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Research article

Impact of Urbanization and Climate Change on Urban Flooding: A case of the Kathmandu Valley

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Abstract

Climate change and urbanization are two phenomena that are now playing an important role in the development of infrastructure. Urban drainage systems are increasingly overburdened during extreme precipitation events, and are stretched to their limits by increasing populations. The present research seeks to contribute to the ongoing dilemma of quantification of the impact of both phenomena on urban pluvial flooding. The research has adopted both a quantitative approach and a qualitative approach, in which different software, such as RClimdex, a statistical downscaling model (SDSM) and PCSWMM are used. The Intensity Duration Frequency (IDF) curve for the current and future climate is developed based on the Gumbel distribution. The research explores the relationship between the increasing urban runoff and flooding due to increased imperviousness and extreme rainfall events due to climate change in the study area. The findings of the research show that future climate change conditions with present urbanization will increase pluvial flooding. There will be a 40 percentage increase in the flooding amount considering the current and future climate for a 25 year return period. Furthermore, the urban drainage management infrastructure designed based on current climate conditions will not be able to cope under future climate conditions.

1. Introduction

Climate change and urbanization are two phenomena that are now playing an important role in the development of infrastructure in urban areas. In many developing countries around the world, urban growth has taken place in such a way that resources to meet the demand for water and sanitation suffer from excessive pressure **[1]**. According to Sårbarhetsutredningen (cited in **[2]**), urban drainage systems are closely related to weather phenomena. Drainage systems undergo problems or see increased numbers of problems when a weather event changes as a consequence of changes in the global mean temperature, resulting in urban flooding **[2]**. The Intergovernmental Panel on Climate Change **[3]** predicted a rise in temperatures with high confidence and a rise in summer monsoon precipitation with medium confidence across South Asia by the end of the 21st century (2081–2100).

The likelihood of flooding is closely associated with the changes in land use linked with urban development that leads to the removal of vegetation and soil. This transformation limits water infiltration and increases the speed and the amount of water run-off on the ground. Additionally, the alteration of natural drainage routes and increases in pressure on existing drainage systems due population growth in turn increases the likelihood of systems being overwhelmed.

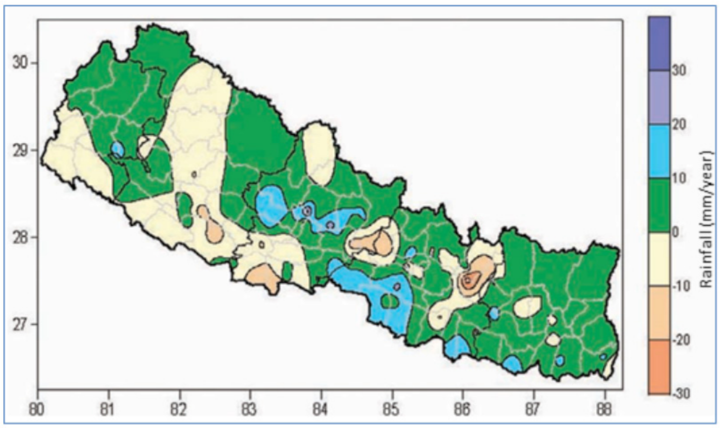


Figure 1: Monsoon rainfall trend from 1976 to 2005 (mm/year) **[4]**

In Nepal, urbanization is considered relatively new. However, there has been a low level of urbanization at a high pace. In the country, only 3.7 % of the population lived in urban areas in 1961 A.D. **[5]** and this has increased to 17.1 % and 37 % from 2011 to 2016 based on the census of 2011 A.D. **[6]**. In addition, the impact of climate change is visible in Nepal with the increasing size of glacial lakes, and rainfall variation. According to a study of Nepal's climate conducted in 1999, the temperature in Nepal is increasing and rainfall is becoming more variable **[7]**. Further, a study by Practical Action with data from 1976 to 2005 (see **Figure 1**) shows that annual rainfall has increased in the eastern, central, western and far western regions, while the mid-western region shows a decline **[4]**.

A study of precipitation recorded at 80 stations across Nepal conducted by MOPE from 1981-1998 demonstrated that the southern part of the country has experienced negative trends while the hills and mountains in the north showed positive trends **[8]**. Nevertheless, extreme events such as heavy rainfall are projected to increase slightly in the monsoon and post-monsoon seasons and to decrease slightly in the winter. In addition, heavy rain events are to change by -21% to +34 % with a multi-model mean of 7 %, showing a slight increase by the 2060's **[9]**.

Urban pluvial flooding is defined as flooding that results from rainfall-generated overland flow, before the runoff enters any watercourse or sewer or when it cannot enter because the drainage system is already full to capacity **[10]**.

Urban pluvial flooding, a product of inadequate management of the urban drainage system and strongly correlated with built-up areas and climate change, has become more evident in Nepal. Urban drainage systems, facing challenges from both increasing urbanization and the impact of extreme events, have now become a concern for urban planners and designers. It is important to assess pluvial flooding risk for future climate scenarios to increase cities' resilience to climate change. In addition, the assessment of the stress urbanization has put on the existing infrastructure also needs to be understood in order to build resilience and attain sustainable development. The quantitative delineation of the contribution of the impact of climate change and urbanization is required for better planning and adaptation.

Kathmandu, the capital of Nepal, has become the hub for different services and economic activities and is focused on tertiary occupation. The capital city, located at latitude 27.7°N and longitude 85.32°E, has a population of 2.5 million and covers an area of 899 km^2. Among the three districts of the Kathmandu valley, namely Kathmandu, Bhaktapur, and Lalitpur, Kathmandu (**Figure 2**) has the highest annual growth rate per annum, with 4.71 % in 2001 and 4.78 % in 2011 **[6]**. Urban growth with a concentrated population has increased the challenges on the infrastructure of the Kathmandu Valley, including the drainage system.

The construction of a sewerage system in the Kathmandu valley started around the 1920s, including a 55 km long brick channel to collect and dispose within a combined sewer system along with rainwater runoff in Kathmandu and Patan. **[11]**. Later, additional concrete pipes were laid as extensions or replacement of the channels. This combine sewage system works as sewage drainage and rainwater transporter during rainfall. However, recently the occurrence of urban flooding was become more frequent in Kathmandu during heavy rainfall events **[12]**.

