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Estimation of Surface Run-off for Urban Area Using Integrated Remote Sensing and GIS Approach

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ABSTRACT

Urban run-off increases significantly due to increased impervious area and reduced drainage network. Evaluation of land use in urban area plays a vital role as input to the estimation of runoff. The hydrological design standard for urban water resources planning and management is commonly based on the frequency of occurrence of heavy rainfall events. In the present study, the occurrence of most frequent heavy rainfall event is investigated for Thanjavur town, located in the State of Tamilnadu, India and used for estimation of run-off depth. The Soil Conservation Service Curve Number (SCS-CN) is used for evaluating run-off depth value for event rainfall starting from 10 mm to 400 mm. The land use detail for the study area was obtained by integration of GIS and remote sensing. The spatial variation of event rainfall is considered with certain percentage of deviation from base rainfall for each triangle area that contributes to the run-off. The results of the analysis indicate that the study area can produce the run-off volume more than that required for urban water management at an average seasonal rainfall.

KEYWORDS: Urban run-off, Remote sensing, Geographical information systems (GIS), Water resources.

INTRODUCTION AND LITERATURE REVIEW

Water shortage in Indian urban areas has already become a serious social problem and is generally considered to be related to increase in population and rapid urbanization. Urbanization increases impervious area which directly affects the water cycle. Groundwater table depletion and increased flood peak are typical consequences from the distorted water cycle (Kim and Yoo, 2009). Impervious surface in urban environment has significant impacts on hydrology, in terms of both water quality and quantity, over a range of temporal and spatial scales. The water generated from urban area can be utilized effectively for improving groundwater table through rainwater harvesting structure. Kim et al. (2002) highlighted that the control of peak discharges from individual high magnitude storm events in the urbanized area is key factor in the urban surface water management. Accurate estimation of urban run-off is critical at all stages of urban planning and water resources management. It is worth mentioning that over the past two decades, the use of Remote Sensing and Geographic Information System (GIS) technologies in run-off estimation from urban watershed has gained increasing attention. The integration of remote sensing and GIS has been widely recognized as a powerful and

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effective tool in detecting urban growth (Ehlers et al., 1990; Treitz et al., 1992; Harris and Ventura, 1995; Yeh and Li, 1996, 1997). In hydrological and watershed modeling, remotely sensed data are found to be more valuable for providing cost-effective data input and for estimating model parameters (Engman and Gurney, 1991; Drayton et al., 1992; Mattikalli et al., 1996). The hydrologist increasingly started using GIS-based distribution modeling approaches (Berry and Sailor, 1987; Drayton et al., 1992; Mattikalli et al., 1996). Only few attempts have been made to relate urban growth studies to the distributed hydrological modeling. Weng (2001) developed a methodology to relate urban growth studies to distributed hydrological modeling using an integrated approach of remote sensing and GIS. Dougherty et al. (2007) investigated the relationship between catchment scale urbanization and basin hydrology through statistics, regression relationships and graphical analysis. Their study aimed to quantify the hydrologic response in an urbanizing basin over time compared to three adjacent non-urban basins in the Occoquan watershed of USA. The result of the study indicates that watershed with more impervious area produces higher annual and seasonal storm discharge per surface area than the non-urban basins. Cheng et al. (2008) studied Wu-Tu watershed, Taiwan for urbanization effects on the watershed. They employed block kriging method to estimate the area rainfall and non-linear programming to derive the hourly excess rainfall. The derived rainfall was given as input to hydrological model and SCS model to arrive at the best parameters to illustrate the hydrological and geomorphic conditions of the study area. Ponce and Hawkins (1996) highlighted the advantages of SCS model in terms of its simplicity, stability, good predictability and accuracy to reflect the watershed characteristic for run-off depth prediction. From the inception of SCS-CN method, scientist, hydrologist, water resources planner and agriculturist have been widely accepted for using run-off volume estimation (Patil et al., 2008).The present work is taken up with the specific objective of estimation of surface run-off using SCS-CN method through integration of GIS and remote sensing for Thanjavur urban watershed. As the rainfall measured at a single station does not represent the whole area, different rainfall amount calculated over the base rainfall with certain percentage of deviation is used to simulate the run-off in the present work.

