Surface Runoff Estimation Over Heterogeneous Canal Commands Applying Medium Resolution Remote Sensing Data with the SCS-CN Method

Priyantha Jayakody and Nilantha Gamage
International Water Management Institute, Colombo, Sri Lanka

Abstract

The precise estimation of surface runoff from rainfall is critical for water resource management. In the recent past, remote sensing and Geographic Information System (GIS) technologies have been widely used in the estimation of surface runoff from watersheds, and from agricultural fields in particular. This is due to the inherent ability of remote sensing to capture spatial heterogeneity of surface parameters such as land use and land cover. This could lead to better performances of surface runoff simulation models. Surface runoff volume/rate estimation involves quantifying the amount of rainfall exceeding infiltration and initial abstractions which must be satisfied before the occurrence of runoff.

The widely accepted SCS curve number method was employed to calculate surface runoff, using a combination of remotely-sensed land use/land cover and hydrometrological data in the Punjab canal command areas. Land use/Land cover maps for four cropping seasons, Rabi 2004-05, Kharif 2005, Rabi 2006-07 and Kharif 2007 were derived using red and near infrared bands of MODIS 8 day products. The existing soil map was reclassified into hydrological soil groups and rainfall data were interpolated using the inverse distance method to represent the spatial rainfall values of each canal command.

The results show that CN values vary from 70 to 95 during the study period. The highest CN value of 94.4 is during the Kharif 2005 season. Meanwhile the runoff-coefficient is changing from 0.01 to 0.25 and 0.01 to 0.43, respectively, during Rabi 2004/05 and Rabi 2006/07. During Kharif 2005 and Kharif 2007, the runoff-coefficient varied from 0.01 to 43 and 0.01 to 0.45, respectively. The study shows that the SCS curve number method can be used for runoff estimation with the help of remote sensing products and GIS technologies from catchments where gauging data is not available.

Introduction

The precise estimation of surface runoff from rainfall is critical for water resource management. In the recent past, the use of remote sensing and Geographic Information System (GIS) technologies have been widely used in the surface runoff estimation of watersheds, and particularly from agricultural fields. This is primarily because a good runoff model has to include spatially variable geomorphologic parameters such as rainfall, soil characteristics, and land use change (Shih 1996; Melesse and Shih 2000a, 2000b). Many methods for estimating runoff exist (Haan et al. 1982; Chow et al. 1988). Runoff volume or rate estimation involves estimating the amount of rainfall exceeding infiltration and initial abstractions, which must be satisfied before the occurrence of runoff. Infiltration excess runoff can be estimated using different techniques. The USDA, Natural Resources Conservation Service-Curve Number (NRCS-CN) is a widely used method that combines remotely-sensed land use data and soils information to determine soil's abstraction. This report presents an application of the curve number method with remote sensing products for estimating runoff in the Punjab irrigation command in Pakistan, and demonstrates the practical importance of how Remotes Sensing and Geographic Information Systems work in similar contexts.

SCS Curve Number Method

The SCS-CN method for estimating direct runoff volume has become widely used as a tool for drainage design, particularly for impoundment structures on un-gauged watersheds (Haan et al. 1982; USDA-SCS 1985, 1986). The equation used (1) has three empirically based parts, based on data from a large number of gauged watersheds distributed throughout the United States (Haan et al. 1982). The first part holds that the ratio of the amount of actual retention, (F), to maximum potential watershed storage, (S), is equal to the ratio of actual direct runoff volume, (Q), to the effective rainfall (total rainfall, P, minus initial abstraction, I_a).

(1) $$\frac{F}{S} = \frac{Q}{(P - I_a)}$$

Where $F = P - I_a - Q$, by theory. All terms are volumes (expressed as mm). It is also assumed that:

(2) $$I_a = 0.2S$$

Where I_a is the portion of the rainfall that will not appear as runoff. Substituting (2) into (1) and solving for Q gives the typical expression of the SCS-CN method (Haan et al. 1982; McCuen 1982):

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

Where $P > I_a$. and

(4) $$S = \frac{25{,}400}{CN} - 254$$

Where the SCS curve number, CN (unit-less, ranging from 0 to 100), is determined from Table 1, based on land-cover, hydrologic soil group (HSG), and antecedent moisture condition (AMC).

Table 1. Five-day antecedent rainfall according to AMC condition.

AMC condition	Five-day Antecedent Rainfall (mm)	
	Dormant season	Growing season
I	< 12.5	< 35
II	12.5 – 27.5	35-52.5
III	> 27.5	> 52.5

If the AMC condition is I then the following formula is applicable.