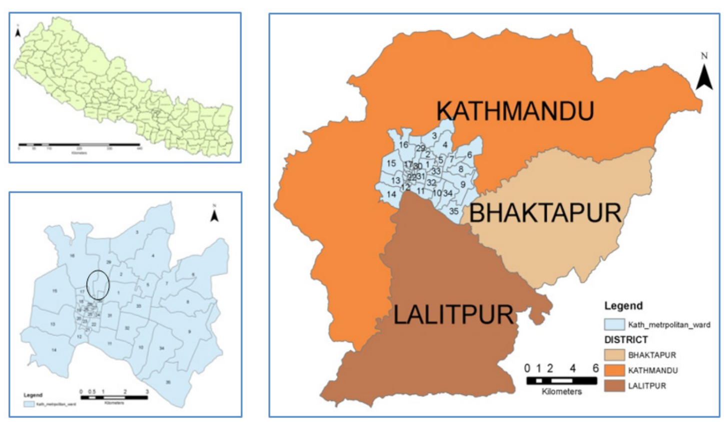


Figure 2: Location Map of Kathmandu Metropolitan city within the Kathmandu valley [13].

The present research focuses on the drainage outlet near Indraini into the Bishnumati river. The combined sewer system network covers an area of 29.96 ha or approx 0.3 km^2 with ward no. 16, ward no. 17 and ward no. 29 of Kathmandu Metropolitan city (**Figure 2**) covering the area of Chhetrapati, Dhobichaur and Paknajol.

2. Methodology

The research follows a post positivism research philosophy with a correlation method. The research has a dynamic aspect of urbanization and climate change linked with pluvial flooding which in turn is seen as a product of the performance of urban drainage. It looks into the historic performance of the urban drainage concerning pluvial flooding and its anticipation for the future.

Both qualitative and quantitative approaches were followed, for which the quantitative approach was used in the simulation while the qualitative approach was used in the validation of the results from the simulation in the field, through questionnaires.

Changes the intensity, duration and frequency or the return period are observed from current and projected data on extreme precipitation and the relationship with urban drainage is explored with the help of modeling and simulation. The representative concentration paths (RCP) that emphasize the atmospheric greenhouse gas concentration (GHG) were used and RCP 4.5 is considered for the future projection scenario. It is to be noted that there was limited access in RCP 6 projection and RCP8.5 seems to be too high for the purpose of the study. The future projection for the study is considered from 2040 to 2070 taking 30 years of data and emissions in RCP 4.5 that peak around 2040.

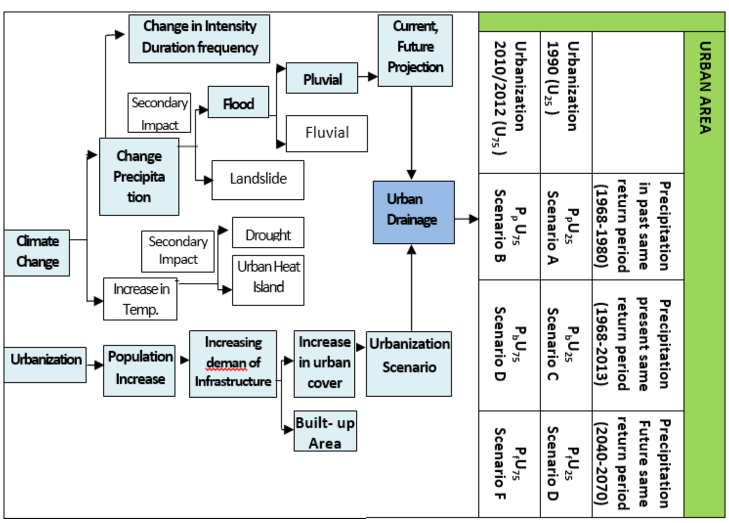


Figure 3: Theoretical framework of the research.

The theoretical framework (see **Figure 3**) developed for the research focuses on urbanization on the one hand and climate change on the other. Urbanization, with the increases in population, may cause an increase in the demand of infrastructure resulting from the increase in urban cover and built-up areas as a byproduct. Increases in urban cover and built-up areas are considered to increase the level of imperviousness, thus decreasing the ability of the land to absorb rainfall-runoff and hence, causing rapid surface runoff. Furthermore, it increases the flow volume and the frequency of high flow events. These were analyzed with different urbanization scenarios in the urban drainage model of the study area. The urbanization scenario for the drainage model was of 2010/12 and 1990.

Table 1: Theoretical framework of the research.

	Precipitation (1968-1990)	Precipitation (1968-2013)	Precipitation Future Projection (2040-2070)
Urbanization Scenario 1980	No increase in imperviousness and intensity (mm/hr) less than (1968-2013) **Scenario A**	No increase in imperviousness and intensity (mm/hr) baseline **Scenario C**	No increase in imperviousness but change in intensity (mm/hr) **Scenario E**
Urbanization Scenario 2010/12	Increase in imperviousness and change in intensity (mm/hr) **Scenario B**	Increase in imperviousness and intensity (mm/hr) baseline **Scenario D**	Increase in imperviousness and change in intensity (mm/hr) **Scenario F**

The result from the model and simulation was analyzed forming a matrix of both the phenomenon (see **Table 1**) from which six scenarios were developed. The scenarios were developed considering urban coverage from 1990 and 2010/12 and the change in precipitation for the time periods of 1968-1980, 1968-2013 and RCP4.5 (2040-2070).

The study was based on the secondary data collected from different government institutions and authorities (see **Figure 4**). The Department of Hydrology and Meteorology (DHM), the only authoritative government organization working in the field of Hydrology and Meteorology in Nepal, is the main source of precipitation data. The data from the time period of 1968-2013 from the Airport station, which is an aero synoptic station, is the basis of this study. The Kathmandu Valley Development Authority (KVDA) provided the spatial and development map of the valley. Similarly, the Department of Mines and Geology (DMG) provided the geological map and the Ministry of Urban Development (MUP) provided the drainage map of the Kathmandu valley.

The RCLIMDEX, developed by Zhang and Yang *et al.* at the Canadian Meteorological Service **[14]**, was used for the trend analysis, where only the precipitation indices were used in this study (see **Appendix 1**). The quality control function within the RCLIMDEX was used to check the errors in the input data, including missing data. The missing data was replaced by code -99.9 into an internal format that R recognizes (i.e. NA, not available).

The study used a General Circulation Model (GCM), chosen from among different climate models. The Statistical Downscaling Model (SDSM) **[15]** was used to obtain downscaled local information for the future time period by driving the relationships with GCM-derived predictors **[16]**. SDSM employs gridded data, such as the National Centre for Environmental Prediction (NCEP) to predict variable information, re-analysis of data sets (for calibration and validation) and CanESM2 GCM data for the baseline and climate scenario periods. The predictant variables describing the conditions at the site scale (i.e. precipitation observed at a station) and daily data regarding the large-scale state of the atmosphere provided by predictor variables are used. The predictand variables used in this study were precipitation data from Kathmandu Airport, station number 1030 from 1968- 2013.

