

Impact Assessment of Land-Use/Land-Cover Changes on Hydrology and Storm Water Drain Network in Yelhanka Watershed, Bangalore



R. L. Gouri, V. V. Srinivas, S. N. Soumya, and M. Amulya

Abstract Globally, urban areas are witnessing rapid development in the recent decades, and there is growth in flash flood incidents following even short-duration storm events of less rarity (return period). Stormwater drains (SWDs) are an integral part of urban infrastructure. Owing to this, the existing natural drainage system gets affected, as the SWD network might replace only a part of the natural system. Further, changes in land-use/land-cover (LULC) associated with urbanization of catchments have implications on generated runoff in terms of increase in peak discharge, runoff volume, and velocity. An increase in runoff velocity causes a reduction in time to peak discharge, resulting in flash floods. In addition, encroachment into storm sewers limits their capacity to convey runoff, causing more devastation during floods due to an increase in stage for a given discharge. The present study is aimed at assessing LULC change in an urban catchment located in Bangalore (North) and evaluating its effect on runoff generation. Remote sensing satellite images corresponding to the years 1996, 2002, 2006, and 2012 have been analyzed to identify changes in LULC. The impact of the changes on runoff is investigated by inputting design hyetographs to Storm Water Management Model (SWMM) developed for the urban catchment for the various LULC scenarios and analyzing the runoff generated by the model. Vulnerable reaches in the existing stormwater drainage network of the studied urban catchment are identified, and the failure state of those drains is marked.

Keywords Storm Water Management Model (SWMM) · Land-use/land-cover (LULC) · Stormwater drains (SWDs) · Urbanization and vulnerability

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1 Introduction

The process of urbanization is often rapid and disorganized in developing countries like India. Performance of stormwater drains (SWDs) is severely affected by an increase in inflow caused by significant changes in land-use and land-cover (LULC) and the associated changes in climate, storm patterns, and hydrological processes (e.g., evapotranspiration, infiltration, and runoff). A surge in peak discharge, volume and velocity of flow, and reduction in time taken for the flood discharge to attain its peak are some of the typical effects of urbanization. Furthermore, the SWD networks demand substantial financial investment for construction/installation, maintenance, and retrofitting. Financial constraints pose a challenge for judiciously allocating the resources toward these activities. In this perspective, there is a need to understand how the performance of the SWDs is affected by LULC changes so that flood mitigation and management strategies can be devised to minimize the consequent direct and indirect damages to the urban environment and population. Most studies in the past have assessed the effect/impact of LULC change on (i) water balance components in agricultural watersheds [14, 16]; and (ii) runoff generation in river basins [6, 7, 9, 12, 15]. They have concluded that reduction of vegetation cover leads to an increase in runoff and vice versa [8, 10] which is the case in urban catchments. There is a stressing need for studies on impact assessment of LULC change on runoff generation in urban catchments in India, as most cities are witnessing rapid development.

The objectives of the present study are to develop a hydrological model, Storm Water Management Model (SWMM), for a rapidly urbanizing Yelahanka watershed in Bangalore and estimate overland flow and runoff entering an existing SWD network in the area for different LULC scenarios. The LULC changes were analyzed based on remote sensing products corresponding to four typical years (1996, 2000, 2006, and 2012) using Geographic Information System (GIS) tools. The changes were found to be significant, especially during recent years. The SWMM developed corresponding to each chosen historical LULC scenario was forced with synthetic design storm hyetographs (DSHs), and watershed responses were recorded, which reflected the implications of the LULC change. Discharge generated from SWMM models was used to assess the performance of each of the drains in the SWD network to identify those that are susceptible to failure. Furthermore, suggestions are provided on possible mitigation measures which could be implemented to enhance/improve the performance of the drains for alleviating/minimizing the flood-damage potential from critical storm events.

The remainder of the chapter is structured as follows. A detailed description of the methodology utilized for the analysis is presented in Sect. 2. Following this, a case study is presented in Sect. 3 on the stormwater distribution system in the Yelahanka watershed of Bangalore city. Subsequently, conclusions drawn based on the study are provided in Sect. 4.