(5) $$CNI = \frac{4.2 * CNII}{(10 - 0.058 * CNII)}$$

If the AMC condition is III, then following formula is applicable.

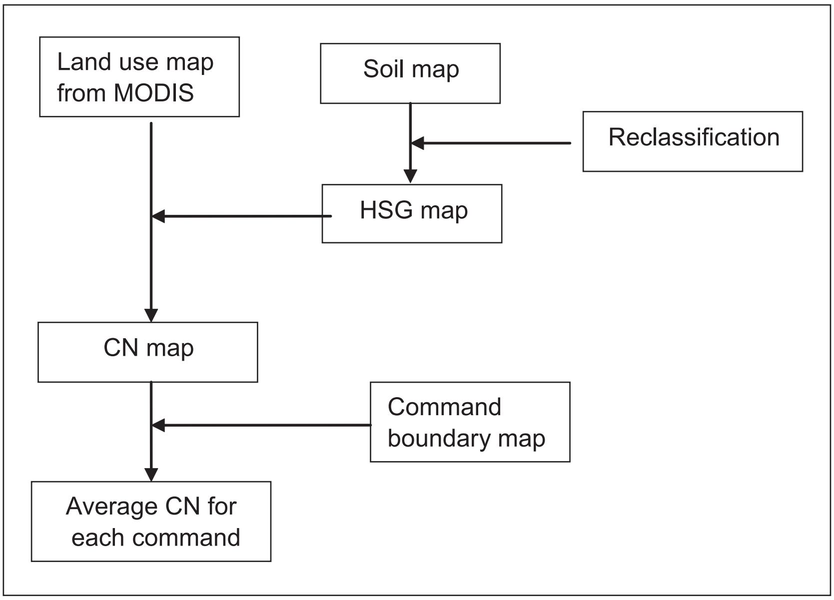
(6) $$CNIII = \frac{23 * CNII}{(10 + 0.13 * CNII)}$$

Methodology

Land use maps for the four seasons (Rabi 04/05, Kharif 05, Rabi 06/07 and the Kharif 07) were generated using MODIS 250 m 8-day time series for the respective seasons. The already available soil map was used for Hydrological soil group categorization. Rainfall data were interpolated using the inverse distance method to represent the relevant rainfall values for each of the 22 commands separately. The flow chart for the detailed procedure is shown in Figure 1.

Soil map was reclassified into hydrological soil groups according to their soil properties and crossed with land use maps to get the curve number maps for the season. The same processes were repeated four times for four seasons. Weighted averages were taken to

Figure 1. Flow chart for the procedure used.



represent the curve numbers for individual commands. Equation (7) explains the method (A and TAW are sub area and total area of particular canal command).

$$\text{(7)} \qquad CN\ (Weighted) = \frac{\sum(CN \times A)}{TAW}$$

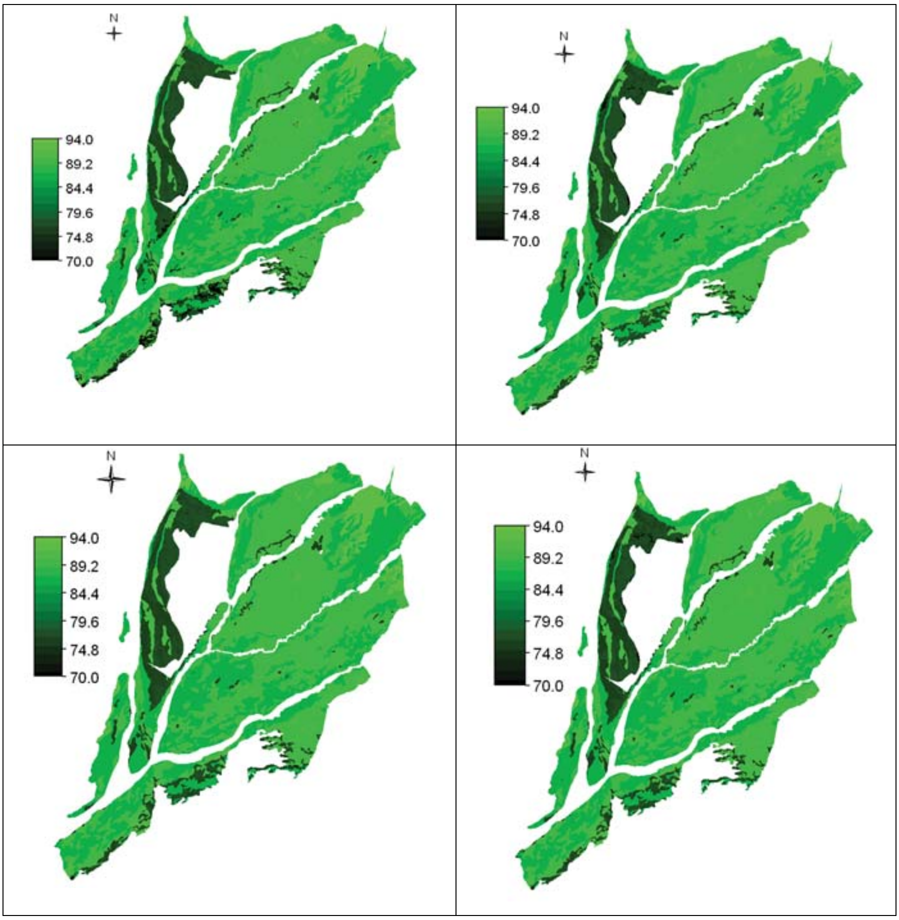
Daily runoff was calculated for the individual 22 commands for the study period and then was summarized to monthly and seasonal values.

