

Impact of Urbanization on Surface Runoff Characteristics at Catchment Scale



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Abstract Increase in population and rapid urbanization are two main challenges to urban water management, especially for cities in developing countries like India. The assessment of changes in catchment surface runoff due to urbanization is critical for water resource planning and management. Uncertainty in rainfall and changing landuse pattern results from urbanization is difficult to correlate with present changing surface runoff conditions. This study has shown an approach to find a relation between these three by using a statistical term dynamic degree with application of the well-established tool, Curve Number (SCS-CN) method to observe surface runoff over the study area in conjunction with Geographic information system and remote sensing. This study assesses changes in runoff characteristics of Raipur catchment which has been delineated from a smallest sub-basin of Mahanadi River in Chhattisgarh, India. Pixel-based Runoff depth of each sub-catchment was estimated by incorporating digital elevation model, rainfall data, and Land Use/Land Cover (LULC) information for the years 1971–2015. Spatio-temporal variation in each sub-catchment has been computed and significant change in runoff has been observed. The motivation of this study aims to understand and to study the changing nature of urban growth pattern/sprawl, to quantify surface imperviousness and changes in surface runoff characteristics.

Keywords Landuse land cover · HEC-HMS · SCS-CN · Surface runoff Urbanization

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1 Introduction

To adequately manage impacts of ongoing or future land use changes, knowledge about existing landuse and trends of change is essential to tackle the problems associated with haphazard and uncontrolled growth. It is evident that land and water, an important life supporting systems are under intense pressure due to human induced accelerating factors [1]. In 2008 the world reached the historical mark of more than half of world's people living in cities than in rural areas [2]. The increasing urban population is expected to grow further, that two-third of the total world's population will be urban habitant until the year 2050 [3]. India holding the second largest population in the world, in terms of an aerial increase, from the year 2005 cities all over the world will expand on average 2.5 times in size till the year 2030 [4]. This increasing rate of urbanization is mostly expected in developing countries [5]. This increase in urban population will cause a huge infrastructure demand that will lead to change in a significant amount of natural lands to urban infrastructure. These urban infrastructures are a kind of scourge to mankind with in this century as it is directly related to urban imperviousness. It is no more covered that increasing the built-up landuse is the cause of less groundwater recharge and high surface runoff in an urban area.

The study of spatio-temporal characteristics of an urban sprawl and land use pattern is useful for the sustainable land-management and urban-land planning [6, 7]. After some significant literature review, USGS earth observational satellite data (Landsat) are found to be best suitable for this study. Hence, landsat imageries were used for the LULC classification. This paper covers LULC analysis of an urbanized catchment using ERDAS Imagine software and rainfall-runoff simulation using HEC-HMS modeling platform for six consecutive time periods has been taken for Raipur catchment. It has been seen that due to high urban growth and building of informal/unrolled structures the surface imperviousness is increasing which is directly affect the runoff condition in the catchment [5]. Hence a huge changing pattern would be seen in groundwater recharge and flooding in urban area. Maximum likelihood classifier has been used to perform supervised classification with satellite imageries. Later the LULC maps were used to generate curve number (CN) values and percentage imperviousness values for the catchment. This is again used as an input in HEC-HMS model to create continuous rainfall runoff simulation for different years.

2 Materials and Methods

Present study is focused on a Raipur city in India. As far as the study concern with catchment scale, a small catchment has been delineated from available DEM (Digital Elevation Model) based upon the one inlet and one outlet point. The above catchment can be seen in Fig. 1. The delineated Raipur catchment area is 1118 km²

