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Characterization of Hydro-meteorological, Morphometric and Anthropogenic Drivers of Inundation and their Interrelationship in a Hilly Watershed of Kathmandu Valley in Nepal

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Abstract
Kathmandu valley, an abode to more than 2.5 million people has experienced a substantial increase in urbanization. More land surfaces are modifying into built-up areas, causing the conversion of pervious surfaces to impervious surfaces. The water storage capacity of the basin is decreasing while surface runoff amount and its rate is increasing. In addition, interference of human activities on river environment is contributing the change in flow regime of rivers. The result is frequent flooding in monsoon in most of the rivers traversing the valley. Thus, study of impacts of urbanization on flooding is beneficial for urban planning and disaster management in the valley. This research analyzed the decadal trends in precipitation, river discharge, and land use/cover data over the course of three decades with an objective to investigate the possible inundation drivers. Similarly, morphometric analysis was also carried out to analyze the natural factors affecting the inundation. The annual, monsoon, non-monsoon, and maximum values of rainfall in the catchment showed no statistically significant increasing decadal trend for confidence level of 0.09 , according to the trend analysis using non-parametric Mann-kendall test and Sen's slope analysis. During the last three decades, the built-up area showed continuous increase of 29.61%, 30.87% and 24.53% accordingly, during 1990-2000, 2000-2010 and 2010-2020, mostly compensated by the decline in the agricultural areas. Even though urbanization increased, a decreasing or statistically insignificant decadal discharge trend was detected. Morphometric analysis showed greater influence of Balkhu and Godawari sub-basin on probable flood.

Keywords
Decadal trend, inundation drivers, land use/cover, Mann-kendall test, morphometric analysis, Sen's slope

1. Introduction

Population in Kathmandu valley increased by 53% (i.e., an average of 5.3% per year) in the last decade (2001-2010) [1] .The population growth rate of Nepal during the same period though, was only 1.4%. This growth of population and expansion of built-up areas in the Kathmandu valley has caused substantial land use/cover changes with significant expansion of impervious areas [1]. The change in land use and land cover associated with urbanization influence the hydrological processes by adjusting the distribution of rainwater through the vegetation and soil into interception, infiltration, evaporation, surface runoff and groundwater recharge [2]. Storm runoff and peak flow rise with urban expansion as the amount of impermeable surface increases, according to White and Greer [3]. According to the studies involving most of the hydrological models, as a watershed becomes more urbanized, floods caused by a given storm are expected to grow larger and peak faster [4]. This study is an attempt to confirm the increasing flows predicted by theory to occur concurrently in an urbanizing watershed. Thus, this study entails quantifying changes in land use/cover, as well as trend analysis of discharge data to verify whether discharge is increasing as urbanization expands, leading to the inundation. In addition, trend analysis of precipitation data is performed to determine whether it is increasing and thus contributing to the likely increase in discharge.

The land surface of Kathmandu valley is transforming significantly in recent years, with 3.94% urban growth rate between 2010 and 2014 [5].Few land use change studies have been conducted in Kathmandu valley. Haack and Rafter[6] did land use/cover change analysis between 1978 and 2000 using GIS tools and concluded the urban growth to be 450% in these years. Similarly, analysis on land use change patterns of Kathmandu valley between time of 1967 and 2000 carried out by Thapa and Murayama [7] concluded the growth particularly increased after 1980s. An analysis of flood events of the decades shows that the number of flood events has increased with 0.87 events per year. An extreme event occurred in July 2002 when 26 flood events occurred in the valley taking lives of 28 people, leaving 283 affected and property losses of 54,455,000 Nepalese Rupees. Areas like Baghauda, Baneshwor, Samakhusi, Dhobikhola, and Kirtipur Municipality are situated along the river basin and area most affected by flood frequently [1].

The major objective of the study is to characterize different driving variables influencing inundation and hence analyze their interrelationship in the Kathmandu Valley. The increasing inundation problem could be caused by increased flow in the valley's rivers as a result of increased rainfall, or changing land use/cover could be a contributing factor. Therefore, the study's goal is to detect trends in hydro-meteorological data and land use/cover, as well as any relationships between these trends. Similarly, several morphological features influence the amount of peak flow and overall flow distribution that any river receives. A morphometric analysis of the watershed is also performed in order to determine the natural processes that contribute to the inundation of the valley. The study does not analyze inundation quantitatively, however assesses the trends in key drivers of inundation.