Results and Discussion

Curve Number Variations

The results show that curve number values vary from 70 to 95 along the entire irrigation canal commands during the study period. Higher CN values are observed in Kharif seasons as more agricultural lands appear in land use maps. The highest CN value for the study area is 90.4 during Kharif 2005 season in the upper part of the command. Figure 2 below shows the CN variation during the four seasons.

Figure 2. Curve number variation during the study period; Rabi 04/05, Kharif 05, Rabi 06/07 and Kharif 07 (top left to right bottom).



Seasonal Runoff Generation

Runoff process is governed by land use, soil types, and rainfall. With the given conditions, land use and soil types are constant, and rainfall plays a major role in runoff generation. Rainfall volume, intensity and the distribution determine the amount of runoff escape from the canal command. The first two seasons (Rabi 04/05 and Kharif 05) show low runoff values due to less rainfall compared to the Rabi 2006/2007 and Kharif 2007 seasons that had higher rainfall. The lower Chenab canal shows the highest runoff (25 %) during Rabi 2004/2005 season and the Muzaffagarh canal command shows the highest runoff (43 %) during the Kharif 2005 season. Generally the canal command in the upper most part and the lower most part of the irrigation scheme shows high runoff compared to the canal commands in the middle part of the irrigation scheme. This is a result of spatial distribution of soil type, land use and rainfall along the whole command. Tables 2 and 3 show predicted runoff for individual canal commands during different seasons.

Table 2. Seasonal rainfall and runoff predicted using the SCS method for the 22 canal commands for Rabi 2004/2005 and Kharif 2005.

Season/Canal commands	Rabi 04/05			Kharif 05		
	Rainfall (mm)	Runoff (mm)	% runoff	Rainfall (mm)	Runoff (mm)	% runoff
Upper Jehlum Canal	281	21	7	469	98	21
Lower Jehlum Canal	258	43	17	374	65	17
Marala Ravi Link Canal	277	10	4	440	78	18
Upper Chenab Canal	236	4	2	477	106	22
Lower Chenab Canal	197	48	25	336	78	23
Central Bari Doab Canal	217	12	5	461	141	31
Upper Depalpur Canal	216	3	1	388	66	17
Lower Bari Doab Canal	170	9	5	217	4	2
Lower Depalpur Canal	185	1	0	252	6	2
Pakpattan Canal	154	1	1	137	1	1
Fordwah Canal	148	0	0	88	0	0
Sadiqia Canal	145	0	0	106	0	0
Haveli Canal	194	31	16	257	40	15
Sidhnai Canal	173	31	18	152	58	38
Mailsi Canal	142	24	17	168	72	43
Bahawal Canal	126	27	21	149	46	31
Thal Canal	253	38	15	354	49	14
Chashma Right Bank Canal	203	30	15	269	31	12
Rangpur Canal	184	21	11	194	49	25
Muzaffargarh Canal	146	20	13	136	48	35
Dera Ghazi Khan Canal	90	0	0	73	1	2
Panjnad Canal	57	1	2	41	0	1