Study Area

Thanjavur town (Fig.1) is situated between 10^0 48’ and 10^0 8’ of the northern latitude and 79^0 09’ and 79^0 15’ of the eastern longitude. The municipality has an area of about 36 km^2. The township and its exterior suburbs extend to an area of about 100 km^2. The soil is fertile because of the deltaic terrain and greater part of the town consists of an undulating plain bisected by the valley of Grand Anacut canal. The climate is tropical and the town falls under the category of medium and high rainfall region with an average annual rainfall of around 958.8 mm. In India, the Arabian sea and the Bay of Bengal are the two oceanic moisture sources that primarily feed the rainfall during the two monsoons. In the Tamilnadu state of India, majority of the rain is received through North East Monsoon (October to early December). The north-west and south-west parts of the town have an elevation of 78 m and 30 m above mean sea level, respectively. The rainfall data for 55 years starting from 1951 to 2006 has been obtained from IMD, Pune. Figure 2 shows the annual rainfall variation for 55 years. Out of 55 years of annual rainfall, 23 years received more than average rainfall. The rainfall seasons of the study area are classified into four groups as Winter (Jan.-Feb.), Summer (Mar.-May), South-West Monsoon (June-Sept.) and North-East Monsoon (Oct.-Dec.). Generally, rainfalls during winter and summer seasons are very meager while comparing monsoon seasons. Early set of south-west monsoon and late set of north-east monsoon bring reasonable rainfall during summer and winter seasons. It can be seen from Figure 3 that the north-east monsoon contributes more rainfall than the south-west monsoon. Table 1 provides number of occurrence of monthly rainfall in different ranges. It can be seen from Table 1 that monthly rainfall of more than 100 mm occurs at least three times per year. Further, it is found from the 55 years of data that most of this rainfall occurs during north-east monsoon season. The maximum 24 hr rainfall is found as 319 mm from 55 years of data. For run-off estimate, 100, 150, 200, 250, 300, 350 and 400 mm rainfall events are considered for simulation.