2. Study Area

Kathmandu valley, the administrative center of Nepal is abode to the capital city, Kathmandu. Surrounded by the hills of Mahabharat Range forming a bowl-shaped valley floor, Kathmandu valley lies between latitude 27°32'13" and 27°49'10" N and longitude 85°11'31" and 85°31'38" E. Major streams like Bagmati, Bishnumati, Dhobikhola, Nakhu, Balkhu, Godawari, Hanumante, Manohara, Kodkhu and Manamati drains the valley.

The study focuses on the watershed of Bagmati River at the Khokana station with drainage area of approximately 603 sq.km. The elevation within the watershed ranges from maximum of 2702 m to a minimum of 1236 m above sea level. Characterized by warm and temperate climate in semi-tropics, the valley gets 80% of its 1755mm average annual rainfall during monsoon[8]. The average yearly maximum and minimum temperature of the valley is 24.2°c and 12.4°c respectively while the average temperature is 18.2°c [9]. Figure 1 shows the location of study area with the hydro-meteorological stations used in the study.

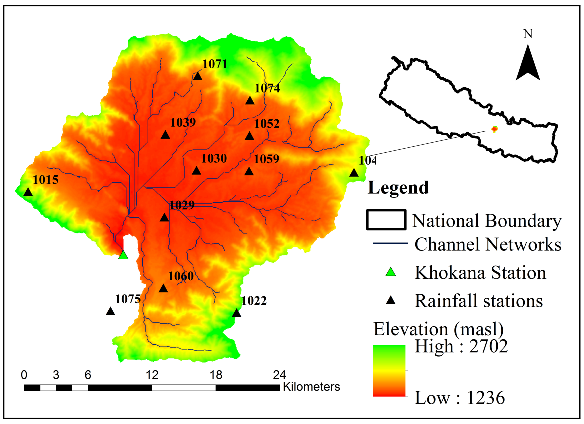

Figure 1: Study Area and Hydro-meteorological Stations used

3. Materials and Methods

3.1 Data and Sources

3.1.1 Hydro-Meteorological Data and Land Use/Cover Data

Daily precipitation records of 12 meteorological stations and daily average discharge and maximum daily instantaneous discharge of Khokana (DHM Station index no. 550.05) hydrological station (Figure 1) from Department of Hydrology and Meteorology (DHM) are the primary data used for the study. Thiessen polygon method was then applied to get the average rainfall for the watershed.

Land use/cover map for year 1990, 2000 and 2010 (Figure 3) were collected from ICIMOD, International center for Integrated Mountain Development (`https://www.icimod.org/`) and land use/cover map for the year 2020 was prepared in ArcGIS using Interactive Supervised Classification Method from Landsat image from satellite sensor, Landsat 8-Operational Land Imager of 22nd January, 2020 and 28th January, 2020. Three major land use/cover classes were considered viz. forest, agriculture and built-up area.

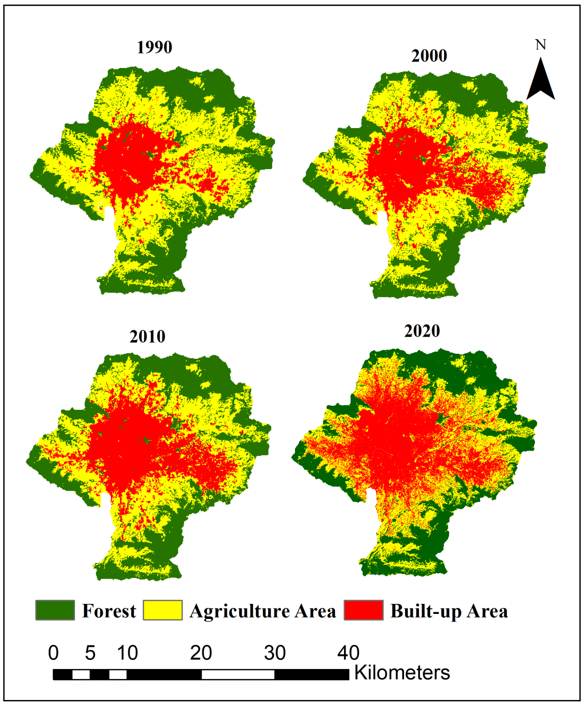

Figure 2: Land Use Maps of year 1990, 2000, 2010 (ICIMOD) and 2020(prepared by Interactive Supervised Classification Method)

3.1.2 Geographical data and remote sensing data

A 30m*30m Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) from USGS site (`https://www.usgs.gov/`) was used for watershed delineation and for morphometric analysis of flow contributing sub-catchments. Landsat image from satellite sensor, Landsat 8-Operational Land Imager of 22nd January, 2020 and 28th January, 2020 was used for mapping the land use/ land cover of the catchment for the year 2020.