2 Methodology

2.1 Methodology for Reliability Analysis of SWDs

In the study, the reliability of the drains was determined under two failure modes. A drain is said to have failed when (i) runoff in the drain exceeds its flow capacity and (ii) the actual flow velocity in the drain exceeds the maximum allowable velocity for scouring control. The reliability of any system generally depends on the interaction between loads on the system and resistance by the system. Loadings are the external stresses that act on the system, and resistance is the capacity of the system to sustain the load. In the context of SWDs, the load is actual discharge generated from urban area (Q_D) into the channel, and resistance is flow capacity (Q_C) of the drain under consideration. In this study Q_C is calculated using Manning's equation (Eq. 1) and Q_D is extracted from the SWMM output.

$$Q_C = \frac{1}{n} b^{5/3} d^{5/3} \left(\frac{1}{b + 2d} \right)^{2/3} s^{1/2} \quad (1)$$

where b , d , and s denote base width, depth, and slope of the drain, respectively, and n represents Manning's roughness coefficient. Failure of the drain is said to have occurred when the actual discharge generated in the drain from the urban watershed (Q_D) exceeds the flow capacity (Q_C) of the drain [5]. In this perspective, discharge-based reliability estimate of a drain (R_d) can be expressed as,

$$R_d = \begin{cases} 1 & \text{if } Q_C \geq Q_D \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

Analogous to discharge-based reliability (R_d), velocity-based reliability (R_v) can be defined for the failure of a drain due to maximum velocity (V_D) exceeding maximum allowable velocity (V_{Max}) of the drain. The value for V_D is extracted from SWMM output, whereas the value of V_{Max} is considered to be 3 m/s [2, 4]. Mathematically, this can be expressed as,

$$R_v = \begin{cases} 1 & \text{if } V_D \leq V_{Max} \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

2.2 Storm Water Management Model (SWMM)

The SWMM, used for the case study, is a dynamic rainfall-runoff simulation model widely used to quantify runoff generated from urban areas. It has two modules, the

first being the rainfall-runoff module and the second being the transportation module [13]. The rainfall-runoff module calculates the runoff generated from a collection of sub-catchments that receive precipitation. The transportation module routes the runoff through the stormwater drains or pipes during the simulation period. Spatial variability is accounted for by dividing the study area into a collection of smaller sub-catchments, each containing some fraction of pervious and impervious sub-areas. Surface runoff from each sub-watershed is calculated after accounting for initial abstractions (evaporation and infiltration). Inputs to SWMM include design rainfall hyetograph for the duration and return period of interest, LULC corresponding to different years, hydrologic soil groups for the study area identified based on the soil map.

3 Case Study

The methodology presented in Sect. 2 was applied to an existing SWD network in the Yelahanka watershed (Fig. 1) located in the northern part of Bangalore, India. The reliability of the network is evaluated by considering its discharge carrying capacity and maximum flow velocity criteria. The area of the watershed contributing flow to drains in the network is about 355 km². The total length of the drain is 176 km, which was further divided into 500 smaller drains for ease of analysis. The watershed was divided into 180 sub-watersheds, which are shown as darkened rectangles in Fig. 2.

For use in the analysis, daily rainfall records corresponding to five rain gauges (base stations) located at GKVK (Gandhi Krishi Vignan Kendra), Yelahanka,