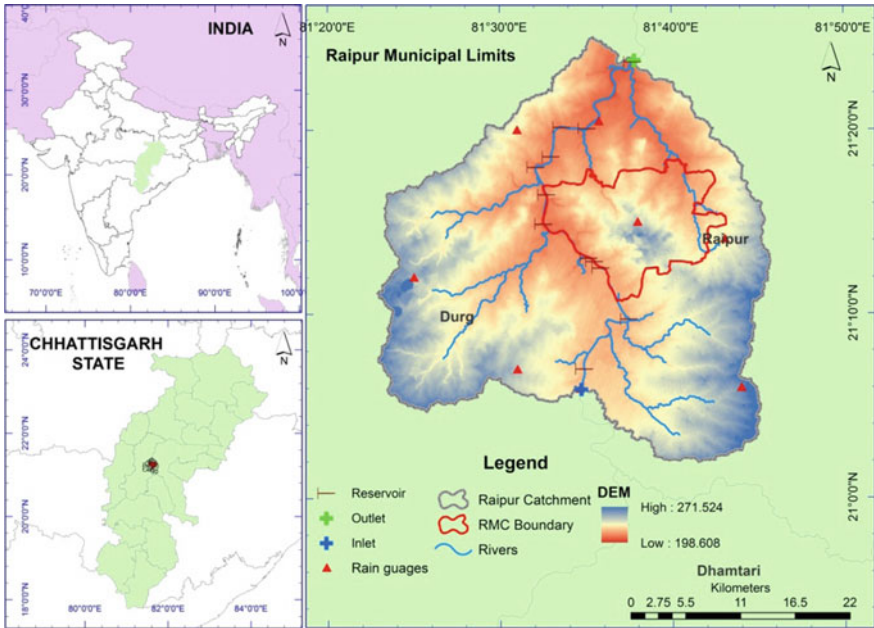


Fig. 1 Location map of the Raipur catchment (designated delta shape is Raipur catchment and red boundary is Raipur municipal boundary)

which is located between 21°00' N and 21°30' N latitude and 81°20' E longitude. The whole of Raipur catchment is part of Kharun sub-basin, which is thickly populated and closely cultivated [8]. The climate of the study area is sub-tropical with three distinct seasons. Temperatures remain moderate for most of the year. May is the hottest month and December is the coldest. The city experiences the average annual rainfall of 1200 mm. The Kharun River flows to the north and located at east of the Raipur city, and passes through the center from the Raipur catchment, which is also a source of domestic water supply to the city [9–11]. All the analysis is performed in the catchment scale using HEC-HMS but the present paper covers the anomalies only inside the Raipur municipal corporation area (shown in Red color) which has approximately 300 km² area. The city has a population of 1.125 million and experienced a growth rate of 51.06% during decade 2001–2011 [12].

The relationship between rainfall-runoff (RR) is very complex and influenced by various storm event and drainage basin characteristics. RR can be estimated using several approaches. CN (Curve Number) based SCS (Soil Conservation Service-Curve) method is well established for dynamic RR modeling for assuming the catchment as semi-distributed model [13]. SCS-CN method has been developed by National Resources Conservation Service (NRSC), United States Department of Agriculture (USDA) in 1969 that is simple predictable and stable conceptual method for computation of direct runoff based on rainfall depth [14]. Present study

covers SCS-CN methodology for estimating the runoff volume for Raipur catchment. Soil map and LULC map of the study area have been prepared using satellite imagery for year 1972, 1989, 1993, 1999, 2002, 2008, and 2015. These data's were used to generate CN map for each year.

HEC-HMS is hydrologic modeling software. It is open source product of U.S. Army Corps of Engineering's Hydrologic Engineering Center (HEC). HMS stands for Hydrologic modeling system. One of the important model components of HMS is Rainfall Runoff Model. This model converts the precipitation data in the particular watershed to runoff. For mathematical modeling purpose, complex sub-basin characters are divided into five components which are modeled separately. They are loss method, canopy method, surface method, transform method and baseflow method. Different methods are available in each component. The methods to be adopted for those components depend on site condition and data availability [15]. In this assessment HEC-HMS 4.5 version is used. Basic Model components and their data requirement are shown in Fig. 2. HEC-HMS has been evolving over past 30 years; recent researches prove that it is accepted for official purposes also. Since