3.2 Methodology

3.2.1 Trend analysis

To identify the precipitation and discharge trend over three decades i.e., 1990-1999, 2000-2009 and 2010-2020 , Mann-Kendall Trend Test [10, 11] was applied and quantification of that trends was carried out using Sen's slope [12]. The Mann-Kendall Trend test is a rank-based non-parametric method to detect statistically significant trends in various climatic variables [10]. The positive Mann-Kendall z value shows increasing trend whereas negative value shows decreasing trend. For confidence level of 0.05, if $|z| > 1.96$, statistically significant trend exists in the hydrologic time series else there is no trend.

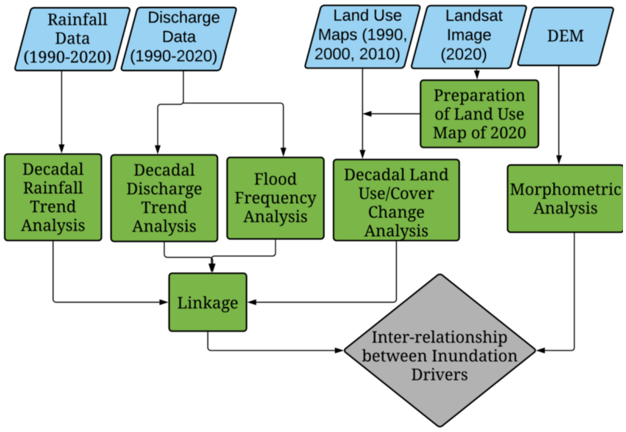

Figure 3: Flowchart of methodology

3.2.2 Flood Frequency Analysis

Flood frequency analysis was carried out to determine the different return period floods using discharge data of three decades separately, the result of which acted as a support to discharge trend analysis. Frequency distribution functions used for prediction of extreme flood events for different return period were:

1. Gumbel's extreme value distribution
2. Log-Pearson type III distribution

3.2.3 Land Use/Cover Change Analysis

Clarklabs IDRISI TerrSet Land Change Modeler (`https://clarklabs.org/terrset/`) was used to estimate the conversion of pervious surfaces to impervious built-up areas over three-decades period 1990 to 2020.

3.2.4 Morphometric Analysis

Aside from rising built-up areas and rainfall amounts, several natural factors play a key role in determining the volume of flow and peak time during any storm. In order to identify the probable natural factors leading the inundation in the valley, the whole watershed was delineated into 10 sub-basins (Figure 4) on the basis of the rivers draining the study area.

Then, morphometric parameters of 10 drainage networks originating from different sources were evaluated in order to assess the influence of sub-basins to flooding on the main channel. Drainage networks for the sub-basins were generated from

30m*30m resolution digital elevation model (DEM) using ArcGIS. These parameters were utilized to evaluate the impact of the sub-basins on the main channel with regard to flooding .Assessment of morphometric parameters require the investigation of different drainage parameters like stream order of various streams, measurement of basin area and perimeter, flow length of drainage channels, drainage density, stream frequency, bifurcation ratio, circulatory ratio, basin relief and time of concentration [13]. Geomorphic principles can be applied to identify the relationship between basin morphometry and stream flooding [14].

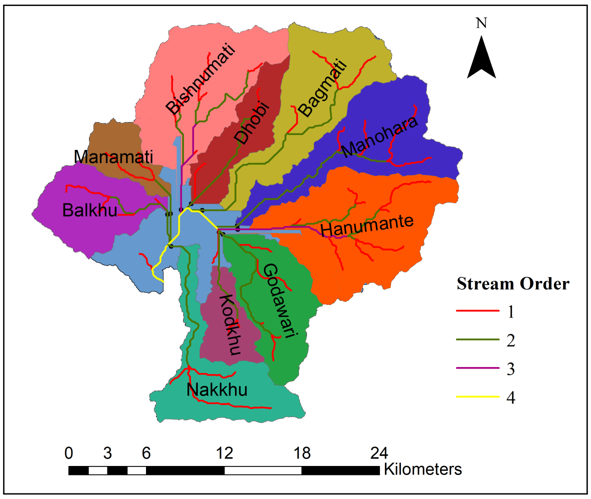

Figure 4: Sub-basins with Stream Order of Drainage Networks

4. Results and Discussion

4.1 Hydro-meteorological Trends

Total annual rainfall, total monsoon rainfall, and annual maximum rainfall for three time slices i.e., 1990-1999, 2000-2009 and 2010-2020 were analyzed with non-parametric Mann-Kendall test and Sen's slope to determine any probable trend over three decades. Similar analysis was carried out for annual average discharge, average monsoon discharge, average non-monsoon discharge and annual maximum instantaneous discharge. Decadal trend analysis was carried out for average rainfall values of selected 12 rain gauge stations for overall watershed and also for discharge value of one hydrological station at Khokana.

