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Estimation of Runoff from Impervious Surface using Multitemporal Remote Sensing Data: A Case Study of Ramnadi Catchment, Maharashtra, India

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Abstract: *Surface runoff in the urbanised Ramnadi watershedof Mula basin in Pune, Maharashtra, is estimated using Landsat TM data of 1989 and 2011. Population calibrated impervious surfaces (IS) were extracted for the watershed by employing a regression analysis wherein IS is defined to be the function of band values, NDVI, Tasselled Cap band II, slope, elevation and population density. Runoff, seen as a function of imperviousness in the area, has been calculated using the Soil Conservation Service Curve Number (SCS-CN) method. Curve numbers have been obtained from the standard tables provided in the National Engineering Handbook-4 published by the USDA, USA. These were derived by analysing the landuse landcover pattern, hydrological soil group and condition for the entire Ramnadi watershed. In order to compute the surface runoff these CN were incorporated in the standard equations given in the SCS-CN method. Major changes in the landuse landcoverpattern in the last 22 years have been detected, with a net growth in built up area from 21.13% (1989) to 45.43% (2011). Growth in the built up area has led to the increase in IS in the watershed. IS area have gone well above 25% around Pune city. The impact of increase in built up area and IS hasaugmented surface runoff in the catchment. Taking into consideration a constant basin area of 52.48 km^2 and an average rainfall of 60.2 mm, the average antecedent moisture condition (class-II)yielded the estimated runoff of 525 million m^3 in 2011 as against 406 million m^3 in 1989. Thus it is quite evident that the growth in built up area and impervious surfaces have enhanced the capacity of the Ramnadi catchment to generate more runoff even with lower order storm events.*

Introduction

Over the last decade there has been a growing concern over the pattern of urban flooding occurring across the globe. The scientific community is often put to the task of answering the queries related to urban flooding and climate change. In the wake of such a situation, understanding the ground realities, addressing the problem of urban flooding and suggesting remedies have been the major thrust of urban hydrological studies. Urbanisation has been a causative factor for the conversion of rural agricultural land into built up area, leading to a

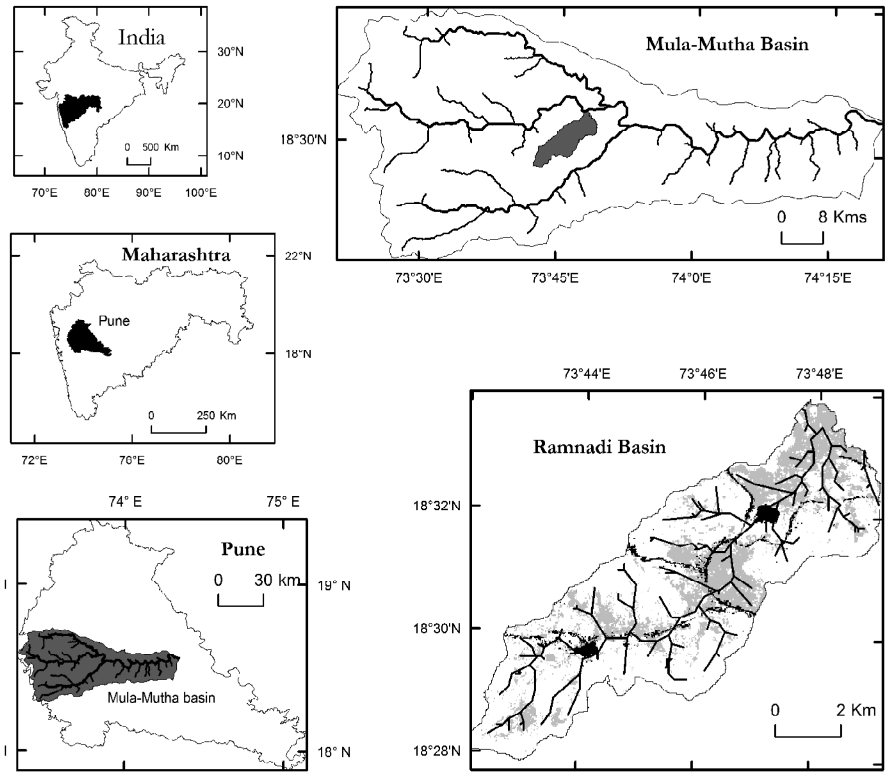

Figure 1. Location of the study area

tremendous increase in impervious surface areas (ISA). Impervious surface area comprises urban built up landscape that does not allow water to percolate. Dominance of ISA in the landscape results in increased concentration of storm water flow causing channel erosion, habitat degradation and severe impairment of aquatic communities (Bird *et al.*, 2002). Increase in ISA correspondingly increases discharge and volume of surface runoff that leads to erosion in watershed. Surface runoff refers to the spread of rainwater that is not able to infiltrate. It depends on a number of factors including the intensity and duration of precipitation, antecedent rainfall, type of soil, drainage and landuse.

Concept and work on impervious surfaces is comparatively recent and it refers to most of the impervious surface landcover types found in urban areas that can be categorised as belonging to either transportation (roads, sidewalks, driveways, parking lots, etc.) or rooftops of residential, commercial, industrial buildings, etc.(Schueler,1994). Impervious surface mapping has gained attention among many municipal government agencies of different countries. Motivated by the importance of impervious surfaces, many researchers from various disciplines have attempted to estimate the amount and distribution of urban impervious surfaces. In these studies, satellite images have been very useful for successful characterisation of different landcover and landuse types (Ward *et al.*, 2000; Yang, 2006). Coarse and medium resolution satellite data (10-100 metres) are often employed for this purpose. With the availability of remotely sensed data and advanced techniques, a number of scholars from spatial sciences are involved in estimation and mapping of impervious surfaces for urban centres (Fankhauser, 1999; Yang *et al*., 2003; Bauer *et al*., 2004; Lu and Weng, 2006). Relationship between land use changes and changes in hydrological condition in urbanised and non-urban basins has been established on a long term basis (Dougherty *et al*., 2007). A number of scholars have worked on the quantification of long-term hydrologic response, in terms of increased surface runoff, in various urbanising basins of the United States (Lee and Heaney, 2003; Weng, 2001). Sharma and Singh (1992) have exclusively used the Soil Conservation Service model along with the Landsat TM data for the estimation of runoff for the Jojri basin from northwest India.

The Soil Conservation Service Curve Number (SCS-CN) method is widely used for predicting direct runoff volume for a given rainfall event. This method was originally developed by the US Department of Agriculture Soil Conservation Service and has been documented in detail in the National Engineering Handbook, Section 4: Hydrology (NEH-4) (USDA, 1956, 1964, 1971, 1985, 1993). Due to its simplicity it soon became one of the most popular techniques among the engineers and practitioners mainly for small catchment hydrology (Mishra and Singh, 2006). SCS developed the method mainly for the evaluation of storm runoff in small agricultural watersheds. It soon evolved well beyond its original objective and was adopted for different land use such as urbanised and forested watersheds (Rawls *et al*.,1981; Mishra and Singh,1999). Its scope also expanded beyond the evaluation of storm runoff and it became an integral part of more complex, long term simulation models (Choi *et al*., 2002; Holman *et al*., 2003; Lyon *et al*., 2004; Mishra and Singh, 2004; Zhan *et al*., 2004; Mishra *et al*., 2005a; Soulis and Dercas, 2007; Geetha, *et al*., 2008; Moretti and Montanari, 2008; Singh *et al*., 2008; Tyagi *et al*., 2008).