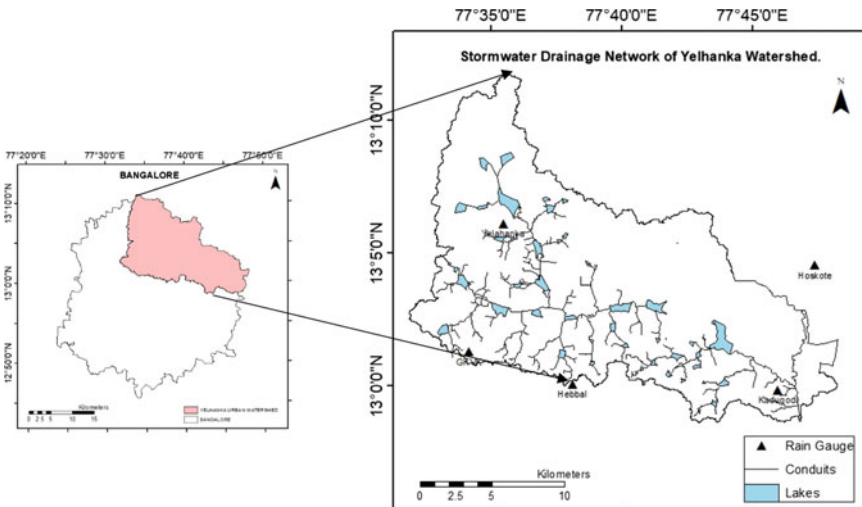


Fig. 1 Location map of Yelahanka watershed

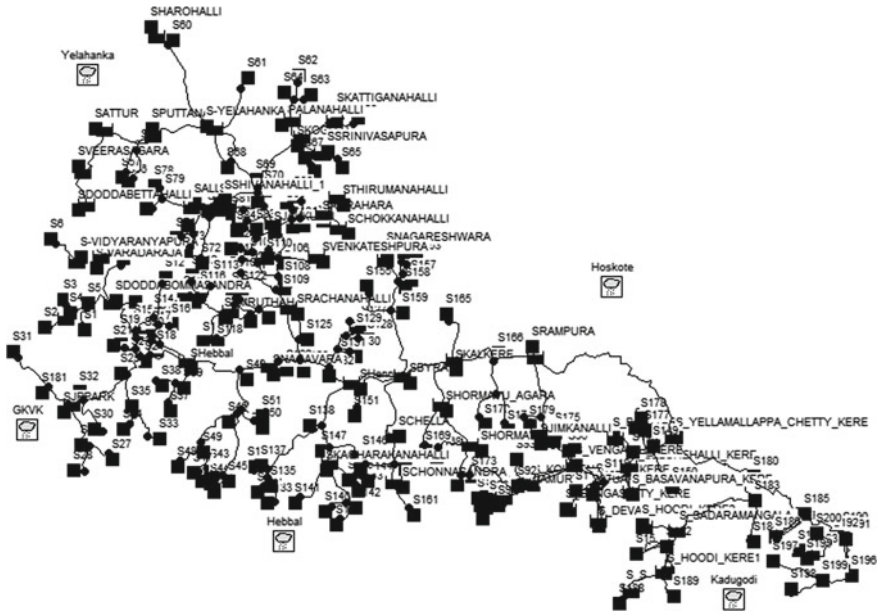


Fig. 2 Representation of the sub-watersheds and rain gauges in SWMM

Hoskote, Hebbal, and Kadugodi were considered for the period 1988–2010. Records of the latter four gauges were collected from the Directorate of Economics and Statistics, Bangalore, whereas those of GKVK were collected from the GKVK Agricultural college campus. Locations of the gauges are shown as “square enclosing clouds” in Fig. 2. Existing SWD network details were collected from the SWD department, Bruhat Bengaluru Mahanagara Palike (BBMP).

Discharge from the Yelahanka watershed into the SWD network was estimated corresponding to various rainfall durations and return periods using SWMM. Inputs to SWMM include design rainfall hyetograph for the duration and return period of interest, LULC corresponding to different years, and curve number for the sub-watersheds. The design hyetographs were constructed based on Intensity-duration-frequency (IDF) curves developed for the study area (Fig. 3). As the records at base stations were available at a daily scale, they had to be disaggregated to hourly scale for the construction of design hyetographs corresponding to sub-daily durations.

The disaggregation was carried out using the *k*-nearest neighbor method [1]. For this purpose, relationships between daily and hourly rainfall records corresponding to a rain gauge located at the Indian Institute of Science (IISc) Campus were considered. The gauge at IISc had 10-min scale rainfall records over the period 2003–2016, and they were found to be reasonably well correlated at daily scale with records corresponding to gauges located at the base stations. IDF curves were developed [3] for each of those stations using the derived hourly rainfall by frequency analysis using Extreme value type-I distribution. Subsequently, those curves were considered as the

