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Article

The Assessment of Climate Change Impacts and Land-use Changes on Flood Characteristics: The Case Study of the Kelani River Basin, Sri Lanka

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Abstract: Understanding the changes in climate and land use/land cover (LULC) over time is important for developing policies for minimizing the socio-economic impacts of riverine floods. The present study evaluates the influence of hydro-climatic factors and anthropogenic practices related to LULC on floods in the Kelani River Basin (KRB) in Sri Lanka. The gauge-based daily precipitation, monthly mean temperature, daily discharges, and water levels at sub-basin/basin outlets, and both surveyed and remotely sensed inundation areas were used for this analysis. Flood characteristics in terms of mean, maximum, and number of peaks were estimated by applying the peak over threshold (POT) method. Nonparametric tests were also used to identify the climatic trends. In addition, LULC maps were generated over the years 1988–2017 using Landsat images. It is observed that the flood intensities and frequencies in the KRB have increased over the years. However, Deraniyagala and Norwood sub-basins have converted to dry due to the decrease in precipitation, whereas Kithulgala, Holombuwa, Glencourse, and Hanwella showed an increase in precipitation. A significant variation in atmospheric temperature was not observed. Furthermore, the LULC has mostly changed from vegetation/barren land to built-up in many parts of the basin. Simple correlation and partial correlation analysis showed that flood frequency and inundation areas have a significant correlation with LULC and hydro-climatic factors, especially precipitation over time. The results of this research will therefore be useful for policy makers and environmental specialists to understand the relationship of flood frequencies with the anthropogenic influences on LULC and climatic factors.

Keywords: climate change; flood; hydro-climatic conditions; Kelani River Basin (KRB); land-use land cover (LULC)

1. Introduction

Floods are one of the most frequent and devasting natural disasters around the world [1,2]. They affect more people than other natural disasters: 55% of the world population was affected by floods, which were 43% of all disaster events during 1994–2013 [2]. Furthermore, floods enormously impact socioeconomic status, the environment, infrastructure, and development [3–7]. Floods occur under different environmental conditions/parameters such as meteorological, hydrological, geographical, and geological. Furthermore, anthropogenic activities can intensify it. Because of the heavy precipitation and storm surges, a large volume of runoff is generated that occupies and inundates land masses near waterways. Floods became more frequent, and disasters were intensified over the last few decades [2,8,9], closely linked to changes in the earth's climate and increased human interventions [10]. For example, flash floods have increased in the Hengduan Mountain region of China over the last decade [8]. Flash floods in Chamoli, Uttarakhand region were analyzed by Verma et al. [11], and they found that the flood intensities have significantly increased. Many other examples of increasing flood risk can be found in literature [12].

The global climate is changing, and its adverse impacts are inevitable. According to the recently released IPCC's sixth assessment report [13], climate impacts are at the high end of previous estimates, affecting all parts of the world. This report also mentions that about 40% of the world population (approximately 3.5 billion people) may be affected by the most severe category of "high vulnerability" related climatic impacts. The land has warmed by more than 0.5 °C compared with the global mean temperature after 1990 [14,15]. Increasing earth temperatures are attributable to greenhouse gas emissions and resultant responses in the earth system [9,16]. It was evident that this warming has affected changes in extreme weather and extreme events globally, i.e., heatwaves, high-intensity precipitation, sea-level rise, and snow and glacier melting [17].

Rapeli and Mussalo-Rauhamaa [18] stated that the heatwaves have intensified due to global warming. Substantial literature can be found to verify this scenario and Wang et al. [19] have researched it in Eurasia. Many researchers have showcased and modelled the relationship between global warming and sea level rise [20–22]. In addition, most of these researchers have pointed out the adverse impacts of sea level rise in countries like Bangladesh [23,24], Maldives [25,26], Fiji Islands [27,28], and Sri Lanka [29]. Similar relationships can be found in the literature highlighting the impacts of global warming on various other extreme weather conditions. However, extreme precipitation is one of the most evident impacts of global warming.

Precipitation changes have not been uniform across the world. Particularly, in mid-latitudes and tropical regions, more frequent and extreme precipitation is expected due to a rise in surface temperature [17,30]. Shared socioeconomic pathways from IPCC's AR6 report [13] indicate that temperature may reach the warming limits around the middle of the 21st century and will cause unavoidable increases in multiple climate hazards such as floods, droughts, storms, cyclones, and landslides.