Total annual rainfall, monsoon rainfall, non-monsoon rainfall and maximum rainfall for the watershed at Khokana station were calculated using thiessen polygon method from daily rainfall data of 12 selected rain gauge stations. For whole watershed at Khokana station, statistically significant decreasing trend was observed on annual rainfall in decade 2000-2009 and significant increasing trend on maximum rainfall in decade 1990-1999, with all other rainfall data in all decades showing no statistically significant trend (Figure5).

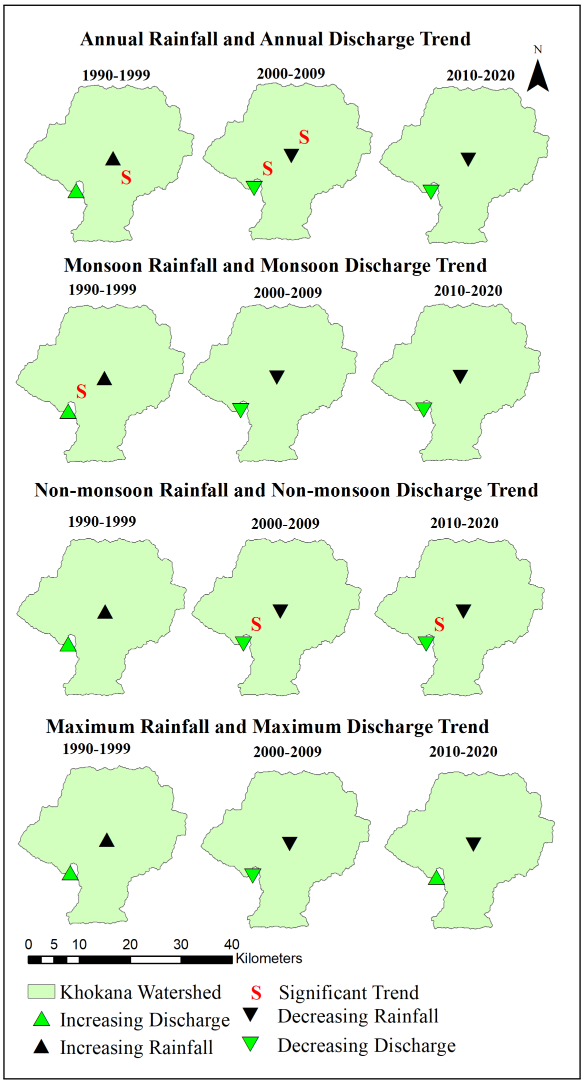

Figure 5: Decadal Rainfall and Discharge Trend in the Kathmandu Valley Watershed

The results from rainfall data analysis will have the direct impact on discharge data. So, trend analysis of discharge data from same time period was carried out for verifying that impact. For decadal trend analysis of discharge data, average annual discharge, average monsoon discharge, average non-monsoon discharge and annual peak discharge were calculated from the discharge data of the hydrological station, Khokana station 550.05. The annual average discharge had significant increasing and decreasing trend in first two decades respectively which held no any significant trend in third decade; the average monsoon discharge increased significantly in 1990-1999 and the trend was insignificant for next two decades; average non-monsoon discharge significantly decreased in 2000-2009 and 2010-2020 and maximum discharge had no statistically significant trend for all three decades as shown in Figure 5.

Thus, in the recent two decades, i.e., 2000-2009 and 2010-2020, when rainfall and discharge trends were studied for annual, monsoon, non-monsoon, and maximum values, they showed either a decreasing or statistically insignificant trend.

In order to support the results from trend analysis of discharge, flow duration curves were constructed using flow data of three decades separately as shown in Figure 7 and it was deduced that, for Khokana station, discharge value up to 50% exceedance was decreasing from first decade to the last and beyond 50% exceedance, discharge value was increasing from first to second decade and decreasing from second to third decade. This indicated the low flow increased in 2000-2009 and decreased in 2010-2020 whereas peak flow was decreasing from 1990 till 2020.