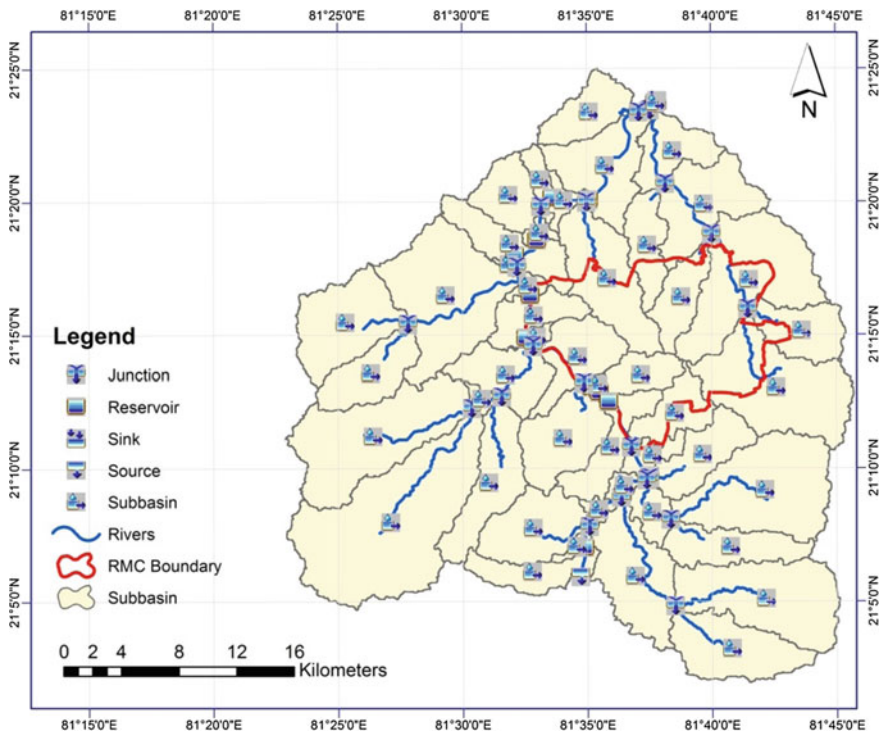


Fig. 2 HEC-HMS model setup with HEC schema of Raipur catchment used for simulation for 47 subdivided sub-basins including 12 anicuts operation into main river

Table 1 Process, input data used to generate HEC-HMS model for Raipur catchment

Process	Method used	Input data	Equation used
Modeling runoff volume	Gridded SCS CN method	Initial abstraction, curve number, percent impervious	$Q = \frac{(P-\lambda.S)^2}{(P-\lambda.S+S)}$
Modeling direct runoff	SCS Unit hydrograph model	Basin lag	$\text{Lag_time} = \frac{t^{0.8} \times (S+1)^{0.7}}{1900 \times Y^{0.5}}$
Modeling base flow	Recession	Observed discharge	$Q_t = Q_0.k^t$
Modeling channel flow	Muskingum Kung	Mannings n , Shape (8 point method)	$S_t = K[XI_t + (1-X)O_t]$

Where,

P = daily rainfall in mm

λ = In the SCS method in Indian condition the NIH, 1998 gave the value of λ coefficient equal to 0.2, although for black soil region $S = 25,400/\text{CN} - 254$

I (m) = Hydraulic length of watershed; Y = Avg. land slope

Q_0 = initial base flow (at time zero) in m^3/s ; k = an exponential decay; K = travel time of flood wave and X = dimensionless weight ($0 < X < 0.5$)

the software has many options in each method, it is flexible for different site conditions. The methods/process applied in this study is denoted in Table 1.

Figure 2 shows a typical model setup in HEC-HMS of Raipur catchment. All the model processes are assigned in HEC-Geo-HMS and input using HEC-DSS tool.