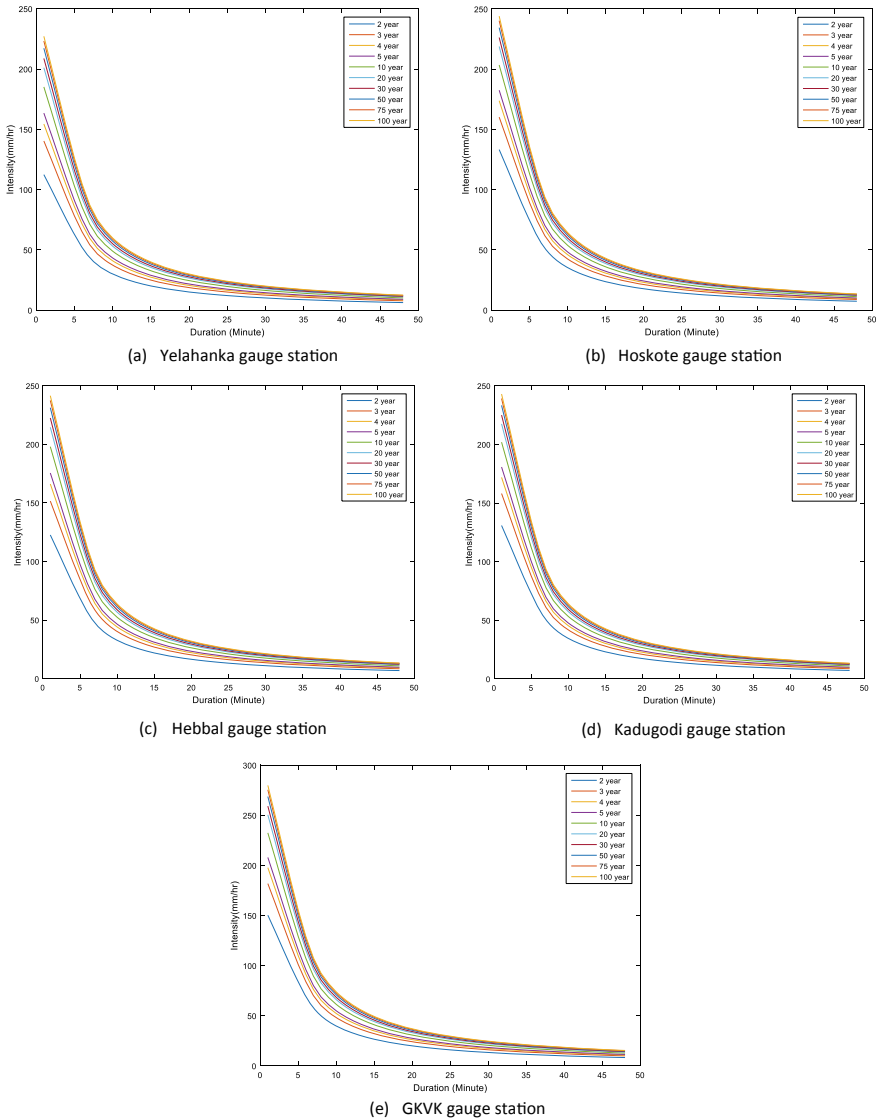


Fig. 3 The IDF curves plotted for the base stations

basis to construct design hyetographs corresponding to various sub-daily durations (1, 2, 3, 6, and 12 h) and return periods (2, 5, 10, 25, and 50 years) for the base stations locations. Herein, it is to be mentioned that records corresponding to gauge at IISc were short, and hence those were not considered for frequency analysis to construct IDF curves. Typical hyetographs plotted for the base stations are presented in Fig. 4.