Due to the widespread use and greater acceptance of the method, its applicability was investigated in various regions and for various land use and climatic conditions. CN values required for this method were obtained experimentally from rainfall and runoff measurements over a wide range of geographic, soil and land management conditions (Romero *et al*., 2007; King and Balogh, 2008). The SCS-CN method has also been the subject of many studies aimed at finding a theoretical basis for the method, facilitating the use of the method in regions and for climatic conditions not previously evaluated and supporting its further improvement (Hjelmfelt, 1991; Yu, 1998). A number of studies, aimed at improving the method and finding a better way to incorporate the Antecedent Moisture Conditions (AMC) have been carried out by Simanton *et al*., 1996; Mishra *et al*., 2005b; Jain *et al*., 2006; Sahu *et al*., 2007; Brocca *et al*., 2008; Kannan *et al*., 2008 and Mishra *et al*., 2008.

The previous work mostly addressed the issues of surface runoff extraction for ungauged watersheds using the SCS-CN method and correlating the results with the land use changes. The present study also follows most of these prior works along with incorporation of impervious surfaces for the estimation of surface runoff in an ungauged basin.

Objectives

The aim of the present study is to analyse the impact of landuse and landcover (LULC) changes on surface runoff in an urbanised watershed. In order to fulfil this goal, the following objectives were set up:

- To assess the growth in built up area and impervious surfaces.
- To estimate the surface runoff using Remotely Sensed (RS) data.
- To analyse the impact of LULC and IS on runoff.

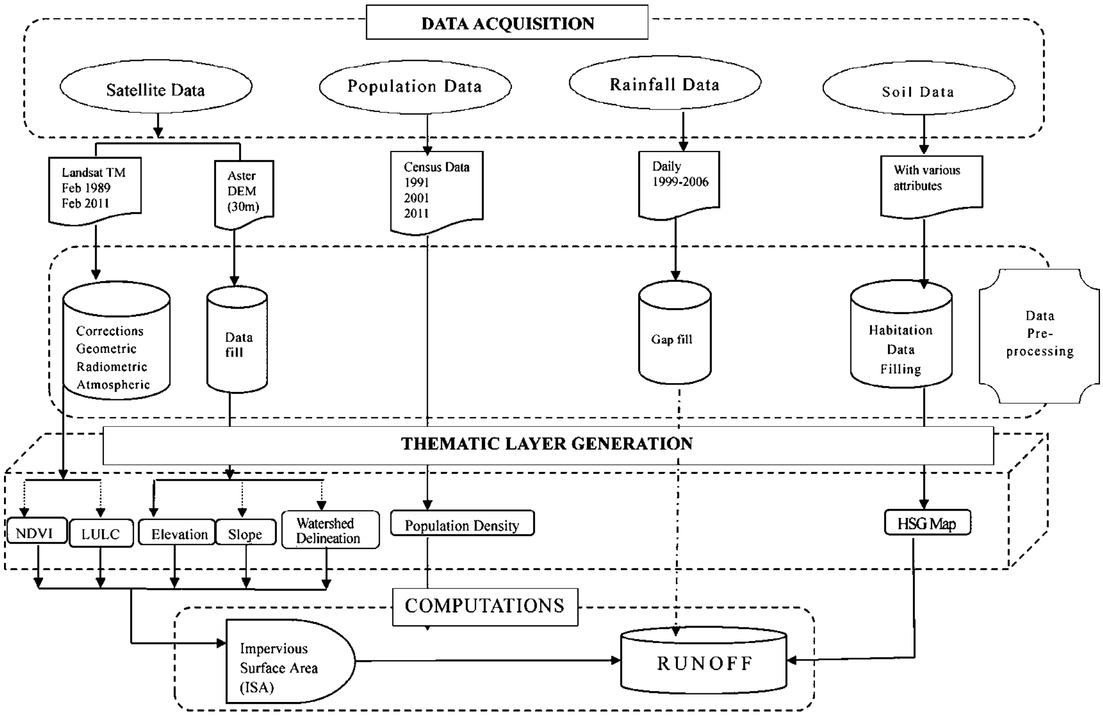

Figure 2. Methodology

Study area

Ramnadi catchment of Mula River in Pune, Maharashtra, India (Fig.1) forms the study area. The Ramnadi watershed is spread over 52.48 km^2, with elevation ranging from 541 m to 926 m above mean sea level. It extends from 18°28' to 18°34' N and from 73°42' to 73°49'15"E. The area is covered by Survey of India toposheet numbers 47F/10, 11, 14 and 15 on 1:50,000. The Ramnadi watershed includes areas of Baner, Aundh, Pashan, Bavdhan, Bhugaon, Bhukum, Mukaiwadi and parts of Pirangut and Lavale. National Highway 4 is the major communication link running through this area.

Materials and methods

The methodology adopted for this study is shown in Fig. 2. In order to employ the SCS-CN method for estimation of surface runoff, the parameters of landuse characterisation and hydrological soil group information were required to be computed first. The satellite images were geometrically and atmospherically corrected. LULC and Normalised Difference Vegetation Index (NDVI) maps were prepared for the period under consideration by supervised classification of Landsat TM images using maximum likelihood technique. Training areas were delineated, which were clearly associated with areas of known identity on the image, on the basis of homogeneity and spectral properties of the categories they represented. Identification of training areas helps in obtaining a classified distribution of landuse classes, six of which, have been identified. These include agricultural fields, natural vegetation, water bodies, hills and hill slopes, barren land and urban built up area including roads. Aster data having 30 m resolution was corrected using the Arc GIS spatial analyst and 3D analyst tools by setting