3 Results and Discussion

Result of supervised classification of landuse land cover of Raipur city area has been shown in Table 2, based on pixel size it shows the total area cover by each landuse classes for each of the year. The results clearly show that urban areas have expanding and water bodies are decreasing since 1989 with continuous population growth. Rapid socio-economic development, huge opportunity of business and market activity inside the central part of the city, such rise in urban area is expected. In other hand agriculture land and vegetation land has random anomaly in different years. Due to coarser resolution imagery it can be consider that the agriculture land and vegetation land has not been recognized at the time of visual interpretation. Also the Raipur city is the most polluted city in India in terms of air pollution [16]. This is also a reason for lack of visual interpretation and histogram error in north side of the city where industrial area is populated.

At the stage of development the landuse category of agriculture and open land area were converted into urban areas. Also in the same way, the landuse types which has lost the spatial extent is open land and agriculture landuse type that reduced an area of 27.62 and 25.82 km^2 respectively to other landuse types. Since 1972–2015 in Raipur city has witnessed significant changes in Water bodies, Open land and Agriculture area due to continuous urban encroachment (Fig. 3).

Table 2 Landuse Landover classification using supervised classification in ERDAS for different satellite products and calculated dynamic degree in percentage

Sat. Sensor	TM				ETM+			Area change in 1972–2015	Dynamic degree in % 1972–2015
Year/LULC	1972	1989	1993	1999	2002	2008	2015		
Agricultural	199.4	92.9	164.3	214.1	184.2	137.1	173.5	-25.82	0.30
Open land	44.3	125.7	67.2	42.2	34.9	28.3	16.7	-27.62	1.45
Urban	3.9	6.3	7.5	9.12	12.9	37.5	53.4	49.49	-29.51
Vegetation	48.9	71.8	58.1	32.0	65.2	95.0	54.3	5.44	-0.26
Water Bodies	3.8	3.8	3.53	3.2	3.4	2.88	2.5	-1.36	0.82
Total	300.4	300.7	300.7	300.7	300.7	300.7	300.5		

Note All values are in km²

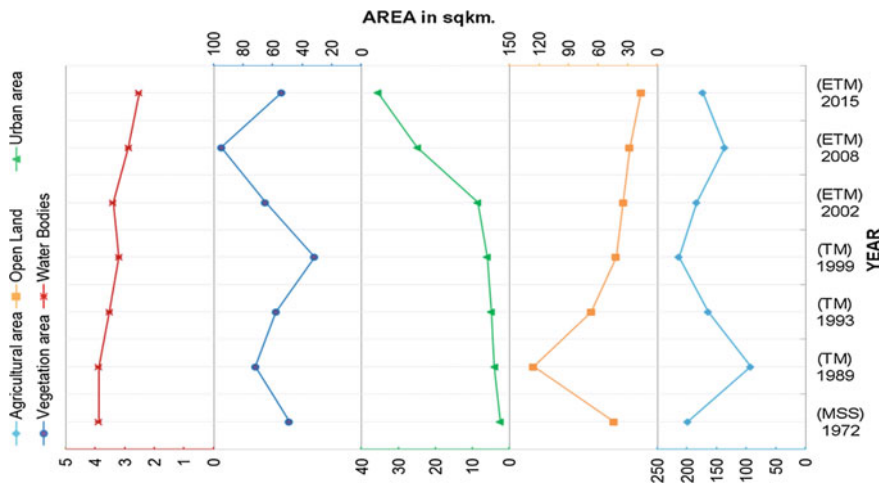


Fig. 3 Temporal variation in landuse landcover classification of Raipur city

To compare this anomaly mathematically one equation has been used in similar study by Wakode, Baier [7]. The changes in landuse in a temporal extent can also be calculated using the dynamic degree equations. Table 2 shows the dynamic degree of landuse types that is a quantitative variation of a landuse category with in a time scale and can be calculated using [7]:

$$K(\%) = (Z_a - Z_b) / Z_a \cdot (1/T) \cdot 100,$$

where

K = the dynamic degree change in a particular landuse type; Z_a and Z_b = the area of a type of landuse before the change and after the change, respectively; T is the time interval between two successive year of landuse change.