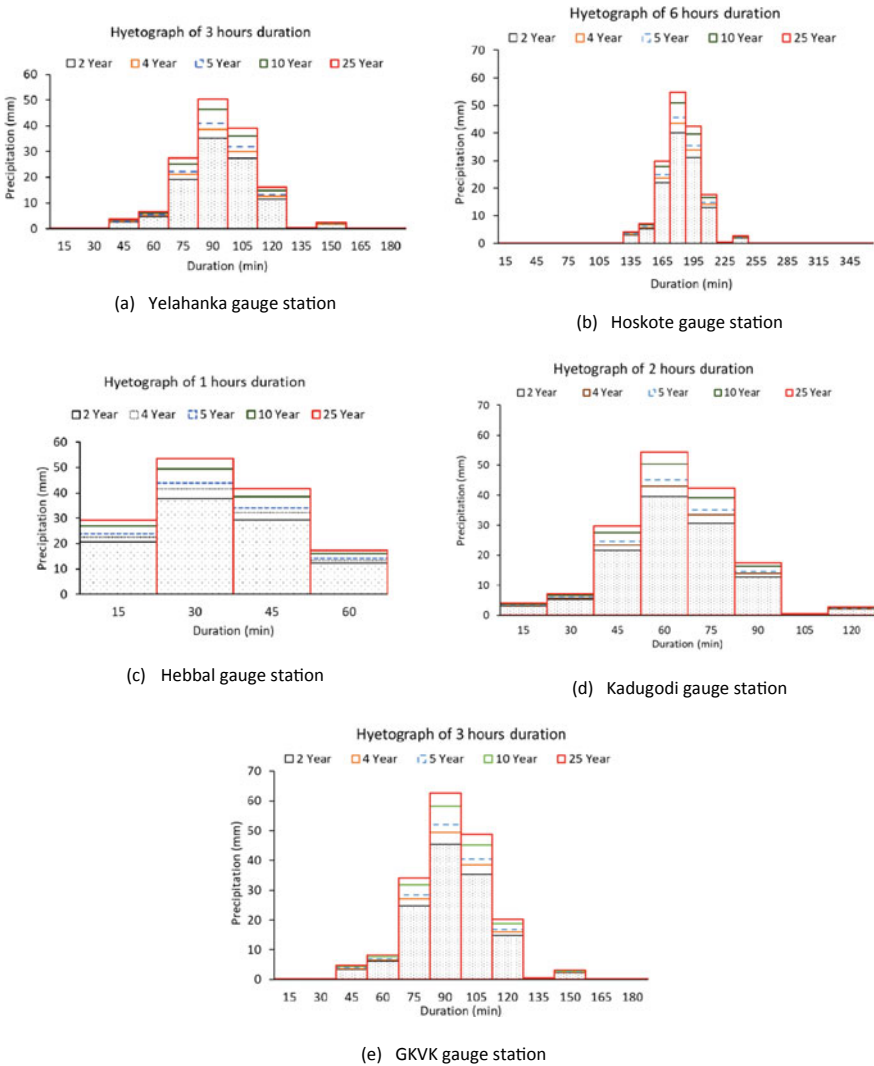


Fig. 4 Typical hyetographs constructed for the base stations

Initial abstractions were calculated using the NRCS curve number method [16]. Implementation of the method involved assignment of curve numbers to each sub-watershed based on LULC information corresponding to different years and hydrological soil groups. The hydrologic soil groups for the study area were identified based on a soil map obtained from the National Bureau of soil survey and land-use planning (NBSS & LUP [11]). For the study area, LULC maps were prepared corresponding to the years 1996, 2002, 2006, and 2012. Among those, maps corresponding to the

years 1996 and 2002 were based on satellite imageries obtained from IRS-IC-LISS-III at 1:50,000 scale, whereas the maps for the years 2006 and 2012 were prepared based on thematic maps available for the study area from Bhuvan-Thematic Services National Remote Sensing Center (NRSC), ISRO, Hyderabad, India, (<http://bhuvan.nrsc.gov.in>) at 1:50,000 scale. A level II classification was carried out to classify land-use in the study area corresponding to the LULC maps.

Flow routing within a drain in SWMM is governed by the conservation of mass and momentum equations for gradually varied, unsteady flow (i.e., the Saint–Venant flow equations). The kinematic wave routing method was considered for routing the flow in the channels (drains) of the SWD network. The rainfall information was provided in the form of design hyetographs corresponding to various return periods (2, 5, 10, 25, and 50 years) and durations (1, 2, 3, 6, and 12 h), and the runoff was generated from each of the sub-watersheds. In SWMM, the hyetographs corresponding to each rain gauge must be allocated to the sub-watershed that comes under the rain gauge's influence. This allocation was done based on Fig. 5, which represents the area of influence of Yelahanka, Hoskote, Hebbal, and Kadugodi and GKVK rain gauges over the Yelahanka watershed.