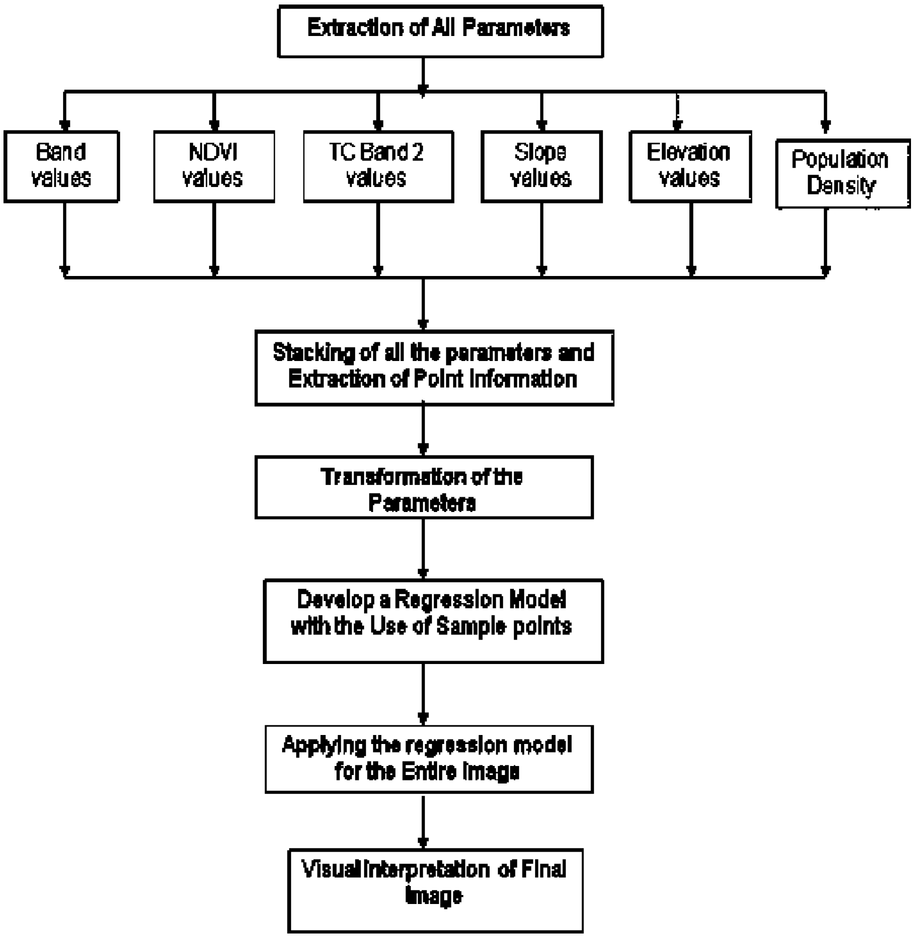

Figure 3. Methodology for the Extraction of ISA

the Z parameter (Frye, 2007) before the extraction of elevation values. Due to the nature of the process of deriving elevation from Synthetic Aperture Radar, most ASTER digital elevation models (DEMs) contain 'voids' or cells where no elevation values are found, as in the case of some water surfaces and shadow patches. Removal of these voids is necessary before further processing, which was done by following the fill and sink procedure for void removal in Arc GIS. Slope values are derived in degrees from elevation values. Tasselled Cap (TC) transformations were adopted for Landsat TM data using in-built values in ERDAS Imagine 9.1 tasselled cap model. These coefficients were originally given by Crist *et al.*, in 1986. Population data at village level and ward level was obtained for 1991 and 2001 and was attached to the polygons of villages/wards, with the help of which, population density was calculated. The methodology for impervious surface extraction consisted of complex analyses with model building, involving thematic layer generation, taking into consideration the population density (Dhorde *et al.*, 2012). Over all nine independent parameters (band values II to V, NDVI, TC band II, slope, elevation and population density) were regressed against the dependent variable IS to generate a multiple regression model for extraction of impervious surfaces.

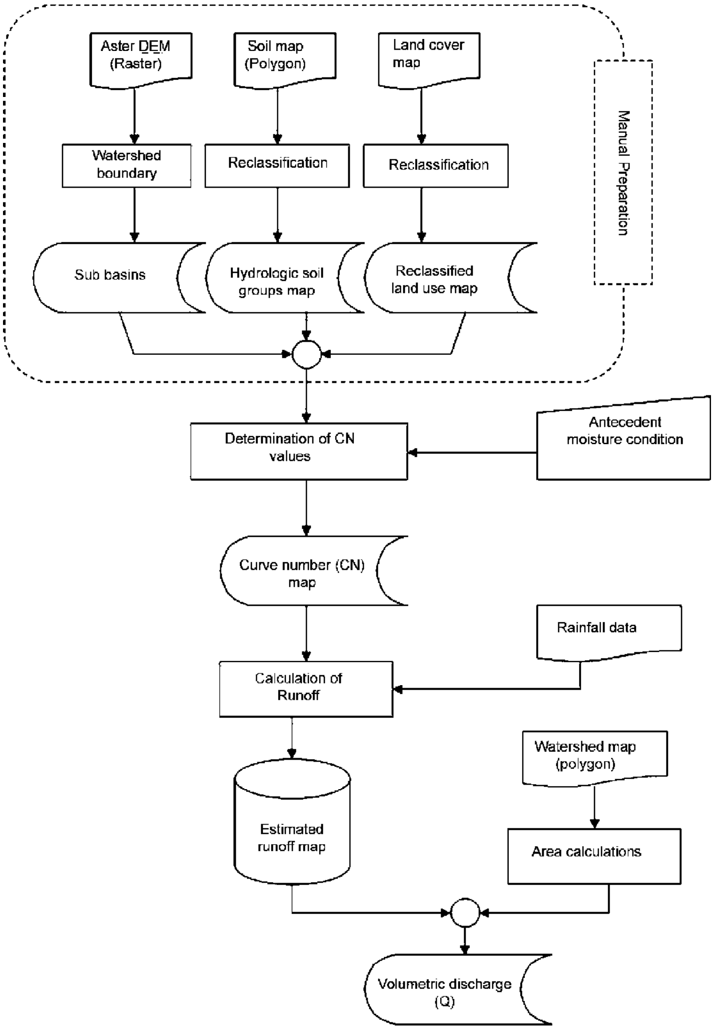

Figure 4. Methodology for Runoff Estimation

Estimation of surface runoff

The methodology for surface runoff estimation consisted of generation of various thematic layers (Fig. 4). For the computation of runoff, variables of rainfall, antecedent moisture condition (AMC), hydrologic soil groups (HSG) and impervious surface area (ISA) have been used. The following section elaborates the methodology adopted for the estimation of surface runoff.

Watershed delineation

The Ramnadi watershed was delineated from the Aster DEM (30m resolution) dataset in Arc GIS. Spatial analyst and Arc SWAT have been used in delineating watershed boundary from the Aster DEM. The main basin and sub basins were derived from the SWAT extension for Arc GIS. Overall 29 sub basins were delineated along with their respective drainage patterns (Fig. 5). These sub basins were identified taking the outlet points which actually indicated the downstream point of each individual sub basin.