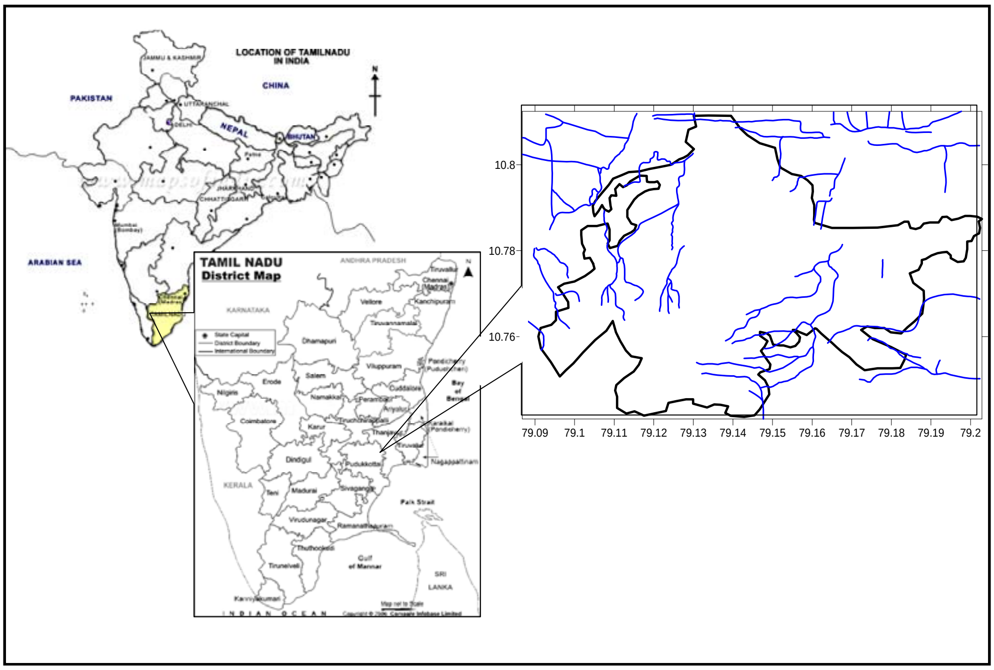

Figure (1): Location map of the study area

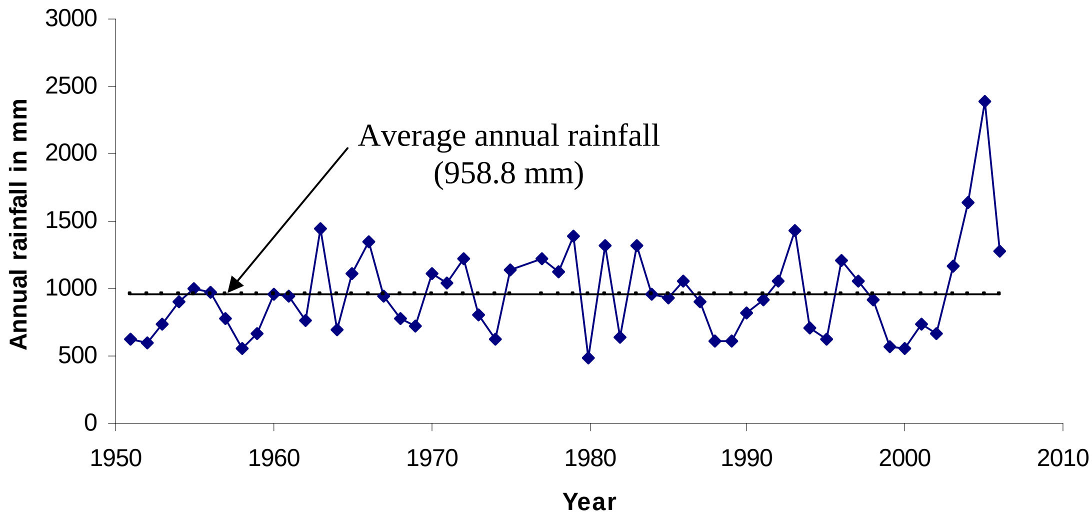

Figure (2): Annual rainfall variations for 55 years (Thanjavur)