Experiments were conducted to examine the effect of LULC change on water balance components such as evaporation, infiltration, and runoff. Each experiment

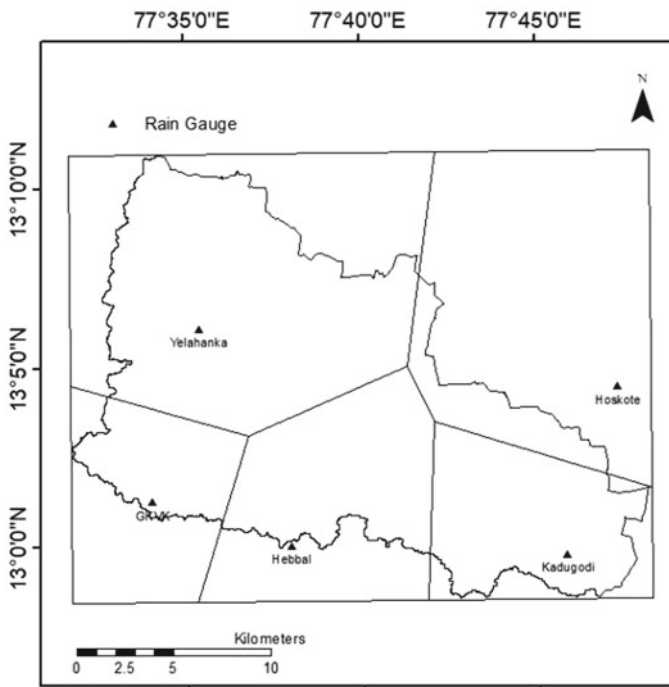


Fig. 5 Area of Influence of rain gauges over the Yelahanka watershed

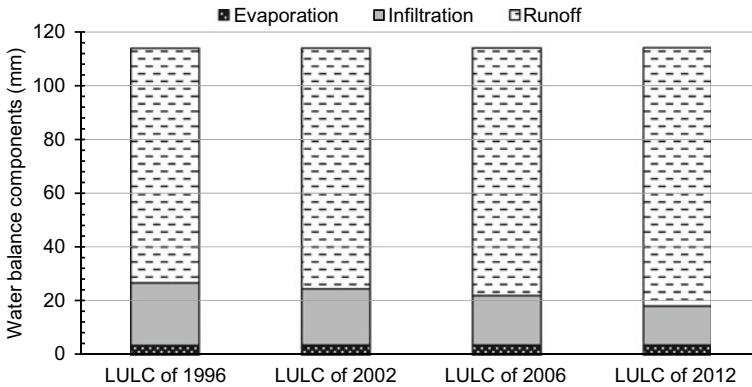


Fig. 6 Water balance components quantified (in-depth units) corresponding to 2 h duration 10-year return period design hyetograph

involved providing a design hyetograph as input to SWMM along with LULC information corresponding to each of the four years (1996, 2002, 2006, and 2012) and analyzing output from the model to quantify changes in each of the water balance components due to LULC change. To quantify the effect of design hyetograph on the results, hyetographs corresponding to various durations and return periods were developed. One of those hyetographs was considered at a time for experimenting. Changes in water balance components due to LULC change were quantified corresponding to each of the hyetographs. Typical results obtained from these experiments are presented in Fig. 6. Comparison of runoff generated for different years shows an increase in runoff and consequent reduction in infiltration. Reduction in infiltration and increase in runoff could be attributed to an increase in imperviousness associated with an increase in the built-up area. On the other hand, change in evaporation was found to be insignificant, possibly due to insignificant changes to factors (e.g., temperature, humidity, wind speed) affecting the component. For brevity, the distribution of catchment response to a design hyetograph corresponding to 3-h duration and 5-year return period is shown in Fig. 6 (Table 1).

Peak flow discharge (Q_D) and velocity of flow (V_{Max}) corresponding to peak flow in the drain for each specified return period and duration were extracted from “Link Flow summary” from the output file generated by the SWMM model at 15-minute scale. The values for discharge reliability R_d and velocity reliability R_v is estimated based on Equations 2 and 3 where the value of Q_C is calculated using Equation 1. For estimating R_v the value of maximum allowable velocity (V_{Max}) for a lined drain is considered to be 3m/s (e.g., [4]). The results are presented in the pictorial format in Figures 7, 8, 9 and 10 for each of the LULC scenarios (1996, 2002, 2006, and 2012) considered. In the figures, the drains that are safe/reliable are shown in green, whereas the drains that are failing/unreliable are shown in red. The effect of LULC change on the SWDs is evident and can be observed in the figures. From the analysis based on LULC for the year 1996, it can be observed that R_d for most of the drains is

Table 1 Water balance components corresponding to LULC for the year 2012 for various return periods and durations