Hydrologic Soil Group (HSG) map

The soil map for the study area was procured

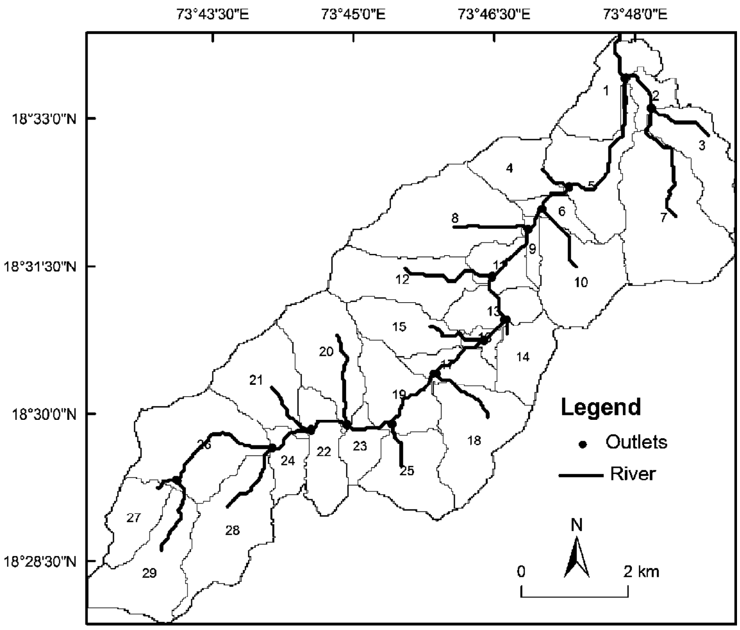

Figure 5. Ramnadi watershed: Sub basins

from National Bureau of Soil Survey and Landuse, Nagpur, on the scale 1:50,000 in digital format. It contained several attributes related to texture, taxonomy, temperature conditions, depth, etc. In order to generate the HSG map, it was essential to group the data as per the

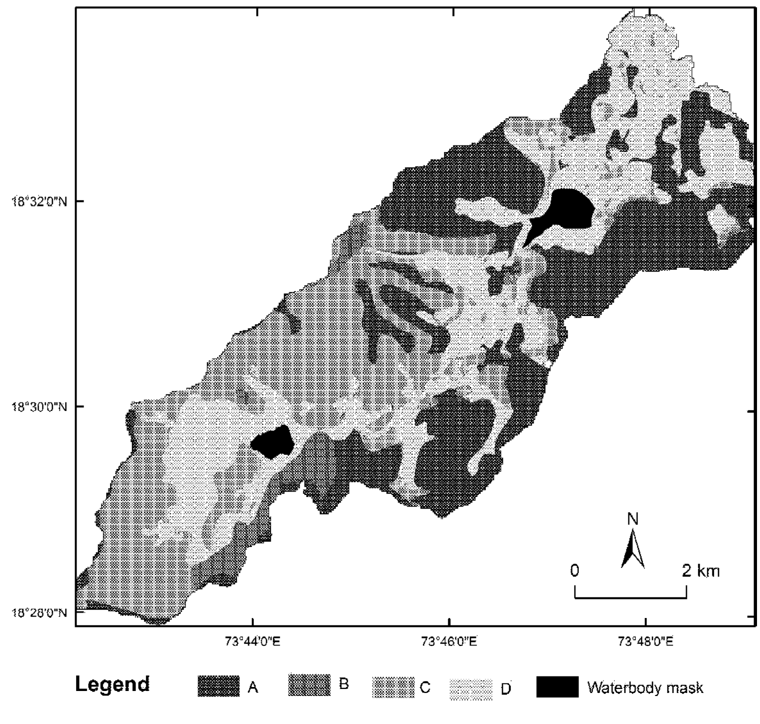

Figure 6. Ramnadi watershed: Hydrological Soil Group (HSG) map

standard norms given in Chapter 7 of the National Engineering Handbook (NRCS, 2007).

Soils are classified into hydrologic soil groups A, B, C and D to indicate the minimum rate of infiltration obtained for bare soils after prolonged wetting. These are used in determining runoff curve numbers. As per the soil attributes attached to the soil data and the HSG description specified in the Table 1, the soil data layer was reclassified as a HSG map (Fig. 6).

CN matrix

The CN values for the study area were generated using the Landuse and HSG combination and by following the CN table given in USDA (1986). Table 2 specifies the CN values for different landuse and HSG combinations for the catchment.

Rainfall computation

Data provided by the Indian Meteorological Department (IMD), for Pashan (within the Ramnadi catchment), shows that the average annual precipitation form 1999 to 2006 was 720.99 mm (28.39 inches). The precipitation used for this study is 2.37 inches (i.e 28.39/12 months). It can be interpreted as the average monthly value or a single rainfall event by assuming that there are about 12 relatively large rainfall events, annually. In short, to apply the SCS-CN method, we assume the condition that any rainfall that occurred had a uniform depth of 2.37 inches (6.0198 cm) over the entire Ramnadi catchment.

Antecedent Moisture Condition (AMC)

An AMC (five days prior to the event) is usually taken into consideration to ascertain the AMC class for each event. The calculated CN value for each polygon is for average conditions (i.e. Antecedent Moisture Condition Class II). The CN values for AMC II can be converted into CN Values for AMC I and AMC III by using the SCS standard tables (USDA-SCS 1993). Since the temporal range of the available rainfall data was within the two satellite data chosen for this study, AMC II was taken to obtain the average condition. For the present analysis the AMC values given in table 3 were used.

Soil Conservation Services-Curve Number (SCS-CN) method

The SCS-CNmethod has been adopted for the estimation of runoff in this study, due to availability of rainfall data from a single station.

The SCS equation governing the excess rainfall 'P_e'can be written as,

$$P_e = {(P - KS)^2}/{(P + (1 - K)S)} \quad \dots\dots eq1$$

where, 'P' is the total (cumulative) precipitation and 'S' is the landuse parameter. The latter is related to the curve number (CN). 'K' is an arbitrary coefficient that has been determined from observations to be 0.2 (SCS-CN, 2007). The formula applies best in heavy rainstorms although 'K' may be smaller than 0.2 in light rainstorms (Sheeder et.al., 2002).

'S' is defined in terms of the landuse parameter, the curve number (CN) as,

$$S = \frac{1000}{CN} - 10(in\ inches) \dots\dots\dots\dots eq.2$$

$$S = \frac{25400}{CN} - \ 254\ (in\ mm) \dots\dots\dots\dots eq.3$$

CN is an indirect reflection of impervious surface cover whereby a completely impervious surface has a curve number of 100 (S = 0). The varying potential maximum retention (S) in 1989 and 2011 is shown in Fig. 7.

In order to estimate the potential maximum retention and surface runoff the Arc CN tool is used. This tool basically employs equation 1 to compute the runoff and equation 2 or 3 to compute the potential maximum retention. This tool also follows the same guidelines as mentioned in the SCS-CN 1972 manual. Thus, for the present study, the sub basin wise land soil intersect was given as an input layer and the runoff in inches and $m^3$was computed by providing the rainfall value. Separate simulations were run for the 1989 and 2011 situations, keeping the rainfall intensity the same (60.2 mm). The thematic maps generated for both the years clearly illustrate the spatial variations in runoff amount (Fig. 13).

Results and discussion

The study undertaken has aided assessment of changes in surface runoff in the Ramnadi catchment, in the last two decades. It has also helped to investigate changes in landuse especially degree of imperviousness in different parts of the catchment. One of the major factors affecting surface runoff is impervious surface in a region and this research has helped to visualise the impact of variation in vegetation cover on the degree of imperviousness. Changes in vegetation were assessed by comparing multitemporal NDVI maps. The study also highlights the expansion of urban centres in the Ramnadi catchment. This growth is accompanied by changes in the landuse pattern wherein the natural landscape is progressively replaced by the cultural landscape.

The following sections highlight the results of the research, with regard to landuse, NDVI, impervious surface and surface runoff.