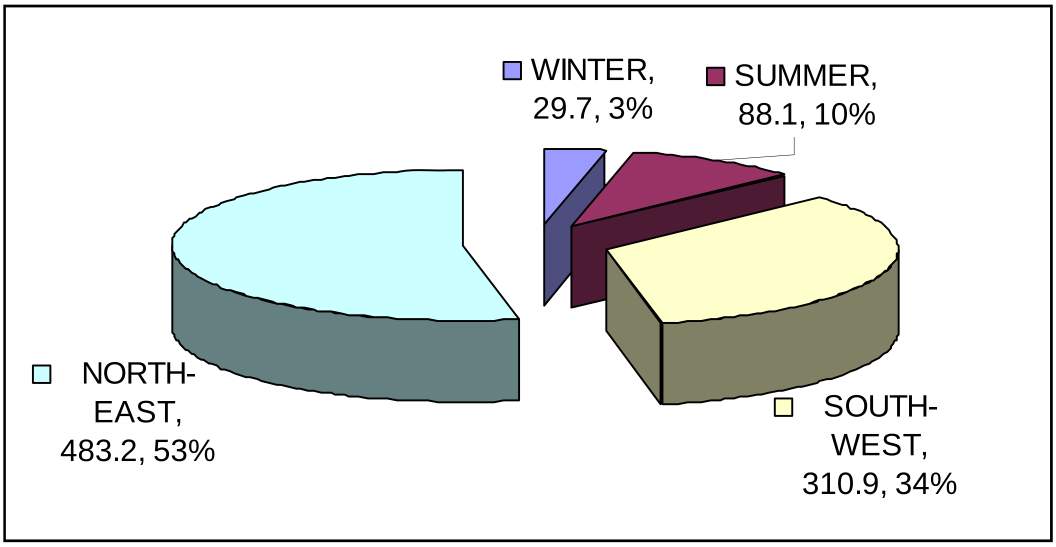

Figure (3): Seasonal average rainfall (in mm) for Thanjavur town

Table 1. Occurrences of different ranges of monthly rainfall over 55 years

Monthly rainfall in mm	No. of occurrences in 55 years
100 to 200	113
201 to 300	46
301 to 400	17
401 to 500	5
501 to 600	2
601 to 700	0
701 to 800	0
801 to 900	1
More than 100	184

Integration of Remote sensing and GIS

In this study, IRS P6_07 April 2006 data and Topographic map with a scale of 1:50000 of year 1970 were used. IRS P6 LISS3 with 23.5 m and three spectral bands were used. ERDAS imagine v.8.4 was used to process the Landsat images and generated land use/cover classes. ArcGIS 10 with spatial analyst module is used to create and handle layers of topographic map. Geometric transformations and geo-referencing convert the implicit geometry of an image into a cartographic planimetry and assign coordinates to the image pixels. For this study, the image was corrected using a polynomial function and ground control points based on the topography map kept as geo-reference. The resulting geo-referenced image was used as a reference for the image-to-image geometric correction process. The base map was prepared from portions of 15 minutes topographic map. Town boundary, roads, tanks, rivers, elevation data and stream channel locations were taken directly from the base map.

With the aid of ERDAS imagine software, Landsat image was enhanced using linear contrast stretching and histogram equalization to increase the volume of visibility for further analysis. The image was then rectified to a common Universal Transverse Mercator

(UTM) coordinate system based on the 1:50,000 scale topographic maps of NRSA province produced by the Indian government. Further, the image was radiometrically corrected using a relative radiometric correction method (Fig. 4). An unsupervised classification with the maximum likelihood algorithm was used to classify the Landsat images using bands 2 (green), 3 (red) and 4 (near infrared). The accuracy of the classification was verified by using Google Earth map. Fig. 4 shows the land use/cover map for the year 2006. Land-use and land-cover patterns for 2006 are mapped by the use of Landsat Thematic Mapper data (Date: 07 April 2006). Five land use and land cover types are identified and used in this study: (1) Vegetation, (2) Agriculture land, (3) Urban or built-up land, (4) Water bodies, (5) Open land. The area of each land use is calculated using raster attributes. The raster attributes calculate the area of each pixel according to the land use it belongs to. Table 1 presents the area of each land use for Thanjavur town as per year 2006.

Table 2. Land use/land cover in Thanjavur urban area – 2006

Land use	Area in sq.km.
Water bodies	2.31
Vegetation	34.33
Built-up area	7.20
Road and railway line and settlement	13.15
Agriculture land	34.09
Sand (river without water)	5.53
Open land	3.24
Total	99.85