On the other hand, demands for natural resources and services increase predominantly due to population growth, urbanization, and climate change. Therefore, changes in land use and land cover (LULC) are predominant among many other changes in the land mass. This physical factor ultimately promotes flooding and its severity [9,31]. Any changes in LULC cause differences in weather patterns (i.e., temperature and precipitation) and resultant hydrological responses (i.e., soil moisture, runoff, peaks, and erosion). Furthermore, LULC can change the levels of exposure, risk, and vulnerability to flooding as well. Recent studies have emphasized that rapid urbanization and deforestation reduce infiltration, increase runoff and flooding time, and disrupt ecosystems [32–34]. Due to such effects of land-use change, it is concluded that hydrologically significant changes will continuously take place in the next decades due to the loss of agricultural and forest lands [35].

Owing to the combined effect of the changing climate and human activities, many nations are highly vulnerable to flood hazards that lead to myriad socioeconomic issues. Asian and African countries are the most severely hit by floods [2,31]. Many countries spend millions of dollars every year to recover from the aftermath of such disasters and disaster prevention, mitigation, and adaptation [36]. Miner and Alipour [37] identified the types of damage that occur during floods in the transportation sector in Iowa, USA.

They paid significant attention to bridges and their recovery stages after inland floods. Similar research work can be found in recent literature, and many studies have assessed the recovery cost of transportation networks [38], agriculture [39], other properties [40,41], etc. However, flood damages were not analyzed extensively in the context of Sri Lanka.

However, a recent analysis of the Global Climate Risk Index (GCRI) [42] stated that Sri Lanka was one of the top 10 countries that were severely affected by climate change in 2018. Sri Lanka is a tropical country that receives intense rainfall due to four main monsoons: the first inter-monsoon (March and April), southwest monsoon (May to September), second inter-monsoon (October and November), and northeast monsoon (December to February) [43]. During these monsoons, the intense rainfall often results in heavy storms that cause severe flood events. Recurring floods are very common in Sri Lanka and cause significant economic and social damage [44–46]. The Kelani River basin is one of the most vulnerable basins in Sri Lanka that gets subjected to annual flooding [44]. It experiences large-scale flooding every two to three years on average that affects approximately 200,000 people [47]. Over the last two decades, the main drivers of major floods have been climate change and land-use change. It has been concluded in many studies that the risk of flooding could increase due to changing climate worldwide over the years to come [48,49], and thus, Sri Lanka would be facing many flood-related issues.

Therefore, the KRB would be an ideal river basin to analyze its floods based on LULC changes. When long-term behaviour and trends of the climate extremes (temperature and precipitation) of the Kelani River basin are analysed, it can be concluded that the temperature and precipitation extremes are rising while the annual average precipitation in the basin is declining [50]. Rapid urbanization took place over the last three decades in many parts of Sri Lanka. For example, a study by Maheng et al. [51] analyzed LULC in the Colombo urban and suburb areas (the capital of Sri Lanka and located in the lower part of the Kelani River basin, Figure 1) in 1997 and 2015 and stated that urban areas have increased by approximately 51% and suburban areas have decreased by 15% over 19 years. Therefore, it is essential to understand the effects of climate change and LULC on flooding conditions in any part of the country.

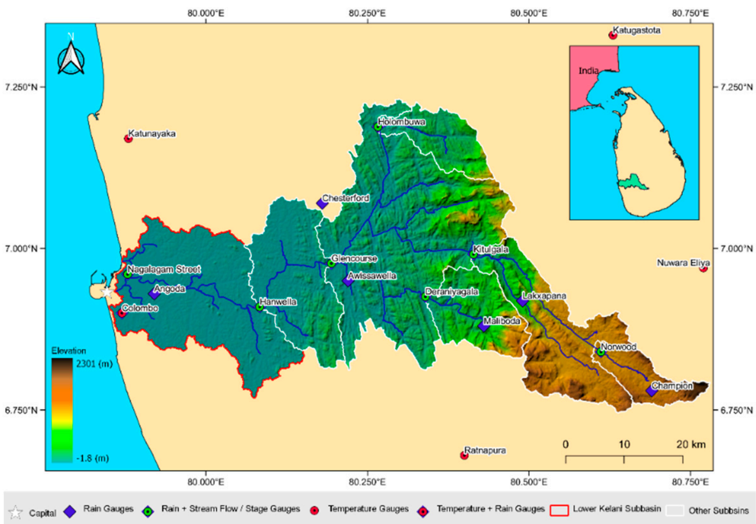


Figure 1. Catchment map of Kelani River Basin (KRB) and the locations of Hydro-Metrological stations.

The overall aim of this study is to assess the impacts of climate change and land-use cover on flooding in the Kelani River basin by analysing relevant observed and remote sensed climatic and land-use and land-cover data. The specific objectives of the current study are (1) to identify historical floods using hydrological time series; (2) to further analyse the selected historical floods with respect to their intensity and frequency; and (3) to statistically assess the impacts of climate change and land-cover change on flood characteristics. Results from this study will be useful to plan and initiate adaptation and mitigation strategies that can be implemented to effectively reduce flood risks caused by continuing climate and land-use land cover changes.