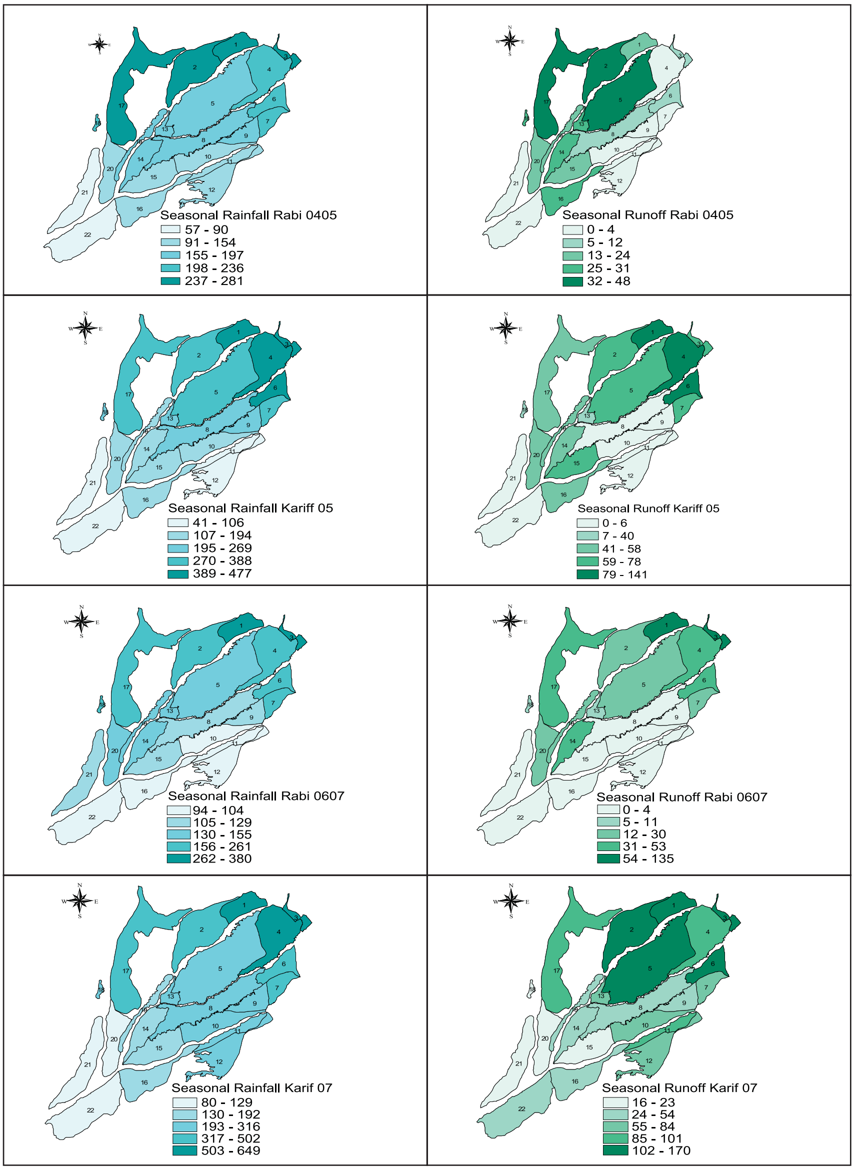
Both Rabi 2006/07 and Kharif 2007 show significant amounts of runoff. During Rabi 2006/2007 upperparts and the lower part canal commands show higher runoff. During Kharif 2007 seasons, no significant differences between the lower and upper part were observed. The Marala Ravi Link Canal shows 43 % runoff during Rabi 2006/2007 and Panjnad Canal shows 49 % of the runoff during the Kharif 2007 seasons. Those are the canal commands which give the highest runoff.

Table 3. Seasonal rainfall and runoff predicted using the SCS method for the 22 canal commands for Rabi 2006/2007 and Kharif 2007.

Season/Canal commands	Rabi 06/07			Kharif 07		
	Rainfall (mm)	Runoff (mm)	% runoff	Rainfall (mm)	Runoff (mm)	% runoff
Upper Jehlum Canal	380	122	32	635	135	21
Lower Jehlum Canal	216	30	14	475	154	32
Marala Ravi Link Canal	315	135	43	649	170	26
Upper Chenab Canal	261	44	17	554	98	18
Lower Chenab Canal	134	19	14	313	142	45
Central Bari Doab Canal	228	53	23	502	128	25
Upper Depalpur Canal	194	24	12	444	83	19
Lower Bari Doab Canal	117	2	2	283	47	17
Lower Depalpur Canal	129	2	2	316	54	17
Pakpattan Canal	94	2	2	252	67	27
Fordwah Canal	95	4	5	250	101	40
Sadiqia Canal	100	2	2	248	82	33
Haveli Canal	141	6	4	299	84	28
Sidhnai Canal	153	37	24	152	35	23
Mailsi Canal	113	2	2	163	22	14
Bahawal Canal	99	0	0	151	34	23
Thal Canal	256	34	13	374	95	25
Chashma Right Bank Canal	202	11	5	257	19	7
Rangpur Canal	155	20	13	192	35	18
Muzaffargarh Canal	137	18	13	129	23	17
Dera Ghazi Khan Canal	111	1	1	104	16	15
Panjnad Canal	104	2	2	80	39	49

Areas where high rainfall occurs normally experience higher runoff but there are locations where it is not true as shown in Figure 3. This is mainly due to land use, which plays a major roll in generating runoff. The upper parts of the irrigation command receive comparatively higher rainfall and hence significant runoff generation.