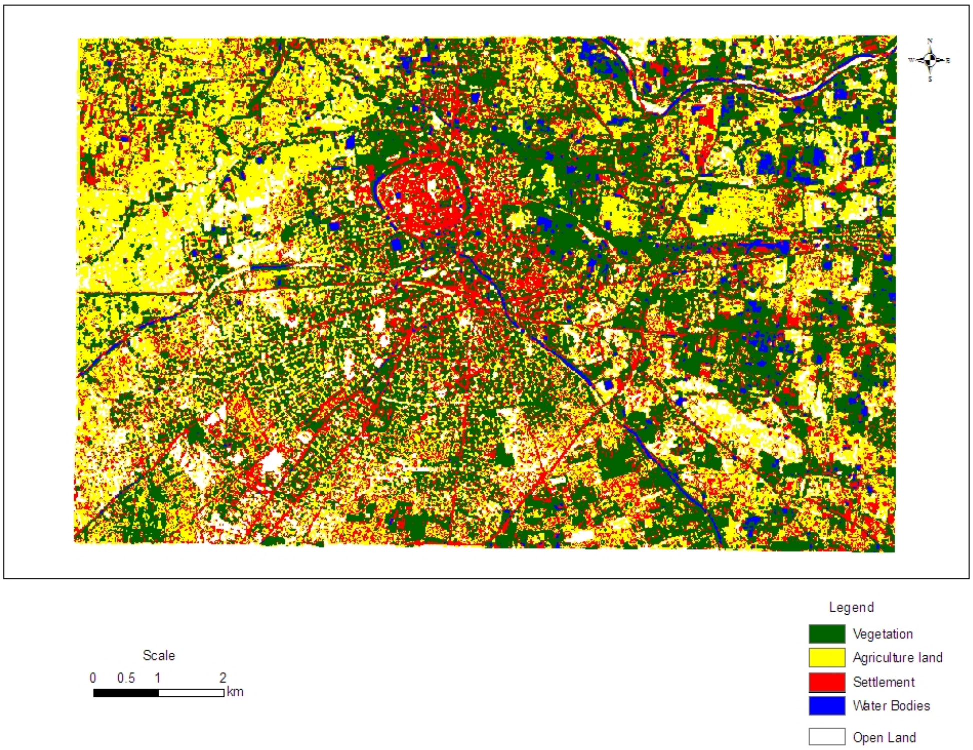

Figure (4): Land use/land cover in Thanjavur urban area using IRS P6_07APR2006 data

Urban expansions around Thanjavur town and considerable change in different land-use categories over a period of 38 years are the main concern for hydrological studies. From the toposheet of year 1970, urban area is demarcated and development area is measured. It is found that the urban area is spread out to an aerial extend of 18.93 sq.km. The urban area which corresponds to year 2006 is measured from imageries. As per 2006 imageries, the urban is spread out to 99.85 sq.km. This shows that Thanjavur town is expanded to 80% more than that of while 1970. This urbanization resulted not only due to population growth, but also due to the development of medical college and other facilities created in and around the town. While comparing the land cover as per toposheet and 2006 imageries, most of the urban expansion has taken place in the agricultural area along the important roads. The drainage system has been delineated from toposheet and is presented in Fig. 5. In addition to this drainage map, drainage pattern as per imageries is identified. In calculating the rate of run-off in a stream resulting from rainfall event, it is essential to determine the size of the area over which the rain falls. For every stream, a well-defined area of land intercepts the rainfall and transports it to the stream. All rainwater that lands within the drainage basin makes its way to the stream, while all rain landing outside the drainage basin makes its way away from the stream and into some other streams. In some cases, the run-off from surrounding area to urban area may contribute if down gradient is towards the urban area.

The latitude, longitude and elevation data for selected points within the urban area limits are taken as input to the Surfer worksheet to generate data file for Surfer Plotter. Krigning method is used for generating grid data. Using map option, 3D surface map with wire frame (Fig.5) were obtained. The flow direction is obtained for the drainage system using grid vector map option available in the Surfer 8.0. The vector map option provides direction and magnitude which can be derived from a grid. The arrow symbol points in the downhill direction and the length of the arrow depends on the magnitude or steepness of the slope. Based on the flow direction, the entire urban basin can be divided into two urban watersheds. Fig. 5 shows the wire frame of drainage map with flow direction. The elevation data for selected points within the urban area limits are taken as input to the Tin Triangle to generate data file for Arc Tool box. The boundary polygon belonging to year 1970 is laid over the tin triangle map to form a new graphic. Using Intersect option available in the Arc tool box, the boundary polygon of year 1970 with tin triangle is separated from the remaining area. The resulting shape file is converted into Arc coverage file which gives the area of each triangle and also the area of each land use it belongs to. Using map option, the data collected for all maps overlaid one another to get the complete 3D feature of topology using SURFER 8.0 software (Fig. 5). This 3D topographic map helps the GIS modeler for better visualization of the study area and to identify the flow direction, elevated area and undulated area.