Instead presenting change in percentage area, dynamic degree has been computed which has a time factor. Negative values in dynamic degree shows higher growth in land use change and vice versa. Using the resulted landuse classification and soil classification curve number map has been generated. This is further used for input for HMS model as Basin CN and percentage imperviousness. The above shown HEC-HMS model in Fig. 2 has been run and simulate for seven different control specifications to compute runoff at each pixel length as it is mentioned the gridded SCS CN method has been implemented for present study. The purpose of selection of grid based method for calculation is because of RMC boundary which is different than sub-basin boundaries in Raipur catchment model. This approach reduces the limitation of composite CN, instead using grid-based method in this study. Daily rainfall data has been used to delineate the runoff quantity in the catchment which is summarized in Table 3 as monthly and distribution curves for runoff and bar diagram for rainfall has shown in Fig. 4.

From this continuous rainfall runoff simulation in Table 3 the annual rainfall is decreasing so that runoff is also decreasing. In Table 3 two variables that are rainfall and CN/year of landuse. Both are changing means it is difficult to interpretate the changes in runoff due to urbanization because landuse is also changing as in the same time rainfall patterns changes which is natural in nature. To draw or conclude result from the present analysis a change in dynamic degree between rainfall runoff and urban-landuse has been computed (Table 4). The annual rainfall and runoff has been successfully correlated by commuting correlation coefficient which is varies from 0.76 to 0.86. Three new parameter is calculated which includes time duration of landuse change are Rainfall, runoff and urban landuse change as % dynamic change. To correlate the change in landuse with runoff the values were plotted in line graph type against duration (Fig. 5). The results shows that the runoff is follow the exact urban landuse distribution which means dynamic degree change in runoff is same as urban landuse change. It may happed due to runoff calculation in this method is dominated by CN values which is directly related with landuse. So it can be concluded that as urban land is increasing the runoff trend is also increasing.

4 Conclusion

This study exhibit the use of RS and GIS techniques, to characterize the process of urbanization efficiently. The freely available historical MSS, TM and ETM + sensor data along with census records have helped in identification of LULC change in Raipur city. It indicated that total urban area has grown since 1972–2015 by 49.49 km². Open land and agriculture landuse types are mostly affected by the urban growth. Reduction of water bodies since 1972 were significant and most of the remaining water bodies shows further reduction of its spatial extent. The total number of registered lakes in Raipur city was 185 in numbers now only 85 has been left. Such losses of surface water resources are also one of the reasons in changes of surface runoff pattern in Raipur city. Result of HEC-HMS model reveals

Table 3 Monthly total rainfall and generated runoff at the outlet of Raipur catchment (Runoff represented in mm as equality distributed through the basin, to calculate exact runoff volume the runoff depth must be multiplied by corresponding sub-catchment area)