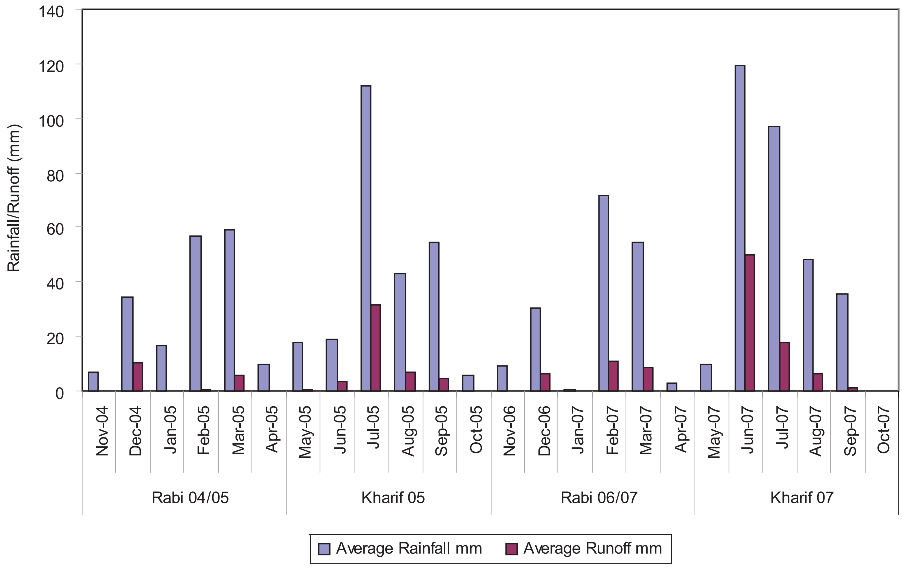
Figure 3. Spatial distribution of seasonal rainfall (mm) and runoff (mm) over canal commands.



Monthly runoff

Monthly Runoff was calculated for four seasons for 22 canal commands. Data were averaged over the whole irrigation scheme for easy explanation. Figure 4 shows that higher rainfall values are not always associated with higher runoff and instead depend on the distribution of the rainfall. The Kharif season generally shows higher runoff values compared to the Rabi seasons.

Figure 4. Monthly rainfall runoff variation during the four seasons (averaged over irrigation scheme).



Conclusions

Rabi 2004/05 and Kharif 2005 seasons show low runoff values due to less rainfall when compared to the Rabi 2006/07 and Kharif 2007 seasons that reported higher rainfall. This indicates that rainfall significantly affects the volume and the rate of runoff. This study demonstrates RS and GIS as a useful supportive tool for runoff estimation and to help understand the spatial variability of these processes. MODIS data is suitable for large scale applications. The study shows that the SCS curve number method can be used for runoff estimation with the help of remote sensing products and GIS technologies from catchments where gauging data are not available.

References

Chow, V. T.; Maidment, D. R.; Mays, L. W. 1988. Applied Hydrology. Singapore: McGraw-Hill.

Haan, C. T.; Johnson, H. P.; Brakensiek, D. L. (Eds.). 1982. Hydrologic Modeling of Small Watersheds. St. Joseph, Michigan: American Society of Agricultural Engineers,

McCuen, R. H. 1982. A Guide to Hydrologic Analysis using SCS Methods. Englewood Cliffs, NJ: Prentice-Hall.

Melesse, A. M.; Shih, S. F. 2000a. Geomorphic GIS Database for Runoff Coefficient Determination. Proceedings of the Second International Conference on Geospatial Information in Agriculture and Forestry, 10-12 January 2000, Lake Buena Vista, FL, Vol. I, pp. 505-512.

Melesse, A. M.; Shih, S. F. 2000b. Remote Sensing and GIS Database for Runoff Curve Number Change Assessment. *Soil and Crop Science Society of Florida Proceedings* 59: 141-146.

Shih, S. F. 1996. Integration of Remote Sensing and GIS for Hydrologic Studies, Chapter 2, In *Geographical Information Systems in Hydrology, Dordrecht*, eds. V. P. Singh and M. Fiorentino. The Netherlands: Kluwer Academic Publishers.