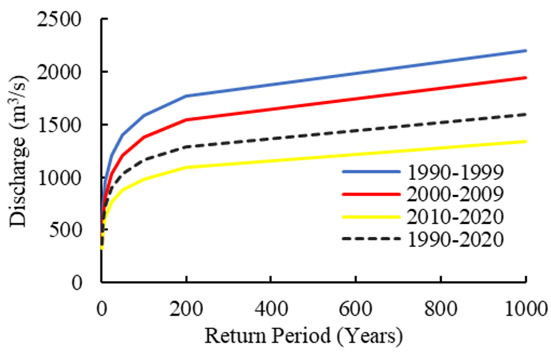

Figure 6: Flood Discharge Values for Different Return Periods using Observed Discharge Data of Different Decades

Additionally, flood frequency analysis was carried out for different return periods using different methods like Gumbel and Log Pearson type III manually and also by software called Hydrognomon `(http://hydrognomon.org/)`. The flood discharge values, nearest to the result from previous paper [15] were taken as the final correct flood discharge values as illustrated in Figure 6. The flood frequency analysis used the maximum instantaneous discharge data of 1990-1999, 2000-2009 and 2010-2020 and the change in magnitude of flood discharge corresponding to same return period was assessed. The flow duration curve and high flood analysis also revealed the decadal decrease in high flood magnitude, supporting the results from decadal discharge trend analysis.

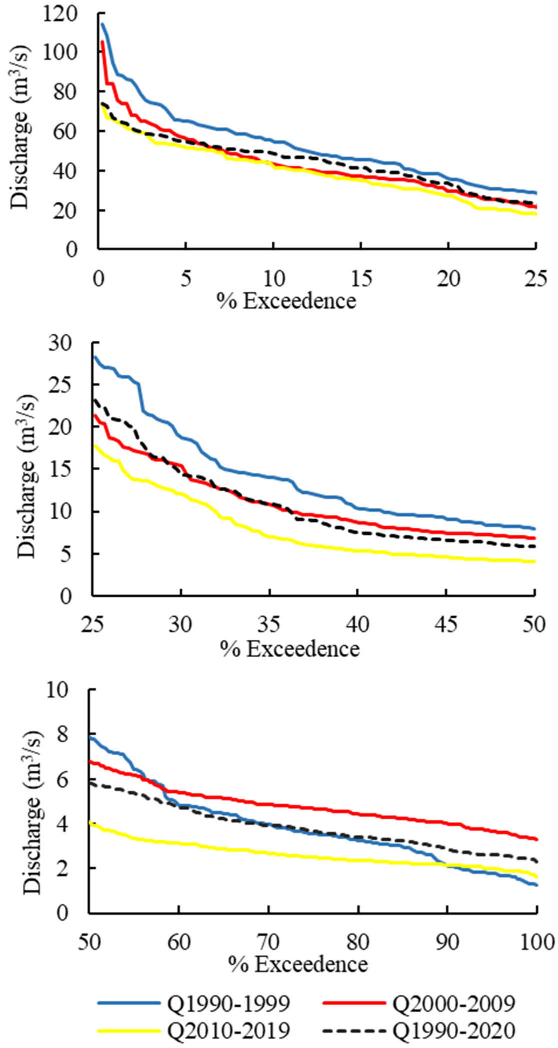

Figure 7: Flow Duration Curve of Khokana Station

4.2 Land Use/Cover Change Trend

Increasing impermeability as a result of urbanization would result in more surface runoff in general. Therefore, land use/cover change was also analyzed to quantify the increasing impermeable areas within the study area in order to support the results from discharge trend analysis. Since results of discharge trend analysis did not justify the prevailing inundation problem in the valley, land use/cover change analysis would provide insights on whether urbanization is the reason behind the inundation or not.Here, the area covered in km are graphically represented in Figure 8 which depicted a growth in the built-up area from 101 to 213 sq.km. Similarly, the changes in land use/cover class considered are graphically expressed in Figure 9 which shows that from 1990 to 2020, forest and agriculture area witnessed negative changes, whereas built-up areas experienced positive changes. As seen in the Figure 10 and 11, the decrease in agricultural area is a major contributor to the growing built-up area.