Landuse landcover change

There has been a considerable decrease in the area under vegetation from 1989 to 2011 (Fig. 8) Natural vegetation has been replaced by urban built up areas, in the wards of Baner, Aundh, Pashan and Bavdhan, due to expansion of urban sprawl. Patches of vegetation lying along the course of Ramnadi earlier are now under urban landuse, which is attributed to the development of the IT industry and emergence of a number of communication links in the region. The southern parts of Bhukum also show a considerable increase in settlements around Manas Lake. Land use land cover analysis of satellite images for 1989 and 2011 validate that there is an increase in built up area by 24.3%, replacing natural vegetation, barren land and hilly terrain within a span of 22 years (Table 4).

Change in impervious surfaces

Overall it can be observed that there has been a definite increase in the percentage of impervious surface area in the catchment. Negligible or low impervious cover is noticed in and around the water bodies, ridges and slopes covered with vegetation. Areas experiencing human intervention in the form of construction activity (roof tops or transport routes), appear to have increased in the past decades, thus leading to an overall increase in the impervious cover. Many areas which were earlier in the protected zone with less that 25% imperviousness are now classed as degraded zone with impervious cover well above 80%. This change in impervious surface from 1989 to 2011 is represented in Fig. 9a and 9b respectively.

Change in surface runoff

In the past two decades, there has been a drastic increase in the net built up area within the catchment. The built up area has almost doubled within this time frame i.e. from 21.13% (1989) to 45.43% (2011). Similarly the soil cover has been highly disturbed due to construction works in the city limits as well as in the villages bordering the city and along the main transportation routes. The values plotted in Fig. 10 represent the paired data for built up and runoff obtained at each sub basin level. Some sub basins which are characterised with lower values of built up area are also the regions with maximum slope and HSG category D. Thus they account for relatively higher values of runoff. As a result the scatter plot obtained at the sub basin level though has a definite positive trend does not yield higher

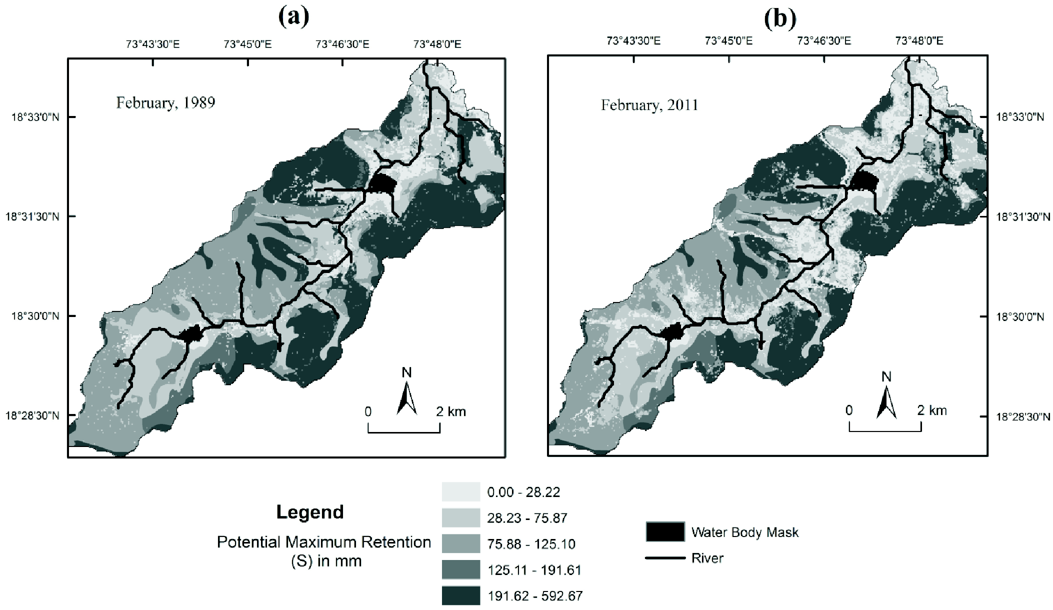

Figure 7. Ramnadi watershed : Potential Maximum Retention (S)