Months	1972		1989		1993		1999		2002		2008		2015	
	Rainfall (mm)	Runoff (mm)	Rainfall (mm)	Runoff (mm)	Rainfall (mm)	Runoff (mm)	Rainfall (mm)	Runoff (mm)	Rainfall (mm)	Runoff (mm)	Rainfall (mm)	Runoff (mm)	Rainfall (mm)	Runoff (mm)
Jan	0	0	0	0	0	0	0	0	13.8	41.2	7.6	19.2	9.4	27.5
Feb	5	10.4	0	0	10.2	18.7	11	18.7	5.2	25.1	11.6	50.9	2.2	9.3
Mar	0	0	12.6	34.4	18.5	99.2	0	99.2	5.7	30.9	24.8	150.1	19.3	106.9
Apr	8.6	28.6	0	0.2	14.2	88.4	0	88.4	3	17.4	5.2	34.5	51.4	350.5
May	21.2	119.5	12	59.8	32.8	214.5	70	214.5	14.1	86.5	0.6	4	13.4	95.8
Jun	213.2	1503	457.1	3288	135.4	985.9	98.6	985.9	196	1404	204	1448	271.6	1989
Jul	199.6	1546	391.1	2909	499.8	3688	135.9	3688	71.8	492.2	125	940.1	173.2	1282
Aug	374.3	2790	227.7	1649	405.2	2991	421	3031	345	2571	229	1628	267.4	1971
Sep	192.4	1484	196.2	1488	166.5	1238	263.7	1238	90.2	676.5	220	1693	219.6	1631
Oct	22	147.1	0	0	45.3	335.1	21	335.1	23.2	171.5	12.6	93.2	0	0
Nov	51	403.4	0	0	0	0	0	0	0	0	0	0	0	0
Dec	2	16.9	13.6	99.5	0	0	0	0	0	0	0	0	13.8	101.1
Total	1089	8049	1310	9528	1328	9659	1021	9659	767	5516	840	6061	1041	7564