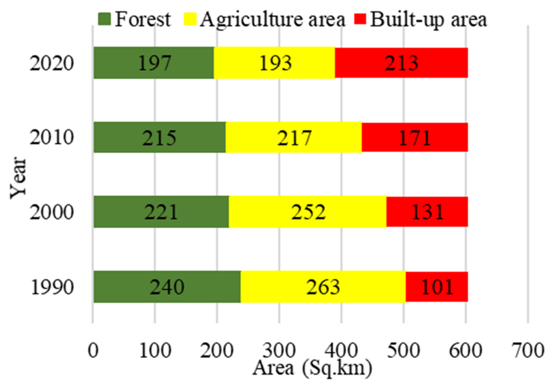

Figure 8: Area Covered by Different Land Use Types in Different Years

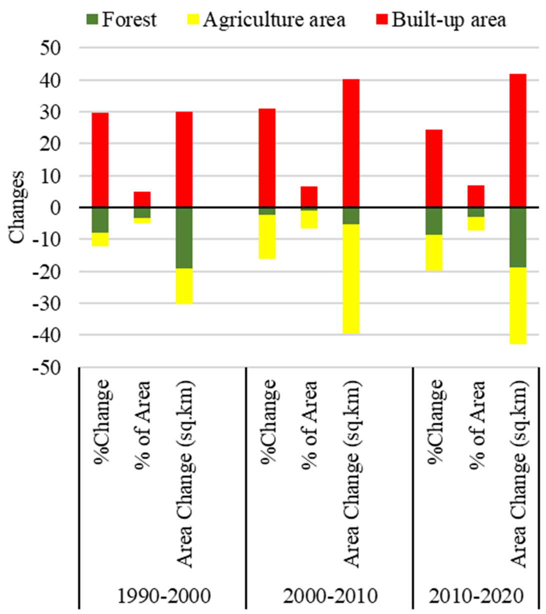

Figure 9: Changes in Different Land Use Types in Three Decades

According to land use/cover change study, the watershed experienced a faster rate of conversion of pervious land to impervious land, which should have resulted in increased runoff. However, because discharge trend analysis did not exhibit the results as expected, land use had a smaller impact on discharge than rainfall.

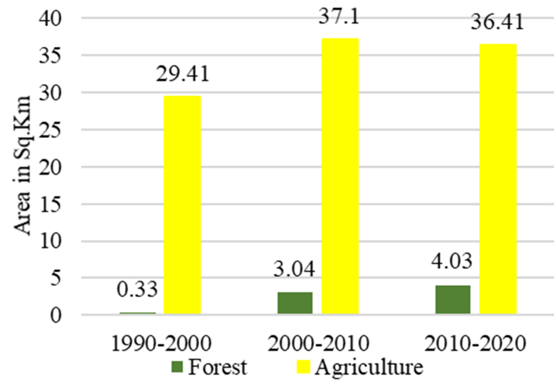

Figure 10: Contribution to Net Change in Built-up Area

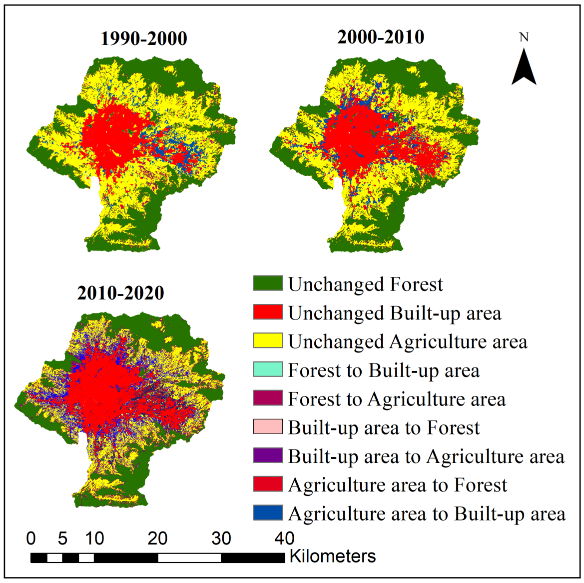

Figure 11: Conversion of Land use Type in Three Decades

Regression and correlation analysis was therefore carried out between rainfall data and discharge data to identify the strength of their relationship in three decades of study. Similarly, discharge and land use/cover were also correlated using land use/cover data from each year from 1990 to 2020 (ESA. Land Cover CCI Product User Guide Version 2. Tech Rep. (2017)). The results from correlation and regression analysis between built-up area and monsoon discharge and that between monsoon rainfall and monsoon discharge are shown in Figure 12.