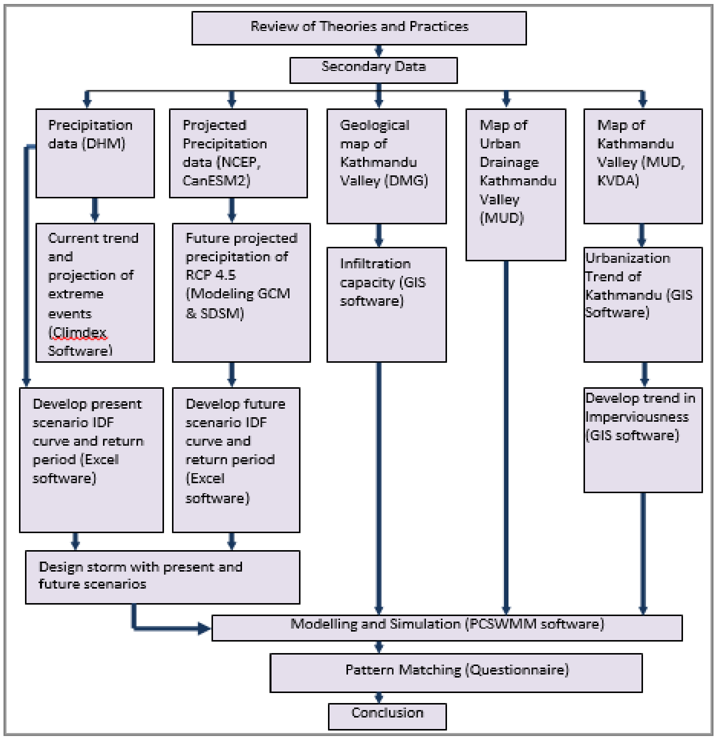


Figure 4: Flowchart of the Research Methodology.

The precipitation variable was transformed by the fourth root with a conditional process. The significance level between the predictor and the predictand was taken to be 5 %, where four predictor variables were screened. Consideration of the predictor was based on the most significant from the analysis, the high partial r and the lowest P value from the correlation matrix and scatter plot. The model was calibrated using the screened predictor variables for the period 1968 to 1995 (around 2/3rd of the total data set) and validated for the period of 1996 to 2005 (around 1/3rd of the total data set).

The bias correction approach was used to eliminate the biases from the daily time series of downscaled data [17]. The bias correction for the modeled rainfall data were performed with the equation:

$P_{deb}=P_{SCEN}$ * (long term average P_{obs})/ long term average P_{CONT}) (1)

Where, P_{deb} is the de-biased (corrected) daily time series of precipitation for the future periods, SCEN represents the scenario data downscaled by SDSM for the future, CONT represents downscaled data by SDSM for the present period, P_{scen} is the daily time series of precipitation generated by SDSM for future periods. "long term average P_{obs}" is the long term mean monthly values for observed precipitation and "long term average P_{cont}" is the long term mean monthly values for precipitation for the control simulated by SDSM.

The performance of the SDSM was evaluated based on some quantitative statistics, i.e. correlation coefficient (r), coefficient of determination (R^2), root mean square error (RMSE) [18], Nash-Sutcliffe efficiency (NSE) [19] and RMSE-observations standard deviation ratio (RSR).

$$r = \frac{\sum_{i=1}^{n}(xi-\bar{x}).(yi-\bar{y})}{\sqrt{\sum_{i=1}^{n}(xi-\bar{x})^2.\sum_{i=1}^{n}(yi-\bar{y})^2}} \quad (2)$$

$$R2 = \frac{\sum_{i=1}^{n}(yi-\bar{x})^2}{\sum_{i=1}^{n}(xi-\bar{x})^2} \quad (3)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(xi-yi)^2}{\sum_{i=1}^{n}(xi-\bar{x})^2} \quad (4)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(xi-yi)^2}{n}} \quad (5)$$

$$RSR = \frac{RMSE}{STDEVobs} = \frac{\sqrt{\sum_{i=1}^{n}(xi-yi)^2}}{\sqrt{\sum_{i=1}^{n}(xi-\bar{x})^2}} \quad (6)$$

Where, x = observed value, $\bar{x}$ = mean of observed value, y = simulated value, $\bar{y}$ = mean of simulated value, n = number of values. The CanESM2 data was used for the scenario generation and downscaling of the future data. Twenty ensembles of synthetic daily weather data series were generated for the period for precipitation to compare with the observed station data. The obtained future projection for precipitation from the SDSM was used in the development of the design rainfall with the help of rainfall intensity frequency curve (IDF curve). The development of IDF curves requires sub-daily rainfall data of longer periods, which was mostly unavailable for most stations in Nepal. The method of Talbot, Sherman, and Ishiguro is used to calculate the intensity of rainfall where there is data available as rain per hour. However, if the existing rainfall data are daily rainfall data in the field, then the method of Mononobe can be used to determine rainfall intensity **[20]**. The daily rainfall data was the most accessible for the study area; therefore, methods to derive the IDF characteristics for short duration events from the daily rainfall statistics were applied **[20]** . Therefore, the Mononobe method was used to derive the IDF characteristics for short-duration events from the daily rainfall statistics.

The Mononobe equation **[21]** was used:

I (mm/h) = R24 / 24 × (24/t) 2/3 (7)

Where,

R24 = Maximum rainfall in 24 hr (mm),
I (mm/h) = Mean rainfall intensity in a period of time t,
T = Rainfall period (hour)

The Gumbel distribution, also known as the Extreme Value Type I distribution methodology, was selected to perform the Extreme rainfall probability analysis. The type I extreme value is the most widely used probability distribution function for extreme values in hydrologic and meteorological studies for predicting flood peaks and maximum rainfalls **[22]**. The Gumbel equations are summarized below:

Frequency precipitation PT (in mm) for each duration with a specified return period T (in years) is given by the following equation:

$PT = P_{ave} + KS$ (8)

Where K is the Gumbel frequency factor given by:

$K=-\sqrt{6}/\pi\ [0.5772 + \ln [\ln [T/(T-1)]]]$ (9)

Where P_{ave} is the average of the maximum precipitation corresponding to a specific duration

In utilizing Gumbel's distribution, the arithmetic average in equation (8) is used:

$P_{ave} = 1/n\ \Sigma i = 1n\ Pi$ (10)

Where Pi is the individual extreme value of rainfall and n is the number of events or years of record

The standard deviation is calculated using equation (11) as follows:

$S = [1/(n-1)\ \Sigma i =1n\ (Pi - P_{ave})\ 2]\ 1/2$ (11)

Where S is the standard deviation of the P data. The frequency factor (K), which is a function of the return period and sample size, when multiplied by the standard deviation, gives the departure of a desired return period rainfall from the average. The rainfall intensity, IT (in mm/h) for the return period T is obtained from:

$IT = P_t / T_d$ (12)

Where T_d is the duration in hours.