SCS-CN METHOD

The Soil Conservation Service Curve Number (SCS-CN) method, (SCS,1956), is an event-based and lumped rainfall run-off model. The SCS Method is widely used in the design of major hydraulic structures such as culverts, detention basins, stream relocation and large drainage ditches. These structures generally have tributary drainage areas ranging from a few hectares to 4000 hectares. To compute the run-off, the first step to be followed is to delineate and measure the drainage area tributary to the point of analysis. Next, the Curve Number (CN) is determined, which is a dimensionless number run-off index determined based on hydrological soil group, land use, land treatment, hydrologic conditions and antecedent moisture condition (AMC). Each soil type is assigned a hydrologic soil group of A, B, C or D depending on its characteristics of infiltration. The CN values may vary from 1 to 100. Higher values of CN indicate higher run-off. The soil moisture conditions of the basin

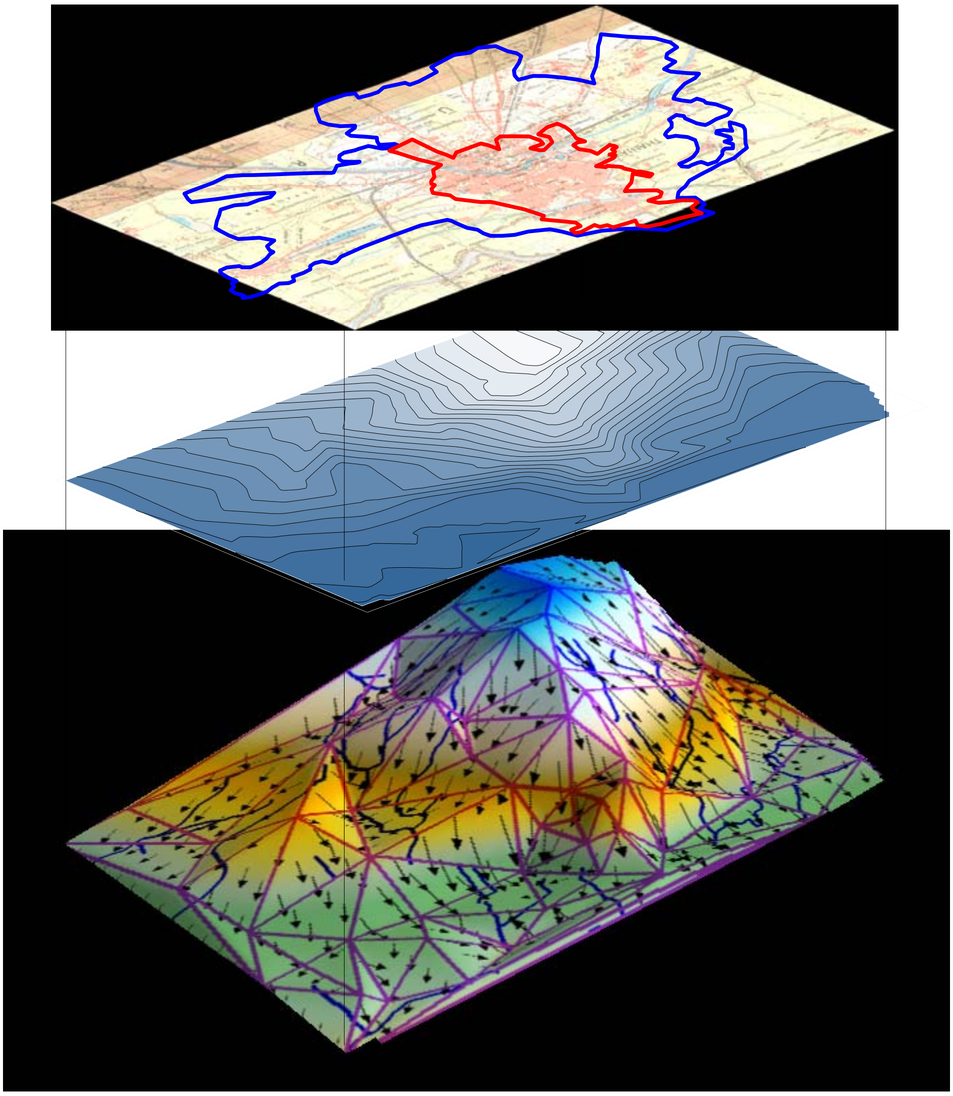

Figure (5): Overlaid 3D topographic map for the study area

existing at the time of occurrence of storm would have a great influence on run-off peak that can result from the storm. High rainfall during summer season may not produce high discharge because most of the water enters to the soil under the existing high infiltration capacity rate. During winter and rainy season, low capacity of infiltration takes places due to the wetness prevailing in the soil, since precipitation occurred in the earlier periods. For different land uses, the value of curve number varies within the area. The weighted curve number is calculated for each polygon of land area.

$$\text{Weighted curve number} = \frac{\sum_{1}^{n} CN_i A_i}{\sum_{1}^{n} A_i} \qquad (1)$$

where CN_i is the curve number for particular land unit and A_i is the area of each land use.

The potential maximum soil retention is calculated for each triangular area by using the following formula:

$$S = \frac{25400}{CN} - 254 \,. \tag{2}$$