This paper is structured as follows. Section 2 discusses the materials and methods that were used in this study. The study area and data used are presented in detail in Section 1. In addition, the methodology followed is clearly presented. Section 3 then presents the results of the analysis. The temporal variation of LULC and climatic trends are presented in Section 1. The correlation of LULC variation to climatic trends is also presented in Section 1. Section 4 finally presents the summary and the conclusions of the study. Section 1 will also help the local planning authorities and the government to orient the solution framework towards identifying sustainable countermeasures for the problem of frequent floods in the Kelani River Basin.

2. Material and Methods

2.1. Study Area

Sri Lanka is situated on the southern tip of India, between the latitudes of 6°–10° and east longitudes 80°–82° with an area extent of 65,610 km^2, and it experiences high rainfall due to extreme low-pressure conditions in the Bay of Bengal and high seasonal precipitation due to the La Niña phenomenon [52]. As was stated above, the KRB is one of the most important river basins in Sri Lanka. The Kelani River basin is located between northern latitude 6° 47′ to 7° 05′ and eastern longitudes 79° 52′ to 80° 13′, covering a basin area of 2230 km^2, with altitudes from −1.8 m to 2300 m above mean sea level as shown in Figure 1. The river basin is broadly categorized into upper and lower basins (Upper basin—above Hanwella Gauge, Lower basin – below Hanwella basin). The upper Kelani River basin is predominantly with vegetation, whereas the lower basin is heavily urbanized. The river basin receives a total annual rainfall of nearly 6000 mm and carries a peak discharge of 800–1500 m^3/s during the monsoonal periods to the Indian Ocean (i.e., especially in the South-West monsoon period from May to September).

The Kelani River is the fourth largest river in Sri Lanka, and it drains to the Indian Ocean through the capital, economic and commercial city of Colombo. The lower Kelani River basin (approximately 500 km^2) lies in the Colombo district, which is the most densely populated city in Sri Lanka. Therefore, the Kelani River basin is a vulnerable river basin during flooding [47,50,52]. Thus, flood risk minimization is very important for reducing economic and social damage.

2.2. Hydro-Climatic and Remote Sensed Data

The present study used the daily data of 13 precipitation stations, monthly data from 5 temperature stations, and daily data from 7 flow measuring stations as indicated in Table 1. The above data were obtained from the department of metrology and the department of irrigation. The mean rainfall calculations were conducted using the Thiessen polygon method, and the gaps were filled for the data sets that had less than 10% missing data. Furthermore, satellite images of Landsat 5 Thematic mapper (for the years 1988, 1998, and 2008) and Landsat 8 Operational Land Imager (for the year 2018) were downloaded from USGS Earth Explorer at https://earthexplorer.usgs.gov/ (accessed on 1 August 2022). Additionally surveyed flood inundation maps were obtained from the irrigation department of Sri Lanka and the Survey Department of Sri Lanka for the years 1989 and 2016 respectively. Moreover, satellite images of the 2016 flood were obtained from Sentinel—1 A satellite mission at https://scihub.copernicus.eu/ (accessed on 1 August 2022).

2.3. Land-use and Land Cover Analysis

The land use and land cover (LULC) maps were produced based on satellite images from Landsat missions and cross-validated by high-resolution satellite images from Google Earth. The classification was conducted for six land-use classes, namely, forests, cultivations, built-up areas, water bodies, bare land, and clouds using the semi-automated classification plugin in QGIS 3.16 long-term release. The semi-automated classification plugin is a supervised classification tool, and it trains areas in pixel-based image classification. More information on this open-source toolbox can be found in Congedo [53]. Here to increase the accuracy, a prior pixel section was conducted with a high-resolution satellite imaginary with google earth. A minimum number of 50 samples of each class was defined, and kappa analysis was conducted with a discrete multivariate technique. Further details of the accuracy assessment of LULC can be found in Makumbura et al. [54], which is a parallel research work conducted by the same research group as the authors of this study. The LULC classifications were conducted for the base years 1988, 1998, 2008, and 2018. To calculate annual values linear regression model was employed to generating values for 1988–2018 [55].

Table 1. Details of Hydro-Metrological stations.