The urban drainage of the study area was analyzed with PCSWMM software, aiming to limit the study to urban flooding without considering pollution and ground water. The modified Green-Ampt method was used for the infiltration. The study of Ying Ma *et. al.* **[23]** showed that the method provided satisfactory simulation results and adequately described the infiltration process in both a laboratory soil column and a field soil profile **[23]**. Dynamic Wave Routing was selected for flow routing as it accounts for Channel storage, backwater, entrance or exit losses, and flow reversal. The analyzed data obtained from the modeling and simulation was validated with pattern matching. It involves an attempt to link two patterns where one is a theoretical pattern and the other an observed or operational one. The tool used was the questionnaires from the case study. The study area has in total of approx. 600 households among which 60 questionnaires were taken according to the formula suggested by Kothari **[24]**. The sample was randomly selected and the survey tried to cover most of the major streets.

3. Results

Present and future rainfall trends

The analysis of the observed daily rainfall data from nine stations in the valley, from 1971-2011, revealed that the total annual rainfall in the Kathmandu Valley shows a slightly decreasing trend of about 5.9 mm/year (see **Figure 5**). However, compared to the large year-to-year variation of around 1,300 mm between the driest and wettest years the decreasing trend was statistically insignificant.

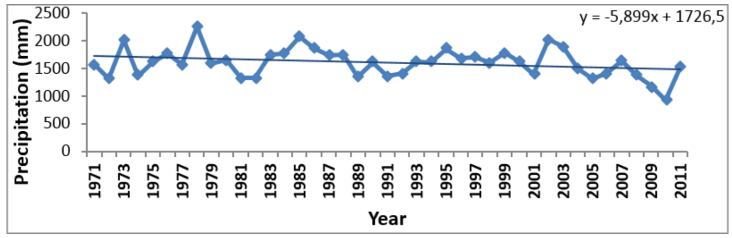


Figure 5: Trend in rainfall in the Kathmandu valley (1971-2011) [25].

The computation using Climdex software of the extreme indices for precipitation for three stations near the study area showed that the simple daily intensity index (SDII) has a positive trend at the Airport station and the Panipokhari station, but a slight negative trend at the Khumaltar station, as shown in **Table 2**. The figures for consecutive dry days (CDD) have a negative trend at the Airport station and a positive trend at the Panipokhari and Khumaltar stations. The figures for extremely wet days also decreased at all three stations.

Table 2: Extreme indices for rainfall (1971 – 2011) (based on [25])

S. No	Station	SDII (mm)	R20mm (Days)	CDD (Days)	CWD (Days)	Rx1 day (mm)	R99p (mm)	PRCPTOT (mm)
1	Airport	0.023	0.095	-0.153	0.02	-0.10	-1.39	1.32
2	Panipokhari	0.066	0.211	1.187	-0.18	-0.25	-1.83	0.34
3	Khumaltar	-0.014	-0.019	0.626	-0.05	-0.36	-0.26	-1.63

The PRCPTOT, annual total wet-day precipitation (RR>=1mm) increased at two stations but decreased at the Khumaltar station. Overall, the increase in consecutive dry days and the decrease in consecutive wet days signifies that the valley witnessed more dry days than wet days. The airport station was considered for analysis of the extreme precipitation as it is considered as a standard station. It also showed a similar trend to that of the Panipokari station, which is close to the site but lacked hourly precipitation data. Further analyzes of the airport station revealed that it had an increasing trend for rainfall of more than 20 mm to 50 mm (see **Figure 6**).

Urbanization

The study of the land cover from 1990 AD to 2010 AD showed increases in the imperviousness in both the Kathmandu Valley and the Kathmandu Metropolitan Area. Imperviousness is considered as the sum of commercial, industrial, institutional, mixed, public utilities, residential and transportation areas which contribute to the land cover. However, the increase in built-up areas in Kathmandu Metropolitan city was far more than in the valley. Based on the KVDA (Kathmandu valley development authority) data, the calculated impervious area of Kathmandu Metropolitan City (see **Figure 7**) was approx. 9.5 km^2 in 1980 AD and approx. 37.35 km^2 in 2010 AD. The imperviousness in Kathmandu Metropolitan City increased from 9.5% to 18.71 % in 1990, 37.35 % in 2000 and 73.67 % in 2010 **[13]**.

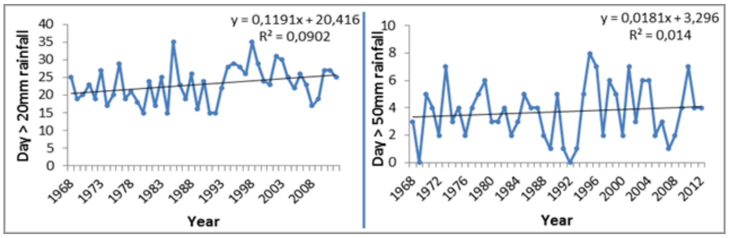


Figure 6: Trend plot of the number of days of heavy rainfall at the Airport Station (**Left: Increase in annual count of days when precipitation ≥ 20 mm at Airport Station. Right : Increase in count of days when precipitation ≥ 50 mm at Airport Station)** **[25].**

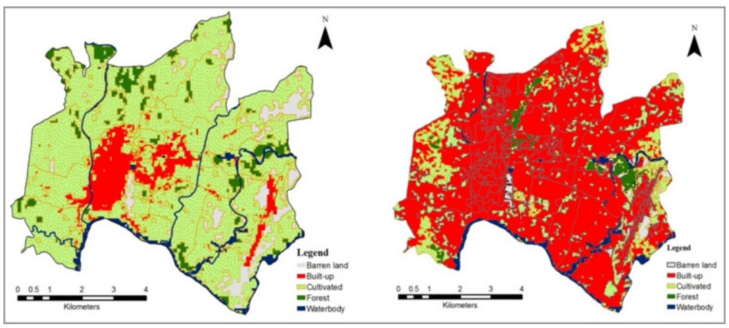


Figure 7: Urbanization of Kathmandu Metropolitan city (**Left: Land cover change in Kathmandu metropolitan city 1980. Right : Land cover change in Kathmandu metropolitan city 2010 [13].**

Climate data and future rainfall intensity

The daily precipitation data obtained from the DHM was used as the predictor in the SDSM for the future projection of the rainfall data. The validation and calibration of the simulated data was checked by comparing the observed and downscaled data for monthly sum, median, variance and mean of the daily precipitation figures. The comparison of the results (see **Figure 8**) obtained from the downscaled data and observed data for the calibration period demonstrated that the simulated precipitation was overestimated in the months from July and August. However, in contrast, the same month was under-estimated in the validation period. The simulated precipitation for the months of June and September was over-estimated in the validation period and for the months of March, October, and November as well. Nevertheless, the overall precipitation pattern was well followed, concluding that the validation and calibration of the simulated data showed satisfactory results.