In order to account for the water losses occurring due to plant interceptions, infiltration and surface storage which occur prior to run-off, initial abstraction (I_a) is calculated as 0.2 times of potential storage (S) if the rainfall is greater than 0.2 S. Otherwise, there will not be any run-off.

The assumption of SCS curve number is that, for a single storm event, potential maximum soil retention is equal to the ratio of direct run-off to available rainfall. This relationship, after algebraic manipulation and inclusion of simplifying assumptions, results in the following expression (USDA-SCS, 1985):

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

where, Q is the direct run-off depth and P is the total rainfall.

Using Equation 3, the depth of run-off for different storms is calculated.

RESULTS AND DISCUSSION

It can be seen from Table 1 that the occurrence of event rainfall between 100 -200 mm is 113 times in 55 years of period. In overall, the rainfall above 100 mm has occurred in 184 times. The rainfall during north-east monsoon is mainly due to the result of low pressure formation or due to cyclone formation in Bay of Bengal Sea. This kind of weather condition brings continuous down pour for a period of three days. The cumulative rainfall varies from 200 mm to 400 mm during the period. In this study, the run-off depth is estimated for event rainfall starting from 10 mm to 400 mm. Table 3 gives the details of Curve Number adopted for the study area. Generally, the rainfall distribution is considered as uniform over the area. But, uniform aerial distribution of rainfall over a basin is rarely observed in nature. The rainfall changes spatially as well as temporally. A means of quantifying the aerial distribution is perhaps provided by the distribution coefficient which can be obtained by dividing the maximum rainfall observed at any point in the basin by the average rainfall over the basin. In this study, to account for the spatial change in the rainfall amount, it is varied by keeping base rainfall as 1 to 40 cm in the order of ±10%, ±20%, ±30%, -10% and -20% deviations. The following approach is adopted to assign a depth of rainfall:

Rainfall depth = base rainfall depth*(lower limit+ rand)*(upper limit – lower limit).