Similarly, the results from correlation and regression analysis between built-up area and maximum discharge and that between maximum rainfall and maximum discharge are shown in Figure 13. The values of Coefficient of Determination (R^2) and Correlation Coefficient (r) from correlation and regression analysis (Figure 12 and Figure 13) showed that the strength of relationship between rainfall and discharge was stronger than that between discharge and land use/cover, with some exceptions.

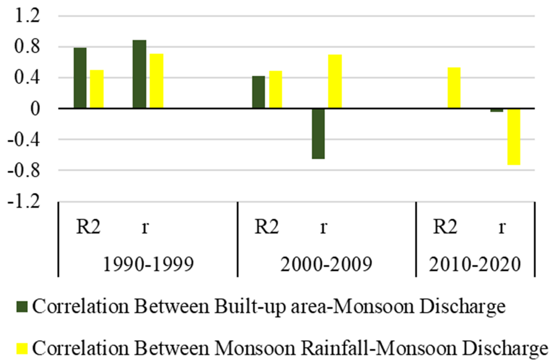

Figure 12: Coefficient of Determination (R^2) and Correlation Coefficient (r) between Built-up area and Monsoon discharge, and Monsoon Rainfall and Monsoon Discharge

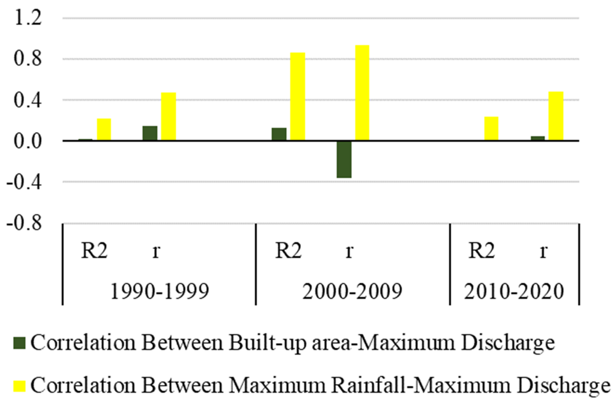

Figure 13: Coefficient of Determination (R^2) and Correlation Coefficient (r) between Built-up Area and Maximum Discharge, and Maximum Rainfall and Maximum Discharge

This also supported the idea that rainfall had a bigger impact on discharge than land use/cover change due to which discharge had either decreasing or statistically decreasing trend in recent decades matching the rainfall trend within the watershed. As a result, land use/cover change, which has been implicated as an anthropogenic driver of inundation, and increase in hydro-meteorological data were not the primary causes of flooding in the valley.

4.3 Morphometric Characteristics

Different morphological factors of the basin might be contributing to greater flood risk in the valley. So morphological analysis was also done using applications of ArcGIS. The evaluation of morphometric parameters of the sub-basins and drainage networks derived from DEM are given in Table 1, 2 and 3. Stream order of the drainage networks of each sub-basin is shown in Figure 4.

Basin with low bifurcation ratio (Rb) values have sharper and higher hydrographs while the hydrographs of the streams can be lower and continuous in basins with high Rb values [16]. Table 2 shows the bifurcation ratio calculated for each basin and they ranged from 1.25-1.667 which is low. The relationship between drainage density (Dd) and surface runoff and permeability gives us information about groundwater potential [17]. Low drainage density indicates highly permeable sub-soil material under dense vegetation, low relief and low runoff; whereas high drainage density describes impermeable sub- soil materials. Sparse vegetation, higher runoff and mountainous relief [18]. Generally, high drainage density basins are areas where permeability decreases, surface runoff increases and stream closeness decreases. High drainage density signifies greater flood risk. Drainage density calculated for sub-basins within the study area were all less than 4 which showed the low drainage density, therefore lesser flood risk [19].

Stream frequency (Fs) may be directly associated with lithological characteristics of the basin and indicates the stream network distribution over the river basin [20] and shows positive correlation with drainage density in the study area. The stream frequency calculated for all sub-basins were of low values indicating permeable ground. So, the low Fs and Dd values showed that the sub-basins area not prone to flooding. In study area, the values of circulatory ratio for sub-basins are in the range of 0.238-0.581, indicating that the area is characterized by high relief and elongated resulting in greater basin lag times although these sub-basins suffered greater urbanization. Circulatory ratio in the range of 0.4-0.5 are strongly elongated [18]. So, sub-basins in the study area are elongated to strongly elongated resulting delayed time to peak flow. Elongation ratio approaching to 1 indicates a nearly circular shaped basin. Table 2 showed that the elongation ratio calculated for all sub-basins were less than 0.7 except for Balkhu sub-basin signifying the elongated basin shape [19]. Both circulatory ratio and elongation ratio confirmed the elongation of all sub-basins and the relatively low flood hazard. Similar circumstances were observed for Yesilirmak river basin [19]. Despite a moderate amount of rainfall and elongated shape in the six sub-basins of the basin, it has been subjected to flooding since 1950.