The model performance evaluation showed lower RMSE and RSR values and higher NSE, R and R^2 values (see Table 3) which clearly demonstrates the higher efficiency of SDSM in simulating the daily precipitation data.

The performance of the model was validated further using the historic data of CanESM2, for which the RMSE values increased, and a similar result was found for RSR. The RMSE and RSR values ranged from 3.22 – 3.63 mm and 0.16 – 0.26 respectively (see **Table 4**). In addition, the NSE value decreased in comparison to the model generated using CanESM2 historic predictors than with NCEP/NCAR predictors ranging from 0.82 to 0.96. However, the R^2 value was constant at 0.98. The reason for the change in RMSE, RSR, NSE and R was that each model was calibrated using NCEP/NCAR predictor variables.

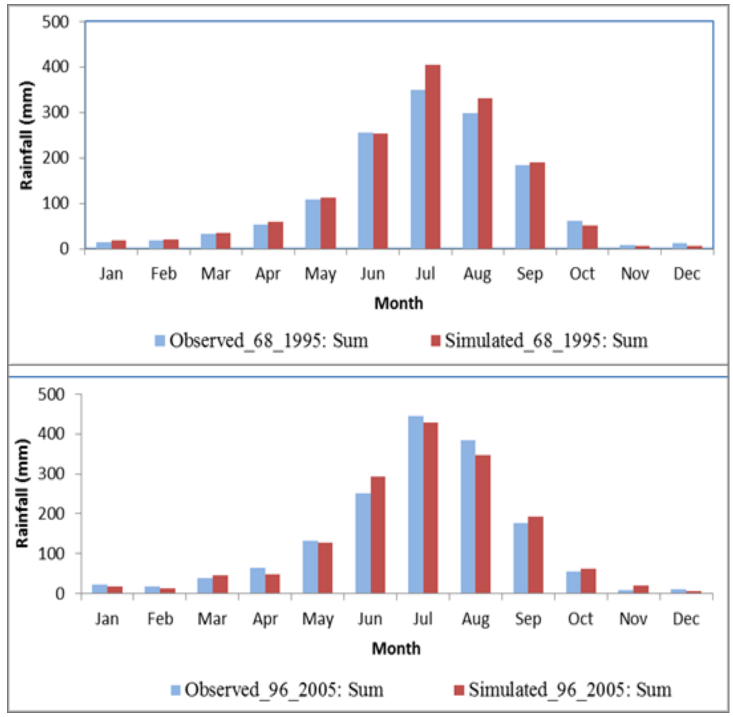


Figure 8: Comparative graphs between observed and downscaled data (**Top: Observed and Simulated (NCEP/NCAR) rainfall at Kathmandu (1030) for Calibration period 1968 to 1995. Bottom : Observed and Simulated (NCEP/NCAR) rainfall at Kathmandu (1030) for Validation period 1996 to 2005**.

Table 3: Statistical evaluation of SDSM performance for calibration and validation periods with NCEP/NCAR.

	Calibration period (1968-1995)					Validation period (1996-2005)				
Location	RMSE	NSE	RSR	R^2	R	RMSE	NSE	RSR	R^2	R
Station 1030	3.17	0.96	0.15	0.99	0.039	4.29	0.74	0.3	0.98	0.04

The performance of the SDSM was also evaluated for validation with the bias corrected precipitation, finding that the RSME and RSR decreased in comparison to the simulation and the CanEMS2 Historic data and the data after the bias correction (see **Table 5**). Similarly, NSE, and R^2 has increased after the bias correction. The results from the evaluation criteria with bias corrected precipitation data revealed that the performance of the SDSM was good in downscaling precipitation. Furthermore, the validation of the SDSM was also conducted with the observed data from 2006-2013 and simulated data from the same period. The results revealed that the R^2 value was 0.93, which shows good correlation between the simulated and observed data.

Table 4: Statistical Comparison of Observed and Downscaled Mean Monthly rainfall by Two Models during 1968 to 2005 for station 1030.

Station 1030	RMSE, mm	NSE	RSR	R^2	R	Mean	Std deviation
Observed						4.23	4.55
NCEP/NCAR	3.63	0.96	0.16	0.98	0.039	4.07	4.47
CanEMS2	3.22	0.82	0.26	0.98	0.031	4.1	4.33

Table 5: Statistical comparison of observed and downscaled and bias correction data during validation (1996 to 2005) for station 1030.

Station Airport (1030)	RMSE, mm	NSE	RSR	R^2	R
NCEP/NCAR	4.2	0.74	0.3	0.98	0.037
NCEP/NCAR bias corrected	2.5	0.97	0.15	0.99	0.03
CanEMS2	7.6	0.86	0.32	0.97	0.04
CanEMS2 bias corrected	6.7	0.88	0.26	0.99	0.03

The calibrated model was used to generate future rainfall data for Kathmandu representing scenario RCP 4.5. The bias correction values were then applied to the daily future precipitation values, which were then used to develop the future rainfall Intensity Duration Frequency curve (see **Figure 9**).

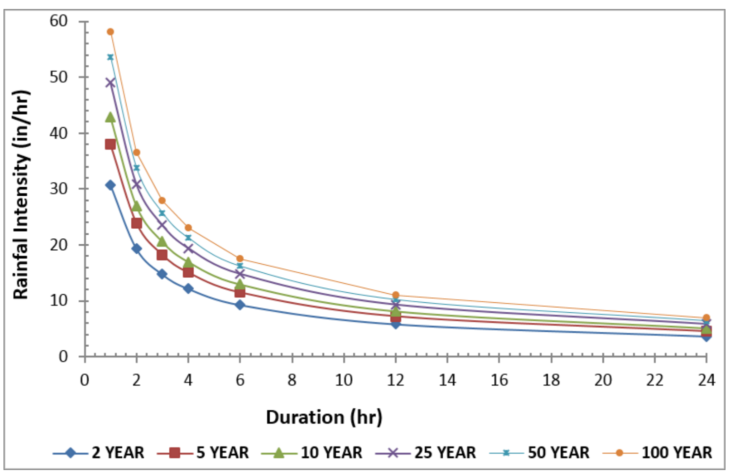


Figure 9: Rainfall IDF curves for scenario RCP 4.5 (2040-2070) Kathmandu Airport station.