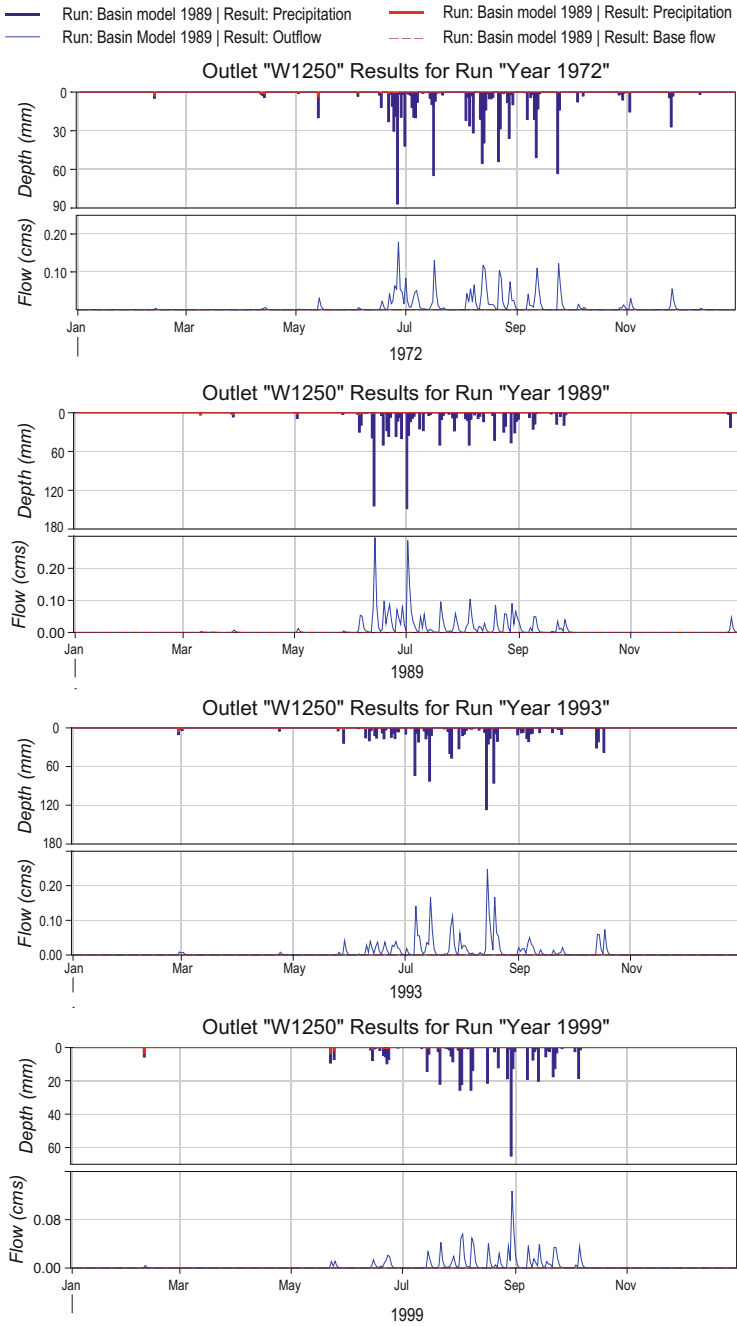


Fig. 4 HEC-HMS Simulated Rainfall (top), Runoff (Bottom) and losses at Sub-basin ‘W1250’—catchment outlet form 1972 to 2015 in chronological order

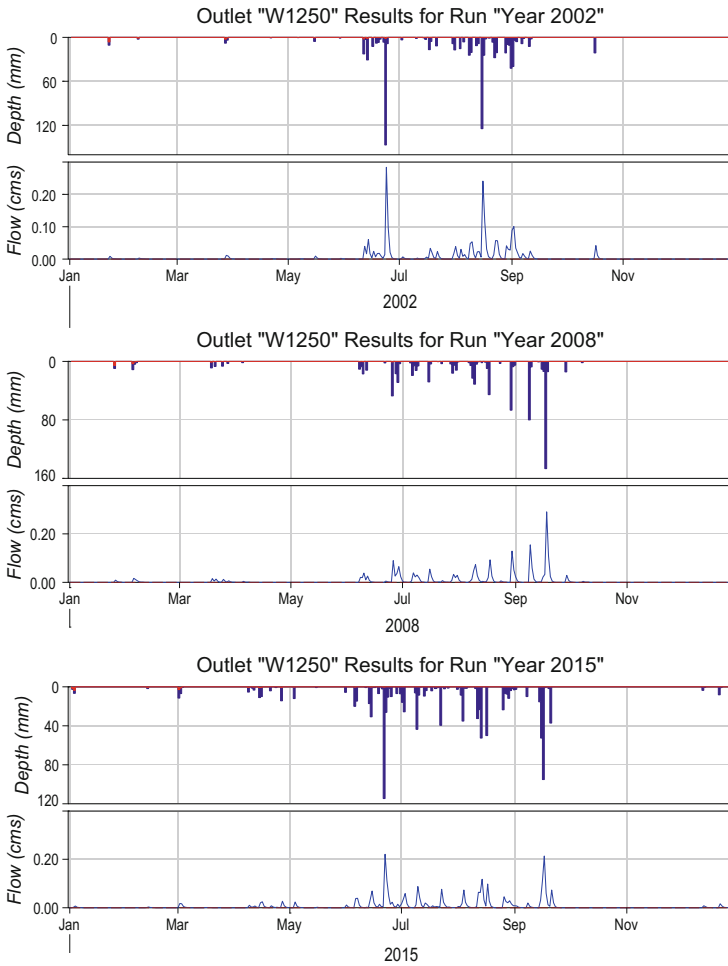


Fig. 4 (continued)

that the landuse change is a most important factor for changing pattern in runoff in Raipur city. The simulation result of HEC-HMS model can also be used for forecasting the future changes in runoff pattern in the city if proper calibration has been applied. This study produces very valuable results for planner/policy makers as it reveals a very comprehensive indication of surface runoff distribution in Raipur city. The results can be conveniently utilized by the water resource engineering decision-makers for scientific management planning to mitigate the quantity of water resources. Moreover, it provides a sound base for planning of land use practices.

