Singh VP (1992) Elementary hydrology. Prentice Hall, Upper Saddle River

Singh VP, Frevert DK (2002) Mathematical models of small watershed hydrology and applications. Water Resources Publications, Highlands Ranch

Singh PK, Gaur ML, Mishra SK, Rawat SS (2010) An updated hydrological review on recent advancements in soil conservation service-curve number technique. J Water Clim Chang 1(2):118–134, IWA Publishing doi:10.2166/wcc.2010.022

Su MD, Lin CH, Chang LF, Kang JL, Lin MC (2009) A probabilistic approach to rainwater harvesting systems design and evaluation. Resour Conserv Recycl 53:393–399

TxDOT (2009) Hydraulic design manual, Texas. Available from: http://onlinemanuals.txdot.gov/txdotmanuals/hyd/hyd.pdf. (accessed July 2010)

Van-Mullem JA (1989) Runoff and peak discharges using Green-Ampt model. J Hydraul Eng ASCE 117 (3):354–370

Viessman W, Lewis GL (2003) Introduction to hydrology, 5th edn. Prentice Hall, Upper Saddle River

Ward S, Memon FA, Butler D (2010) Harvested rainwater quality: the importance of appropriate design. Water Sci Technol 61(7):1707–1714

Zhang Y, Chen DH, Chen L, Ashbolt S (2009) Potential for rainwater use in highrise buildings in Australian cities. J Environ Manage 91(1):222–226