The comparison between the IDF curve for the current climate (see **Appendix 2**) and the future climate (see **Figure 9**), i.e. 1968-2013 and 2040-2070, respectively, showed that there is an increase in the frequency of higher intensity rainfall under this climate change scenario. The comparison of the percentage change in rainfall intensity between 1968-2013 and 2040-2070 (see **Table 6**) showed that there would be an average increase of 12.58 %, ranging from 15.39 % to 9.77 %, in extreme rainfall intensities. It can be noted that the change in intensity in the frequency of extreme events was more in a short return period (2 years) than in the longer return period (50 years).

Table 6: Percentage change in intensity (1968-2013) & RCP4.5 (2040-2070)

Percentage change in intensity (1968-2013) and RCP_4.5 (2040-2070)						
Duration	Return Period (T)					
(Hours)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
1	15.39	13.03	11.94	10.89	10.28	9.77
2	15.40	13.02	11.94	10.89	10.28	9.77
5	15.38	13.02	11.93	10.88	10.28	9.78
10	15.40	13.06	11.90	10.91	10.27	9.74
15	15.43	12.94	12.02	10.74	10.18	9.63
24	15.51	13.16	11.92	10.83	10.32	9.75

Impact of present and future rainfall on Urban drainage

The percentage change in intensity was used to assess urban drainage in the study area where six scenarios were developed based on imperviousness percentage (U_{25}, U_{75}) and different time series (1968-1980; Pp, 1968-2013; Pb, 2040-2070; Pf). Four parameters were selected for analysis of the impact: the flooding amount, nodes flooded (see **Appendix 3**), node surcharge, and conduit surcharge. The results of the four parameters in the same return period with different imperviousness percentages (U_{25}, U_{75}) and different time series were compared as scenario A and scenario B, scenario C and scenario D, and scenario E and scenario F.

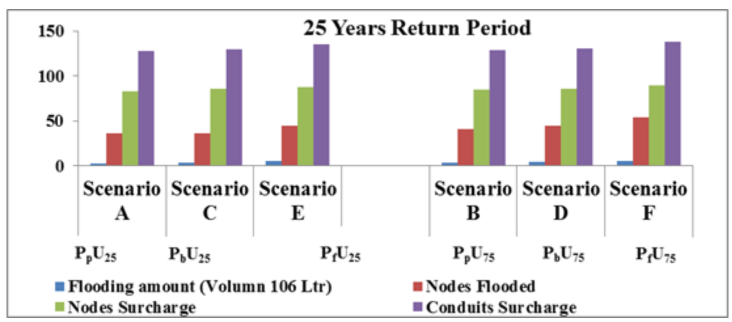


Figure 10: Comparing parameters for the 25 year return period with changes in time series.

A visual inspection of the comparison of the scenarios (see **Figure 10**) at different return periods clearly shows the fact that changes in urbanization increase the four parameters (see **Appendix 4**). Furthermore, the comparison of the scenarios based on time series (Pp, Pb, Pf) suggests that the parameters will have higher values under future climate change conditions.

The comparison of the different scenarios was also performed to identify the impact of the parameters (**Appendix 5**). Considering the time series Pb (1968-2013) and change in urbanization (25 % imperviousness (U_{25}) to 75 % imperviousness (U_{75})), i.e. scenario CD (see **Table 7**), the percentage changes in the parameters, namely flood amount, nodes flooded, node surcharge, and conduits surcharge, were 14.92 %, 21.62 %, 1.16 %, 0.77 %, respectively. Considering the time series Pf (RCP 4.5,2040-2070) and change in urbanization (25 %

imperviousness (U_{25}) to 75 % imperviousness (U_{75})), i.e. scenario EF, the changes in the parameters were 18.1 %, 24.32 %, 2.33 % and 2.31 % increases in flood amount, nodes flooded, node surcharge, and conduits surcharge, respectively.

Table 7: Comparing the parameters for four scenarios (C, D, E, F) in the 25 year return period with baseline P_bU_{25}.

S.No.	Description	Scenario C	Scenario E	Scenario CE
		P_bU_{25}	P_fU_{25}	
1	Flooding amount (Volume 10^6 Ltr)	3.65	5	37.1
2	Nodes Flooded	37	45	21.62
3	Nodes Surcharged	86	88	2.33
4	Conduits Surcharged	130	135	3.85
		Scenario D	Scenario F	Scenario DF
		P_bU_{75}	P_fU_{75}	
1	Flooding amount (Volume 10^6 Ltr)	4.19	5.7	40.28
2	Nodes Flooded	45	54	24.32
3	Nodes Surcharged	87	90	3.49
4	Conduits Surcharged	131	138	5.38
	Compare difference with P_bU_{25} baseline	Scenario CD	Scenario EF	Scenario CF
1	Flooding amount (Volume 10^6 Ltr)	14.92	18.1	55.2
2	Nodes Flooded	21.62	24.32	45.95
3	Nodes Surcharged	1.16	2.33	4.65
4	Conduits Surcharged	0.77	2.31	6.15

Similarly, considering 25 % imperviousness (U_{25}) and comparing different timelines in the time series P_b (1968-2013) and Pf (RCP 4.5,2040-2070), i.e. scenario CE (**Table 7**), it was found that there were increases of 37.1 % in flood amount, 21.62 % in nodes flooded, 2.33% in node surcharge, and 3.85 % in conduit surcharge. Considering 75% imperviousness (U75) and comparing different timelines in the time series P_b (1968-2013) and Pf (RCP 4.5, 2040-2070), i.e. scenario DF, the increase was 40.28 % for flood amount, 24.32 % for nodes flooded, 3.49 % for node surcharge and 5.38% for conduit surcharge. The result reveals that the percentage change in the four parameters increased from time series Pp, Pb, Pf.

The overall comparison of the results of the six scenarios for the 25 year return period showed that the change in climate represented by the time series RCP 4.5, 2040-2070 had a major impact, as seen in scenario CE and scenario DF, in the increases in the four parameters.