Table 4 Rainfall runoff correlation and dynamic degree change with urban landuse

Year	Annual rainfall in mm	Annual runoff in mm	Urban landuse in km ²	Dynamic degree in %		Correlation between rainfall and runoff
				Rainfall	Runoff	
1972	1089.3	8048.7	3.9	-	-	$y = 7.5069x - 10.717$ $R^2 = 0.82$
1989	1310.3	9528.2	6.3	-3.62	-1.19	$y = 7.3315x - 6.5197$ $R^2 = 0.86$
1993	1327.9	9659.1	7.52	-4.84	-0.34	$y = 7.4213x - 16.299$ $R^2 = 0.79$
1999	1021.2	7407.3	9.12	-3.55	3.85	$y = 7.3506x - 8.2597$ $R^2 = 0.81$
2002	767.2	5516.3	12.98	-14.11	8.29	$y = 7.4469x - 16.413$ $R^2 = 0.76$
2008	840.2	6061	37.5	-31.48	-1.59	$y = 7.381x - 11.711$ $R^2 = 0.79$
2015	1041.3	7563.5	53.39	-6.05	-3.42	$y = 7.423x - 13.836$ $R^2 = 0.86$

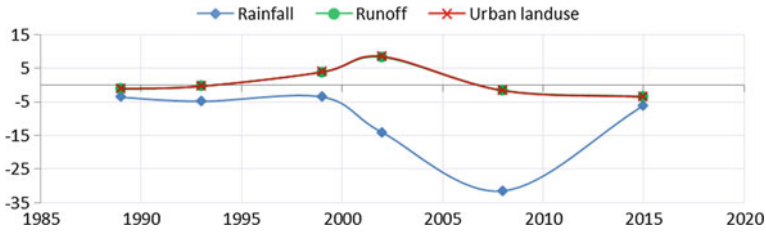


Fig. 5 % Dynamic degree change between Rainfall, runoff and urban landuse

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References

1. UNICEF: Water in India: situation and prospects, in UNICEF, India Country Office (2013)
2. Un, D.: World Urbanization Prospects: The 2014 Revision. United Nations Department of Economics and Social Affairs, Population Division, New York, NY, USA (2015)
3. Un-Habitat: Planning Sustainable Cities: Global Report on Human Settlements 2009. Routledge (2016)
4. Angel, S., et al.: The Dynamics of Global Urban Expansion, Transport and Urban Development Department. World Bank, Washington, DC (2005)
5. Montgomery, M.R.: The urban transformation of the developing world. *Science* **319**(5864), 761–764 (2008)
6. Strohschön, R., et al.: Land use and water quality in Guangzhou, China: a survey of ecological and social vulnerability in four urban units of the rapidly developing megacity. *Int. J. Environ. Res.* **7**(2), 343–358 (2013)
7. Wakode, H.B., et al.: Analysis of urban growth using Landsat TM/ETM data and GIS—a case study of Hyderabad, India. *Arab. J. Geosci.* **7**(1), 109–121 (2013)
8. Sinha, M.K., et al.: Assessment of groundwater vulnerability using modified DRASTIC model in Kharun Basin, Chhattisgarh, India. *Arab. J. Geosci.* **9**(2), 1–22 (2016)
9. GIZ, ASEM, and RMC: Annexures City Sanitation Plan for Raipur (2011)
10. RMC: Detailed Project Report, Sewerage, Storm, Surface water drains and lake protection works for Raipur city. Meinhardt (Singapore) Pte. Ltd (2010)
11. RMC: Raipur City: Storm Water Drainage Report (2011)
12. Census-of-India: Census of India 2011, District census handbook: Raipur, pp. 1–452 (2011)
13. Nigam, G.K., et al.: Field assessment of surface runoff, sediment yield and soil erosion in opencast mines in Chirimiri area, Chhattisgarh, India. *Phys. Chem. Earth, Parts A/B/C* (2017)
14. Jena, S.K., et al.: RS and geographical information system based evaluation of distributed and composite curve number techniques. *J. Hydrol. Eng.* **17**(11), 1278–1286 (2012)
15. Feldman, A.D.: Hydrologic modeling system HEC-HMS: Technical reference manual. US Army Corps of Engineers, Hydrologic Engineering Center (2000)
16. Verma, M.K., et al.: Computation of air quality index for major cities of Chhattisgarh state. *Environ. Claims J.* **28**(3), 195–205 (2016)