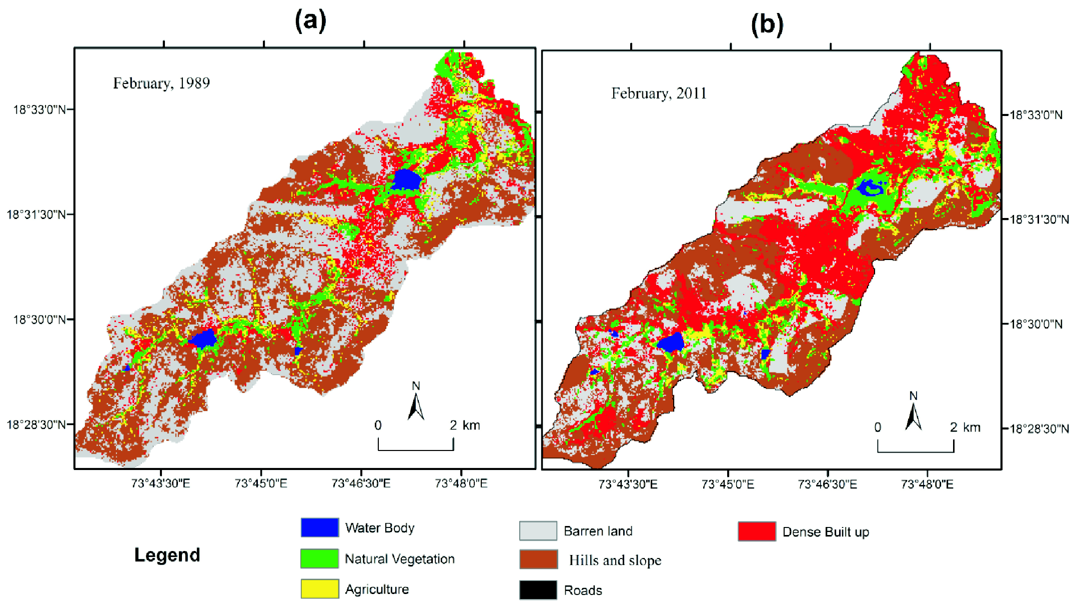

Figure 8. Ramnadi watershed : Landuse / landcover maps

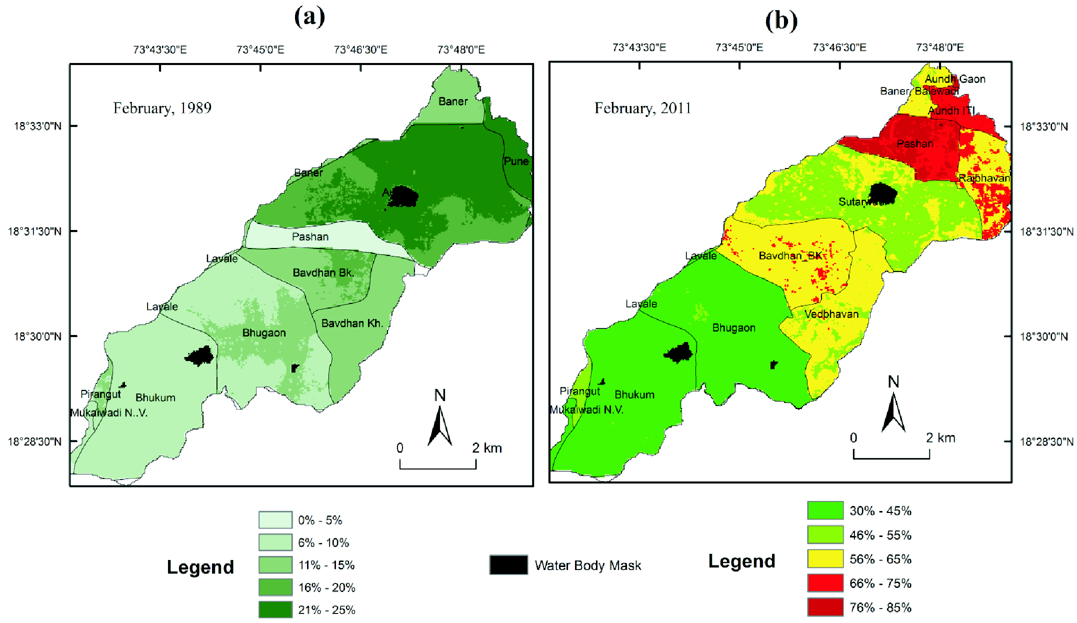

Figure 9. Ramnadi watershed : Change in Impervious Surface Area (ISA)

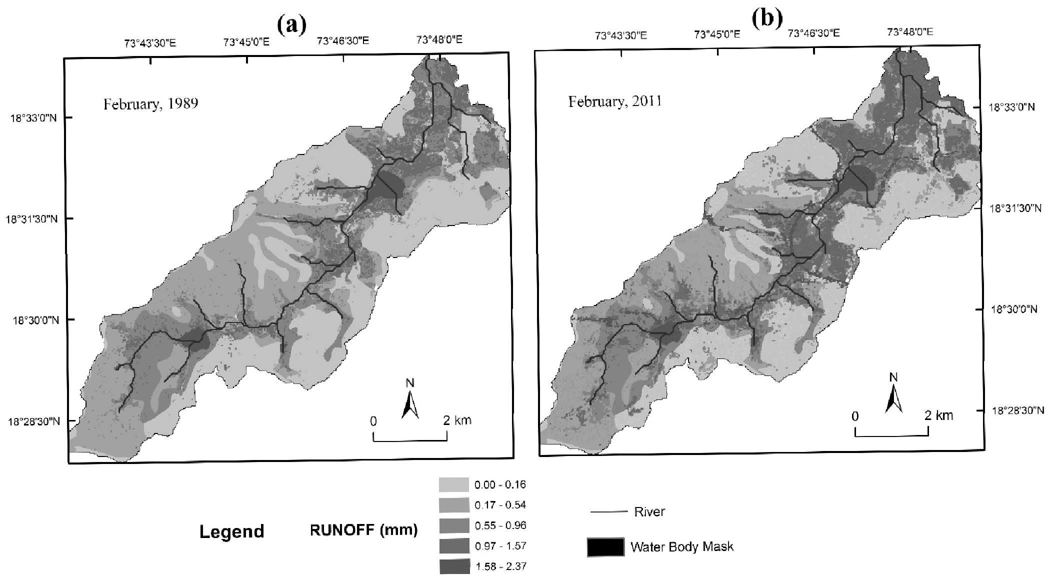

Figure 13. Ramnadi watershed : Surface Runoff maps

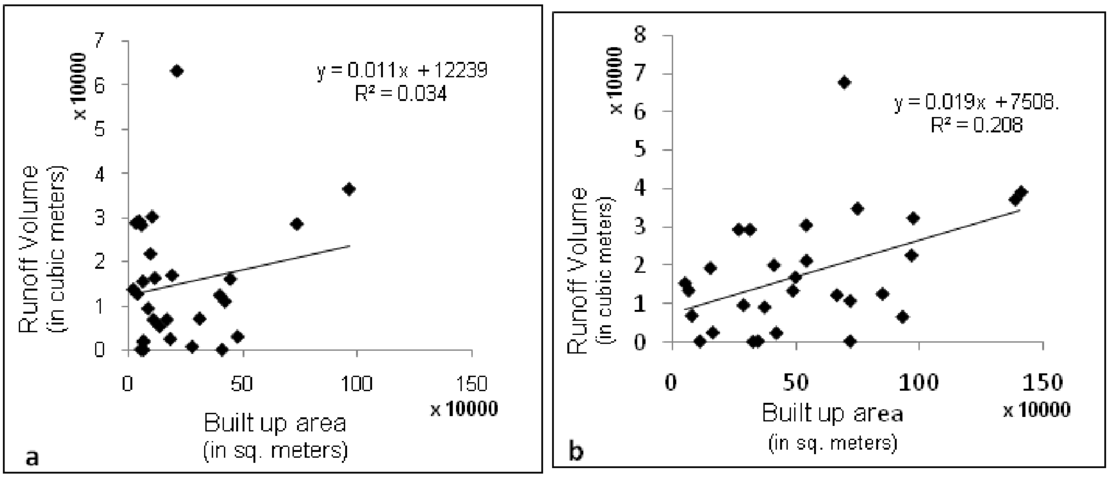

Figure 10. Ramnadi watershed: Relationship between builtup area and surface runoff volume

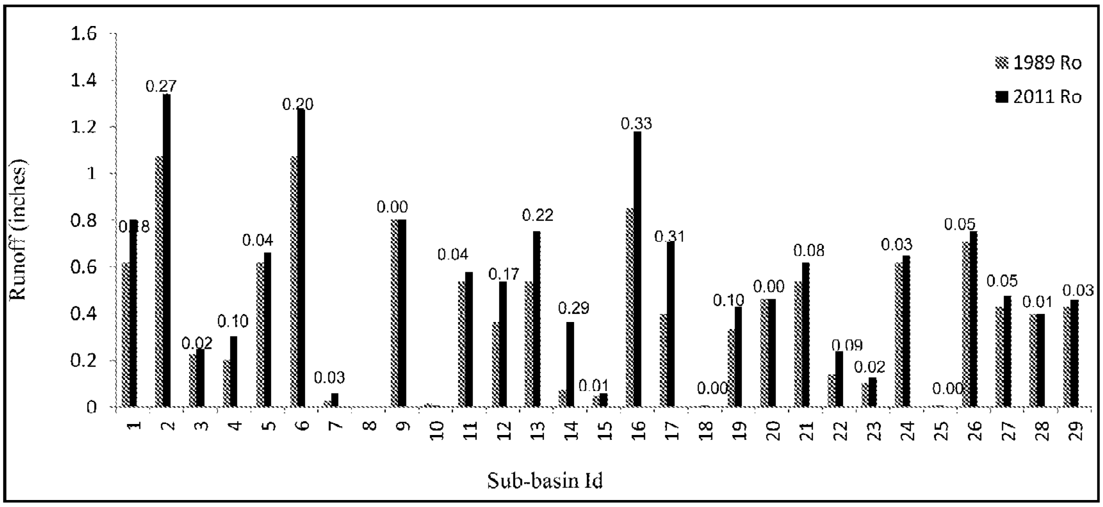

Figure 11. Ramnadi watershed: Sub basin wise estimated runoff

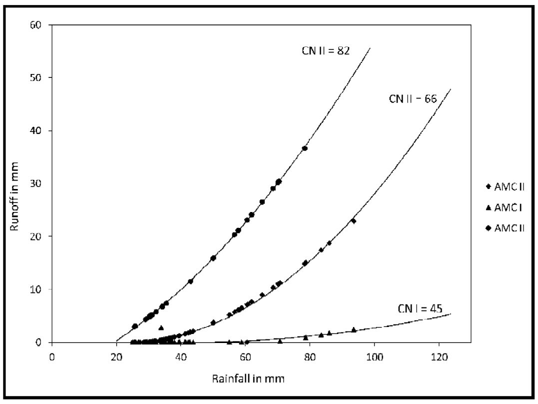

Figure 12. Ramnadi watershed: rainfall runoff plot

values of correlation (Fig. 10).