The analysis of the four parameters for different time series (2 year, 10 year, 25 year and 50 year return periods) revealed that under the climate change scenario the four parameters increase for all return periods (see **Figure 11**). In addition, the change in urban cover analyzed in all three time series, Pp, Pb & Pf, showed a gradual increase in the four parameters. The future climate scenario has the highest increase in values in both the 25 % and 75 % urbanization scenarios. Nevertheless, it was clear that the future climate change with maximum urbanization has the maximum value among all the scenarios.

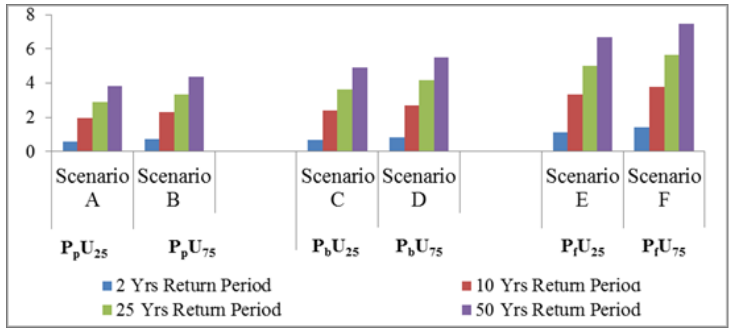


Figure 11: Comparing parameters for the 25 year return period with changes in time series.

The validation of the result was performed on the site where a number of questionnaires were conducted. The general perception of the people was that the amount of rainfall and heavy rainfall over a short time period had decreased. Flooding was usually considered as the product of clogging of the drainage system which seems to be true in some areas where the model did not show flooding in cases of extreme events.

A group comprising 69.6 % males and 30.4 % females was surveyed, with approximately 76 % below the age of 40 years and 24 % above 40. Around 23.9 % of the respondents had lived in the area for more than 40 years while 45.7 % had lived there for more than 20 years, 26.1 % for more than 10 years and 19.6 % for 5 years. It can be seen that almost 82.61 % of the respondents felt there had been a change in annual rainfall patterns (see **Figure 12**) while 4.35 % felt no change had occurred and 13.04 % did not know. Around 84.8 % of the people felt the rainfall amount had decreased, with the remaining having no thought or idea regarding the issue. Most of them (89.13 %) felt heavy intensity rainfall events had increased, but that continuous 2-3 day rainfall events were similar to the past (see **Figure 12**).

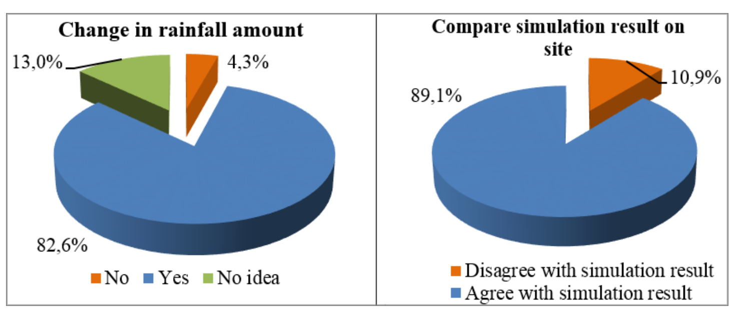


Figure 12: Comparing parameters for the 25 year return period with changes in time series.

The simulation of the drainage system for the 2 year return period from 1968 to 2013 was matched with the questionnaire answers. It showed that there were some interesting issues. One example was that four of the respondents replied that water had entered their building in their area, while the simulation showed no flooding. The reason behind this was that the houses were below the road level. These houses were usually the oldest houses in the settlement.

It is noteworthy that the performance of other neighboring networks was also represented in the answers from the respondents. Particularly in the case of Gangalalmarg, where the people experienced flooding but the model simulation showed no flooding. Therefore, leaving these respondents as outliers, the views of the remaining 90 % of the respondents matched the simulation results. Around 53.3 % of the people thought blocked drainage was the problem for flooding while the remaining 40 % and 6.7 % thought change in road levels and heavy rainfall were the reason, respectively.

4. Discussion

Urbanization, seen as the combination of densification or the increase in density of the population and building units, leads to transformation of space. An urban area created with densification has the presence of urban services (paved street, electricity, light, sewerage) and a concentrated nonagricultural population. The urban services of the area, such as roads, roofs, parking lots, etc., replace the permeable soil with impermeable surfaces that store little water. This in turn decreases the ability of the land to absorb rainfall-runoff, reduces infiltration of water into the ground, and accelerates runoff to ditches and drainage systems, overwhelming the drainage system and resulting in urban flooding. In highly urbanized areas, over half of rainfall becomes surface runoff, and deep infiltration is only a small fraction of the natural situation **[26]**.

The urbanization of the Kathmandu Metropolitan City by 1990, with around a 25 % area of imperviousness (considered as the sum of commercial, industrial, institutional, mixed, public utilities, residential, and transportation areas) when compared with the imperviousness of 75 % in 2010, showed that the latter places a high degree of pressure on the drainage system. The increase in land cover has a dual effect of increasing run-off and decreasing the infiltration rate on the one hand and decreasing the peak time on the other. Hence, increasing the four parameters of flooding amount, number of conduits surcharged, and number of nodes flooded and surcharged, as revealed in this study.

Extreme events, which leads to changes in the frequency, intensity, spatial extent, duration, and timing of a climate event, have also put pressure on drainage systems. The worldwide impact of climate change on rainfall extremes and urban drainage leads to increases in rainfall intensity on small urban hydrology scales range from 10 % to 60 % from control periods in the recent past (typically 1961–1990) up to 2100 **[27]**, **[28]**.
The intensity of extreme climate events in the study area showed an increasing trend, where rainfall of 20 mm to 50 mm per day had an incremental trend. The study showed that there would be an average increase of 12.73 %, ranging from 15.58 % to 9.89 %, in extreme rainfall intensities when the rainfall intensity of the baseline for 1968-2013 and time series RCP 4.5, 2040-2070 were compared. The increase in rainfall intensity showed higher volumes of rainfall over short time periods, directly linking it to an increase in runoff and thus overwhelming the drainage system and resulting in urban flooding. The comparison of the four parameters in different time series in the study area showed similar results, where the percentage of flood volume, conduit surcharge and nodes flooded and surcharged increased under the future climate scenario.