Duration in hours		Return period in years			
		2	5	10	25
		Depth in mm			
1	Total precipitation	66.7	94.0	105.6	118.2
	Evaporation loss	1.2	2.0	2.1	2.2
	Infiltration loss	37.9	43.3	44.9	46.2
	Surface runoff	27.9	48.2	57.8	68.5
2	Total precipitation	68.2	96.2	108.1	120.9
	Evaporation loss	2.3	2.5	2.5	2.5
	Infiltration loss	31.8	37.2	38.6	39.7
	Surface runoff	34.4	56.6	66.7	77.9
3	Total precipitation	68.4	96.4	108.2	121.1
	Evaporation loss	3.1	3.2	3.2	3.2
	Infiltration loss	26.0	29.9	31.2	32.3
	Surface runoff	38.1	61.3	71.6	83.0
6	Total precipitation	68.6	96.5	108.3	121.2
	Evaporation loss	3.1	3.1	3.1	3.1
	Infiltration loss	25.4	29.6	31.0	32.2
	Surface runoff	38.5	61.4	71.6	82.9
12	Total precipitation	68.9	96.9	108.7	121.7
	Evaporation loss	2.9	2.9	2.9	2.9
	Infiltration loss	25.9	30.2	31.6	32.9
	Surface runoff	38.2	61.1	71.3	82.6

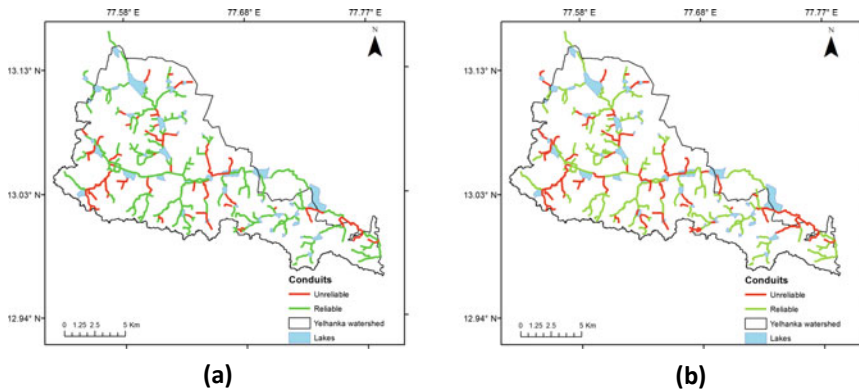


Fig. 7 **a** R_d values for LULC 1996, for 3-year return period and 2-h duration hyetograph. **b** R_v values for LULC 1996, for 3-year return period and 2-h duration hyetograph

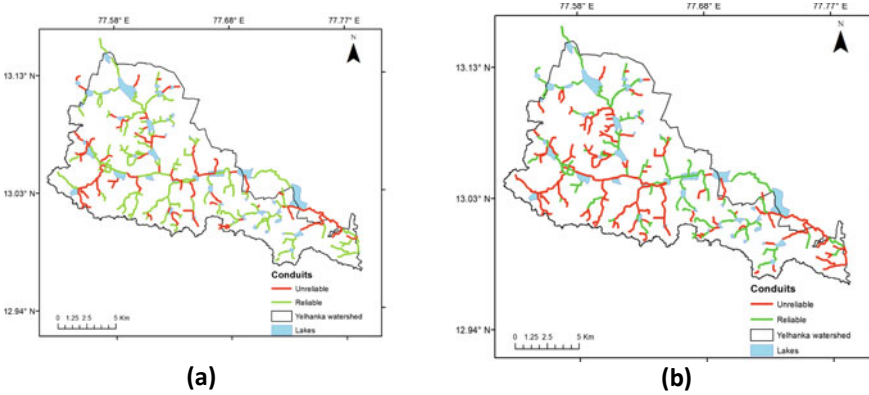


Fig. 8 a R_d values for LULC 2002, for 3-year return period and 2-h duration hyetograph. b R_v values for LULC 2002, for 3-year return period and 2-h duration hyetograph