The estimated surface runoff for the entire catchment (for AMC II category) yielded a runoff volume of $4.0592 \times 10^8 m^3$ in 1989, which increased to 5.2503×10^8 m^3 in 2011 (Fig. 11). However, this estimation is based on the fact that the net catchment area is constant (52.48 km^2) and the rainfall is the average rain of 60.2 mm (2.37 inches). Figure 12 shows that AMC III category computations have much higher values for runoff. This means that during the wet season, this catchment has the potential of generating high amount of surface runoff.

Table 1. Hydrological soil groups

HSG	SOIL CHARACTERISTICS
Group A	These soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sand or gravel and have high rate of water transmission (>0.762 cm h^{-1}).
Group B	These soils have moderate infiltration rates when wetted and consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (0.381–0.762 cm h^{-1}).
Group C	These soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture. These soils have a low rate of water transmission (0.127–0.381 cm h^{-1}).
Group D	These soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (0–0.127cm h^{-1}).

Table 2. CN values for different landuse and HSG combinations

Cover Description		Curve numbers for HSG			
Cover Type	Average Impervious (%)	A	B	C	D
Agriculture	5	67	77	83	87
Barren	5	39	61	74	80
Dense Built up	65	77	85	90	92
Hills	5	30	58	71	78
Natural Vegetation	5	36	60	73	79
Roads	> 95	98	98	98	98
Sparse Built up	30	57	72	81	86
Water body	100	100	100	100	100

Table 3. Classification of rainfall abstraction

AMC Group	Characteristics of Soil	Total 5 day Antecedent Rainfall (mm)
I	Lowest Runoff Potential	< 35.6 mm
II	Average Condition	35.6 - 53.3 mm
III	Highest Runoff potential	>53.3 mm

Table 4. Ramnadi watershed: Changes in landuse landcover between 1989 and2011

Landuse classes	1989	2011	Change
Agriculture	5.26	8.68	3.42
Barren land	34.30	10.35	-23.95
Built up	21.13	45.43	24.30
Hills and hill slopes	31.92	27.77	-4.15
Natural Vegetation	6.23	6.77	0.53
Water Bodies	1.16	1.01	-0.15

Figure 13 depicts the estimated surface runoff, taking into consideration the actual average rainfall of 60.2 mm. Keeping the rest of the parameters same, if one considers the 2007 situation when 95.2 mm of rainfall was recorded in 24 hours, the approximate runoff volume generated would be 3.9505×10^9 m^3. This indicates that there is direct impact of urbanisation on surface runoff. Thus an increase in the amount of surface runoff generated within the Ramnadi catchment during the study period (1989 and 2011) is clearly evident for all the rainfall criteria (actual average rainfall, storm event of 2007 with 95.2 mm rainfall and during various AMC conditions).

Conclusion

The present study shows that there has been an increase in the built up area from 21.13% in 1989 to 44.3% in 2011. Due to its proximity to the main city (Pune) coupled with suburban growth pattern and impact of developmental strategies of local government, Ramnadi watershed area has experienced a rapid increase in population leading to changes in LULC and subsequent alteration in the pervious surfaces to impervious ones. The percentage of impervious surfaces for most of the high built up areas have increased from

25% to 85% from 1989 to 2011, indicating the rapid degradation of the pervious surfaces and lowering of the infiltration capacity of these regions. An overall decrease in NDVI values has been observed during this period, with higher values of 0.68 found along water bodies. Urbanised parts of the watershed, including the core of the city and national highway (NH 4) show NDVI values falling to −0.29. Transportation routes, being completely impervious surfaces, have greater potential for generating runoff and its expansion in recent years have added to percentage of impervious surfaces to total area thereby augmenting surface runoff. An increase in surface runoff has thus been estimated from 7.73mm to 10.01mm in AMC I and from 23.6mm to 26.4mm in AMC III condition.

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References

Bauer, M.E., Heinert, N.J., Doyle, J.K. and Yuan, F. (2004) Impervious surface mapping and change monitoring using Landsat remote sensing, *Proceedings, American Society of Photogrammetry and Remote Sensing Annual Conference.* May 24–28, Denver, Colorado. unpaginated CD ROM, 10 p.*ASPRS, Annual Conference Proceedings*, Colorado.

Bird, S., Harrison, J., Exum, L., Alberty S., and Perkins, C. (2002) Screening to identify and prevent urban storm water problems: estimating impervious area accurately and inexpensively. *Proceedings*, *National Monitoring Conference of the National Water Quality Monitoring Council.* May 20–23, Madison:16p.

Brocca, L., Melone, F., and Moramarco, T. (2008) On the estimation of antecedent wetness conditions in rainfall-runoff modelling, *Hydrological Processes*, 22(5): 629–642.

Choi, J.Y., Engel, B.A., and Chung, H.W. (2002) Daily streamflow modelling and assessment based on the curve number technique. *Hydrological Processes*, 16(16), 3131–3150.

Crist, E.P.,Laurin, R. and Cicone, R.C. (1986) Vegetation and soils information contained in transformed Thematic Mapper data. *International Geosciences and Remote Sensing Symposium (IGARSS)' 86 Symposium, ESA Publications Division*, ESA SP-254.

Dhorde, A.A., Dhorde, A., and Joshi, G. (2012). Population calibrated land cover impervious surface coefficients for Upper Bhima basin. *International Journal of Geomatics and Geosciences*,, 2,(4): 1027–1047.

Dougherty, M., Dymond, R. L., Grizzard Jr, T. J., Godrej, A. N., Zipper, C. E., and Randolph, J. (2007) Quantifying long-term hydrologic response in an urbanizing basin. *Journal of Hydrologic Engineering*, 12(1):, 33–41.

Fankhauser R. (1999) Automatic detection of imperviousness in urban areas from digital orthophotos. *Water Science and Technology*, 39: 81–86.

Frye, C. (2007) Setting the Z Factor parameter correctly in Arc GIS resources, online publication,http://blogs.esri.com/esri/arcgis/2007/06/12/setting-the-z-factor-parameter-correctly/http://blogs.esri.com/esri/arcgis/2007/06/12/(Retrieved on 2013-09-11).