However, urban areas face the adverse effect of both climate change and urbanization combined. The quantitative representation of the comparison of both phenomena helped in addressing the dilemma of the amount of contribution from each one. This was performed with a pairwise cross comparison i.e. scenario CD and scenario EF with scenario CE and scenario DF for different return periods. The comparison revealed that the flooding would be more intense (increases in flood volume, conduits surcharged, nodes flooded and surcharged) with the future climate change scenario when compared to the impact on parameters due to climate change and urbanization. It points out that the volume of water, number of conduits surcharges and number of nodes surcharges and flooded were greater in scenario CE and scenario CF, compared to scenario CD and scenario EF. Integrating both the phenomenon in scenario CF, it is clearly seen that impact on urban drainage was maximum with the highest flood volume of 55.2 %, 45.95 % node flooded, 4.65 % nodes surcharged, and 6.15 % conduits surcharged. This therefore shows that the urban drainage management infrastructure designed based on current climate conditions will not be able to cope with the increased storm depth under future climate conditions.

5. Conclusion

The findings of this research have quantified the delineation of urbanization and climate change in pluvial flooding. The transformation of space due to urbanization results in the replacement of permeable soil with impermeable surfaces (such as roads, roofs, parking lots, and sidewalks), thus decreasing the ability of the land to absorb rainwater. In addition, it reduces infiltration of water into the ground, causing rapid surface run-off. The increase in the volume of the surface run-off overwhelms the drainage system. The pressure on the drainage system with run-off water going beyond its capacity will be more frequent with increased urbanization, leading to increases in the frequency of flooding.

Furthermore, the changing climate resulting in increased frequency and intensity of rainfall leads to rainfall extremes. Heavy rainfall over a short duration in urbanized area with high impermeability will further decrease the peak time, overwhelming the drainage system and causing pluvial flooding. The flooding will occur in a number of areas inside the urban area, as a higher number of nodes will be flooded with the increase in the flooding amount. The flooding will have a direct impact on the livelihood of the urban population, restricting transportation, and damaging buildings and infrastructure.

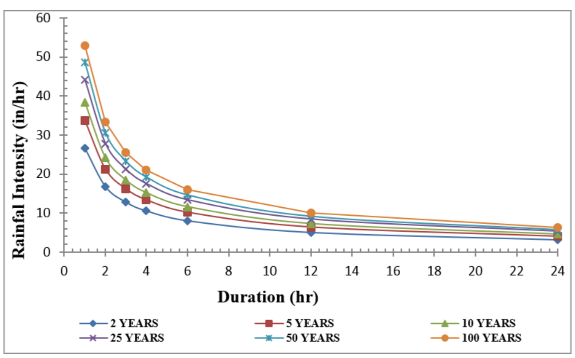
This study has revealed the relationship between urbanization (impervious areas), climate change, and drainage. The findings suggest the need to increase the imperviousness in high-urbanized areas with the use of soft landscape instead of hard landscape and to maintain the existing imperviousness in low urbanized area. Incrementing drainage size may be one of the measures to reduce flooding. Nevertheless, cost is be a primary factor, especially in a developing country like Nepal. Thus, planning for existing and new up-coming cities needs to consider future urbanization as well as future climate change conditions.

Appendixes

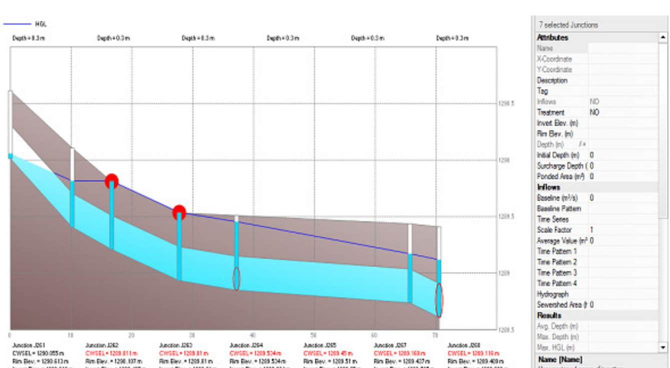
Appendix 1: Precipitation indices considered for the trend analysis [14].

ID	Index Name	Description	Unit
SDII	Simple Daily Intensity Index	Annual total precipitation divided by the number of wet days (defined as PRCP>=1.0mm) in the year	mm/day
R20	Number of very heavy precipitation days	Annual count of days when PRCP>=20mm	Days
CDD	Consecutive dry days	Maximum number of consecutive days with daily rainfall <1 mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days with daily rainfall >=1 mm	Days
Rx1 day	One day Precipitation	Maximum 1 day precipitation amount	mm
R99p	Extremely Wet days	Annual total precipitation when RR>99th percentile	mm
PRCPTOT	Annual total precipitation	Annual total precipitation in wet days when daily rainfall >=1 mm	mm

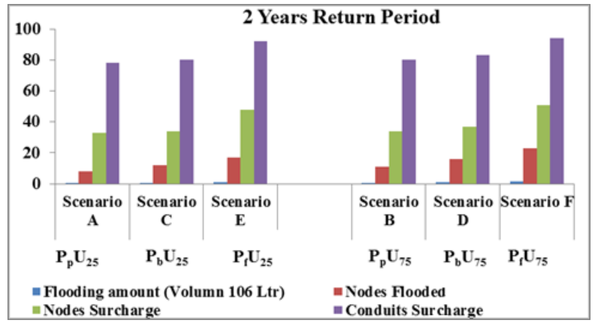
Appendix 2: Rainfall IDF curves (1968-2013), Kathmandu Airport station 1030.



Appendix 3: Conduit profile with nodes flooded.



Appendix 4: Comparison of parameters for 2 year return period with change in time series.



Appendix 5: Comparison of parameters of four scenarios (A, B, C, D) for 25 year return period with baseline P_bU_{25}

S.No.	Description	Scenario A	Scenario C	Scenario AC
		P_pU_{25}	P_bU_{25}	
1	Flooding amount (Volume 10^6 Ltr)	2.91	3.65	20.15
2	Nodes Flooded	36	37	2.7
3	Nodes Surcharged	83	86	3.49
4	Conduits Surcharged	128	130	1.54
		Scenario B	Scenario D	Scenario BD
		P_pU_{75}	P_bU_{75}	
1	Flooding amount (Volume 10^6Ltr)	3.34	4.19	23.32
2	Nodes Flooded	41	45	10.81
3	Nodes Surcharged	85	87	2.33
4	Conduits Surcharged	129	131	1.54
	Compare difference with P_bU_{25} baseline	Scenario AB	Scenario CD	Scenario AD
1	Flooding amount (Volume 10^6Ltr)	11.76	14.92	35.07
2	Nodes Flooded	13.51	21.62	24.32
3	Nodes Surcharged	2.33	1.16	4.65
4	Conduits Surcharged	0.77	0.77	2.31

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