For example, in the case of ±10% deviation, the depth of rainfall corresponding to 5 cm is calculated as follows: Rainfall depth = 5*(0.9+rand)*(1.1-0.9).

The value of random number varies between 0 and 1. Hence, the depth of rainfall for each triangle area will be different. Table 4 shows the simulated run-off depth for different cases considered for the study. It can be seen from Table 4 that the rainfall corresponding to 1 cm does not produce any significant run-off. The run-off depth which resulted for various percentage deviations considered from base rainfall shows significant changes with respect to uniformly distributed rainfall.

The urban area which belongs to year 1970 is demarcated from 2006 satellite imageries and run-off depth is simulated. The area which belongs to year 1970 is considered as an old Thanjavur town and settlements are densely packed. It can be seen from Table 4 that the run-off depth for the old urban is found more than while considering the entire area in the analysis. This indicates that more urbanization results in more run-off. The population of the town as in 2001 census is 215725 and estimated population for year 2008 is 221185. The present *per capita* supply of protected drinking water is 135 litres. The daily total demand of water for the town works out to be 29.86 million litres per day (MLD) and the quantity of water required per annum is 10,900 million litres of water. The average annual rainfall during north-east monsoon of the town is 483.2 mm. For 40 cm of rainfall, the depth of run-off produced from the urban catchment is 32.298 cm. This can generate 32,250 million litres of water whereas annual water requirement is 10,900 million litres of water. The available water from the urban catchment is almost three times more than what is required for the present day population of the town. The storage and utilization of this water are the major concerns to the municipal engineers. From the toposheet, 46 tanks are identified for Thanjavur town area which includes the expanded area. This clearly shows that in ancient time, water was stored in the surface structures not only to improve the groundwater level, but also to be utilized for domestic purposes. But, only 35 tanks are identified for the corresponding area from the imagery. Further, it is traced out that eleven tanks are occupied and few are covered by full vegetation.

Table 3. Details of curve number adopted for the study area

Description	Curve Number
Hydrological soil group: B Land use and cover type – fully developed urban areas (vegetation established)	69
Open space	66
Vegetation	77
Agricultural land	98
Settlement	100
Water bodies	

Table 4. Simulated run-off depth in cm using curve number

Rainfall depth in cm	Run-off depth in cm (Urban area – 99.85 sq.km)						Run-off depth in cm
	Rainfall uniform over the area	±10% deviation	± 20% deviation	± 30% deviation	- 10% deviation	- 20% deviation	(Urban area belonging to 1970 –18.93 sq.km)
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	1.145	1.159	1.126	1.161	0.995	0.911	1.499
10	4.567	4.606	4.631	4.755	4.115	3.765	5.241
15	8.739	8.725	8.989	8.604	8.138	7.451	9.608
20	13.300	13.222	13.293	13.676	12.173	11.542	14.226
25	17.884	18.154	17.885	18.006	16.830	15.562	18.971
30	22.635	22.587	22.109	22.089	21.130	19.952	23.788
35	27.445	27.269	28.100	27.416	25.635	24.229	28.650
40	32.298	32.161	32.060	32.176	30.389	28.125	33.543

CONCLUSION

The success of any water resources project depends, primarily, on the reliable estimate of run-off volume. In this study, an integrated remote sensing and GIS-based SCS CN method is used to estimate run-off from event rainfall for the urban catchment area. The land use in the study area has shown an increase in urban area and a reduction in agricultural land between years 1970 and 2006. The urban area has grown up from 19 sq.km to100 sq.km over the period of 36 years. The simulated run-off depth value for old area corresponding to the year 1970 is found to be more than the run-off generated from the area belonging to the year 2006. From the study, it is found that the available water from the urban area from heavy rainfall events can produce water almost three times more than what is required for the present day population of the town. Hence, conserving the storm water through existing tanks and in new storage systems can ease the urban water problem to a greater extent. Restoration of the existing tanks to their original capacity in the study area should be considered by urban planners.

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