Geetha, K., Mishra, S. K., Eldho, T. I., Rastogi, A. K., and Pandey, R. P. (2008) SCS-CN-based continuous simulation model for hydrologic forecasting, *Water Resource Management*, 22(2): 165-–190.

Hjelmfelt, A.T. (1991) Investigation of curve number procedure, *Journal of Hydraulic Engineering*, 117: 725–737.

Holman, P., Hollis, J.M., Bramley, M.E., and Thompson, T.R.E. (2003) The contribution of soil structural degradation to catchment flooding: a preliminary investigation of the 2000 floods in England and Wales, *Hydrology and Earth System Sciences,* 7: 755–766,

Jain, M. K., Mishra, S. K., Suresh Babu, P., Venugopal, K., and Singh, V. P. (2006) Enhanced runoff curve number model incorporating storm duration and a nonlinear *Ia-S* relation, *Journal*

of Hydraulic Engineering, 11(6): 631–635.
Kannan, N., Santhi, C., Williams, J. R., and Arnold, J. G. (2008) Development of a continuous soil moisture accounting procedure for curve number methodology and its behaviour with different evapotranspiration methods, *Hydrological Processes*, 22(13): 2114–2121.
King, K. W. and Balogh, J. C. (2008) Curve numbers for golf course watersheds, *Transactions of the American Society of Agricultural Engineers,* 51(3): 987–996.
Lee J.G., and Heaney J.P. (2003) Estimation of urban imperviousness and its impacts on storm water systems. *Journal of Water Resources Planning and Management*, 129: 419–426.
Lu D.S., and Weng Q.H. (2006) Use of impervious surface in urban land-use classification. *Remote Sensing of Environment*, 102: 146–160.
Lyon, S. W., Walter, M. T., Gerard-Marchant, P., and Steenhuis, T. S. (2004) Using a topographic index to distribute variable source area runoff predicted with the SCS curve-number equation, *Hydrological Processes,* 18(15): 2757–2771.
Mishra, S.K. and Singh, V.P. (1999) Another look at SCS-CN method, *Journal of Hydraulic Engineering*, 4(3): 257–264.
Mishra, S.K. and Singh, V.P. (2006) A relook at NEH-4 curve number data and antecedent moisture condition criteria, *Hydrological Processes*, 20(13): 2755–2768.
Mishra, S.K., and Singh, V.P. (2004) Long-term hydrological simulation based on the Soil Conservation Service curve number. *Hydrological Processes*, 18(7): 1291–1313.
Mishra, S.K., Geetha, K., Rastogi, A.K., and Pandey, R.P. (2005a) Longterm hydrologic simulation using storage and source area concepts, *Hydrological Processes,* 19(14): 2845– 2861.
Mishra, S.K., Jain, M.K., Pandey, R.P., and Singh, V.P. (2005b) Catchment area-based evaluation of the AMC-dependent SCS-CN based rainfall-runoff models, *Hydrological Processes*, 19(14): 2701–2718.
Mishra, S.K., Pandey, R.P., Jain, M.K., and Singh, V.P. (2008) A rain duration and modified AMC-dependent SCS-CN procedure for long duration rainfall-runoff events, *Water Resources Management,* 22(7): 861–876.
Moretti, G. and Montanari, A. (2008) Inferring the flood frequency distribution for an ungauged basin using a spatially distributed rainfall-runoff model, *Hydrology and Earth System Sciences*, 12: 1141–1152.
NRCS: National Resources Conservation Services (2007) *National Engineering Handbook*-National Resources Conservation Services, Part 630:Hydrology, Chapter 7: Hydrologic soil groups, United States Department of Agriculture, Washington.
Rawls, W.J., A. Shalaby, A. and R.H. McCuen,. R.H. (1981) Evaluation of methods for determining urban runoff curve numbers. *Transactions of the American Society of Agricultural* Engineers, 24(6):1562–1566.
Romero, P., Castro, G., Gomez, J.A., and Fereres, E. (2007) Curve number values for olive orchards under different soil management, *Soil Science Society of America Journal*, 71(6): 1758–1769.
Sahu, R.K., Mishra, S.K., Eldho, T.I., and Jain, M.K. (2007) An advanced soil moisture accounting procedure for SCS curve number method, *Hydrological Processes*, 21(21): 2872–2881.
Schueler, T.R. (1994) The Importance of Imperviousness. *Watershed Protection Techniques* 1(3): 100–111.
Sharma, K.D., and Singh, S. (1992) Runoff estimation using Landsat Thematic Mapper data and the SCS model. *Hydrological Sciences Journal*, 37(1): 39–52.
Sheeder, S.A., Carlson T.N. and Ross J.D. (2002) Dual Urban and Rural hydrograph signals in three small watersheds. *Journal of the American Water Resources Association,* 38: 1027–1040.
Simanton, J.R., Hawkins, R.H., Mohseni-Saravi, M., and Renard, K.G. (1996) Runoff curve number variation with drainage area, walnut gulch, Arizona. *Transactions of the American Society of Agricultural Engineers*, 39(4): 1391–1394.
Singh, P. K., Bhunya, P. K., Mishra, S. K., and Chaube, U. C. (2008) A sediment graph model based on SCS-CN method, *Journal of Hydrology*, 349(1–2): 244–255.
Soulis, K. and Dercas, N. (2007) Development of a GIS-based spatially distributed continuous hydrological model and its first application. *Water International*, 32(1): 177–192.
Tyagi, J. V., Mishra, S. K., Singh, R., and Singh, V. P. (2008) SCS-CN based time-distributed sediment yield model, *Journal of Hydrology*, 352(3–4): 388–403.

USDA (1956, 1964, 1971, 1985, 1993) *SCS National Engineering Handbook*, Section 4: Hydrology. Soil Conservation Service, United State Department of Agriculture, Washington, DC, USA.

USDA: United States Department of Agriculture (1986) *Urban Hydrology for Small Watersheds*. Soil Conservation Service Technical Release 55 Manual.

Ward, D., Phinn, S.R., and Murray, A.T. (2000) Monitoring growth in rapidly urbanizing areas using remotely sensed data. *Professional Geographer*, 52: 371–386.

Weng, Q. (2001) Modeling urban growth effect on surface runoff with the integration of remote sensing and GIS. *Environmental Management*, 28: 737–748.

Yang, L, Xian G, Klaver, J.M., and Deal, B. (2003) Urban land cover change detection through sub-pixel imperviousness mapping using remotely sensed data. *Photogrammetric Engineering and Remote Sensing*, 69: 1003–1010.

Yang, X. (2006) Estimating landscape impervious index from satellite imagery. *IEEE Geoscience and Remote Sensing, letter*, 3: 6–9.

Yu, B. (1998) Theoretical justification of SCS-CN method for runoff estimation, *Journal of Irrigation and Drainage Engineering*, 124(6): 306–310.

Zhan, X. and M. Huang (2004) Arc CN-Runoff: an Arc GIS tool for generating curve number and runoff maps. *Environmental Modelling and Software*, 19(10): 875–879.

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