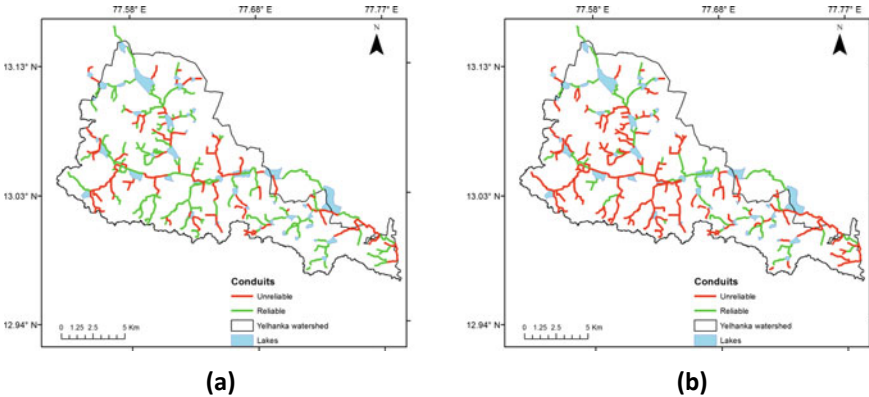


Fig. 9 a R_d values for LULC 2006, for 3-year return period and 2-h duration hyetograph. b R_v values for LULC 2006, for 3-year return period and 2-h duration hyetograph

positive, whereas from analysis based on LULC for the year 2012, R_d for most of the drains is negative and such drains are identified as vulnerable reaches in the SWD network being studied. These drains are found to be inadequate to convey discharge corresponding to various design hydrographs (durations greater than 3 hours, return period higher than 5 years), and the velocity of flow is exceeding the maximum allowable velocity, which may cause scouring. More drains were in failure mode in reliability analysis with maximum velocity than with maximum discharge for each of the LULC scenario. Furthermore, the count of drains in failure mode increased with the change in LULC from 1996 to 2012.

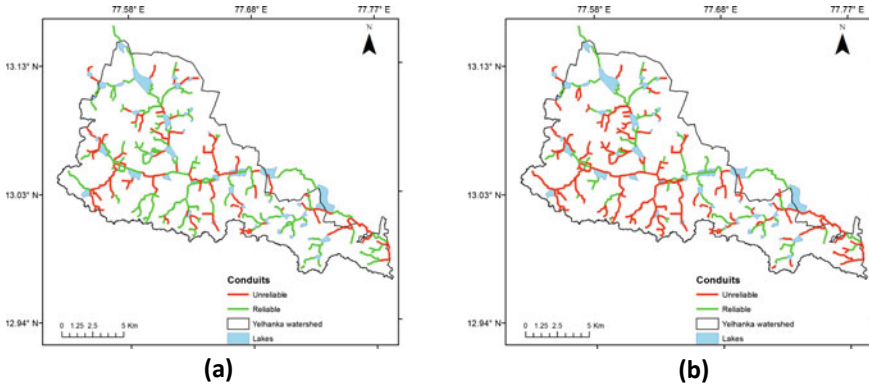


Fig. 10 **a** R_d values for LULC 2012, for 3-year return period and 2-h duration hyetograph. **b** R_v values for LULC 2012, for 3-year return period and 2-h duration hyetograph

4 Results and Concluding Remarks

SWMM models were developed for the Yelahanka watershed in Bangalore city for LULC scenarios corresponding to four years (1996, 2002, 2006, and 2012). The overland flow/runoff corresponding to synthetic design hyetographs of various durations (1, 2, 3, 6, and 12 h) and return periods (2, 5, 10, 25, and 50 years) was estimated. Furthermore, its characteristics (peak discharge, maximum velocity) were analyzed in each of the drains of an existing SWD network. Between the years 1996 to 2012, a significant increase in runoff volume and reduction in infiltration was observed for the various LULC scenarios considered, owing to an increase in imperviousness in the Yelahanka watershed. Furthermore, the discharge reliability R_d and velocity reliability R_v was calculated by extracting conduits flow summary from SWMM outputs. The results indicated that for storms of higher return periods (> 5 years) and durations (> 3 h): (i) the discharge exceeds capacity in several drains, and (ii) flow velocity is higher, which causes scouring in a considerable number of drains. Comparison of discharge generated corresponding to various LULC scenarios indicated that the number of surcharged drains and the duration of flooding in those have increased owing to urbanization. More drains were in failure mode in reliability analysis with maximum velocity than with maximum discharge.

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