Table 1: Morphometric Properties of Sub-basins

Sub-basins	Basin Length (Km)	Area (Sq.km)	Perimeter (Km)	Longest Flow Path (Km)
Nakkhu	16.62	54.78	53.78	20.51
Balkhu	10.50	44.52	31.03	10.30
Manamati	9.12	21.14	25.97	7.93
Bishnumati	16.19	72.56	48.72	15.69
Dhobi	12.86	34.13	35.63	11.72
Bagmati	19.01	73.15	54.70	21.36
Manohara	18.16	71.62	54.70	20.70
Hanumante	17.41	83.91	50.76	17.82
Godawari	12.58	52.07	35.33	13.20
Kodkhu	10.60	23.46	30.30	9.23

Increased relief refers to steep slopes and high slopes implying higher runoff rates in the basin. Higher basin relief (Bh) values result in reduced flow collection time and consequently an increase in flood peaks [17]. From the study, Bagmati, Manohara and Hanumante sub-basin had the least relief ratio of < 0.08, Manamati, Bishnumati, Dhobi and Kodhku sub-basin had relief ratio between 0.08 to 0.1 and Balkhu and Godawari sub-basin had maximum relief ratio > 0.1. This indicated that Balkhu and Godawari sub-basin are subjected to higher flood risk than other sub-basins. As time of concentration is indirectly proportional to the relief ratio, time of concentration were lowest for Balkhu and Godawari sub-basin indicating the faster flow collection time, thus increasing the flood risk.

From overall analysis of rainfall, discharge and land use/cover, even though there was significant urbanization in the study area, discharge did not increase significantly. This generated an uncertainty regarding the actual cause behind inundation problem. Thus, it can be concluded that since land use's effect was not directly observed on discharge in rivers draining the valley, many other factors like river width encroachment, improper river training works, conversion of flood plain areas to settlement areas etc. might be the contributing factors of inundation problem.

Table 2: Morphometric Properties of Sub-basins

Sub-basins	Bifurcation ratio	Elongation Ratio	Circulatory Ratio
Nakkhu	1.500	0.503	0.238
Balkhu	1.333	0.717	0.581
Manamati	2.000	0.569	0.394
Bishnumati	1.250	0.594	0.384
Dhobi	1.500	0.513	0.338
Bagmati	1.500	0.508	0.307
Manohara	1.333	0.526	0.301
Hanumante	1.667	0.594	0.409
Godawari	1.250	0.647	0.524
Kodkhu	2.000	0.516	0.321

Table 3: Morphometric Properties of Sub-basins

Sub-basins	Basin Relief (m)	Relief ratio	Time of concentration (min)
Nakkhu	1326	0.080	167.993
Balkhu	1239	0.118	118.415
Manamati	811	0.089	115.075
Bishnumati	1438	0.089	157.615
Dhobi	1111	0.086	160.914
Bagmati	1425	0.075	170.995
Manohara	1109	0.061	200.358
Hanumante	864	0.050	168.313
Godawari	1392	0.111	111.311
Kodkhu	696	0.066	120.832

5. Conclusion

There was no statistically significant increasing decadal trend in rainfall and discharge. But the built-up area was found to be consistently increasing over the last three decades with 29.61%, 30.87% and 24.53% rise between 1990-2000, 2000-2010 and 2010-2020 respectively, mainly compensated by the decrease in the agricultural areas. So, it showed that the discharge values are decreasing disregarding the increasing urbanization on contrary to our expectations. Similarly, stronger correlation between rainfall and discharge than that between built-up area and discharge verified the greater influence of rainfall on discharge than that by the urbanization. And morphometrical analysis of sub-basins concluded that, among 10 sub-basins, Balkhu sub-basin and Godawari sub-basin had the higher influence morphometrically to produce probable floods.

Thus, the possible drivers dealt in the study are considered to have lesser impact on inundation. So, more research into other possible contributing factors like river width constriction, improper river training works, exploitation of ground water and surface water, and so on is needed to determine the actual cause of the inundation problem in the study area.

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