Station Name	Latitude (Degree)	Longitude (Degree)	Data Period	Precipitation Data Availability	Temperature Data Availability	Discharge/Stage Data Availability
Champion	6.78	80.69	1988–1989	Yes	No	No
Norwood	6.836	80.615	1988–2017	Yes	No	Yes
Laxapana	6.919	80.49	1988–2017	Yes	No	Yes
Maliboda	6.88	80.43	1988–2017	Yes	No	No
Deraniyagala	6.924	80.338	1988–2017	Yes	No	Yes
Kithulgala	6.989	80.418	1988–2017	Yes	No	Yes
Holombuwa	7.18	80.26	1988–2017	Yes	No	Yes
Chesterford	7.07	80.18	1994–2015	Yes	No	No
Avissawella	6.95	80.22	1988–2011	Yes	No	No
Glencourse	6.978	80.203	1988–2017	Yes	No	Yes
Hanwella	6.91	80.082	1988–2017	Yes	No	Yes
Angoda	6.93	79.92	1994–2011	Yes	No	No
Colombo	6.91	79.88	1988–2017	Yes	Yes	No
Nagalagam Street	6.96	79.88	1988–2017	No	No	Yes
Katunayake	7.17	79.88	1990–2017	No	Yes	No
Katugastota	7.33	80.63	1990–2017	No	Yes	No
Nuwara Eliya	6.97	80.77	1990–2017	No	Yes	No
Ratnapura	6.68	80.4	1990–2017	No	Yes	No

2.4. Analysing Flood Characteristics

The historical floods for the Kelani River basin were detected based on peak–over–threshold (POT) method using the water engineering time series processing (WETSPRO) tool by Willems [56] with flood classification levels and respective discharges according to the severity. Before applying the POT method, the specific discharge (discharge/area) was obtained for each outlet. The specific discharge removes the effect of the size of subbasins. Kithulgala subbasin shares its outlet with the Norwood subbasin. Furthermore, the Glencourse subbasin shares its outlet with Norwood, Kithulgala, Deraniyagala, and Holombuwa. Similarly, the Hanwella subbasin shares its outlet with all the subbasins including Glencourse. Therefore, the subbasin area is obtained by adding the areas of subbasins that share the same outlet. Subsequently, once the specific discharges were calculated, the POT method was applied to obtain historical flooding events [57]. Flood peaks and maximum and mean peaks were determined for three decal segments (1988–1997, 1998–2007, and 2008–2017) for comparison.

2.5. Precipitation Trend Analysis

Precipitation trend analyses were carried out to identify the trends using historical precipitation data in each subbasin. The precipitation gauges used for the present study are shown in Figure 1, and coordinates and periods are denoted in Table 1. The Kelani River basin has a well-distributed precipitation gauge network (refer to Figure 1). Thus, it can be assumed that the precipitation gauges around the river basin represent the rainfall patterns in the basin. The present analysis employed the monthly rainfall data derived from the daily data. Further, the missing data were filled with the inverse distance method as it is one of the better-suited methods to fill the missing data in the regions of low country wet zone areas [58–60] than the other methods [61]. Subsequently, Pettitt's test, SNHT, Buishand's test, and von Neumann's test were carried out to check the homogeneity of the rainfall data series [58–60]. Afterward, the Mann–Kendall test [62] and Sen's slope estimator test [63] were carried out to identify the trends in the precipitation data. The Mann–Kendall test is one of the most widely used nonparametric tests in the world to test climatic trends [64–66]. The Mann–Kendall test can be formulated as follows in Equation (1):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{1}$$

$$sgn(x_i - x_j) = \begin{cases} 1 & if\ x_j - x_i > 0 \\ 0 & if\ x_j - x_i = 0 \\ -1 & if\ x_j - x_i < 0 \end{cases}$$

where x_j and x_i are climate data in months/years j and i here $j > i$. The Mann–Kendall test is a qualitative measurement of the trend. Therefore, in order to quantify the trends, Sen's slope method [63] was coupled with the Mann–Kendall method. More details about the procedure can be found in Khaniya et al. [65]. The mathematical explanation of Sen's slope (T_i) method is given in Equation (2). Depending on the sign of the Q_i, the trend can be identified as an increasing or decreasing trend.

$$T_i = \frac{x_j - x_i}{j - i}\ for\ i = 1, \ldots\ldots.., N \tag{2}$$

$$Q_i = \begin{cases} T_{\frac{N+1}{2}} & if\ N\ is\ odd \\ \frac{T_{\frac{N}{2}} + T_{\frac{N+2}{2}}}{2} & if\ N\ is\ even \end{cases}$$

3. Results and Discussion

3.1. Land-use Land Cover Variation of the Kelani River Basin

The classified LULC classes from multiband Landsat images are shown in Figure 2 for the years 1988, 1998, 2008, and 2018. The expansion of built-up areas and rapid urbanization can be clearly visible in the lower Kelani River basin where a drastic development has occurred over the last three decades. The reddish patches verify these changes. In addition, the temporal variation clearly showcases the migration of built-up areas towards the upstream areas. The urbanization reached almost 1/5th to 1/4th of the catchment area (approximately). In addition, the booming of small reddish patches can be seen all over the catchment. Population increases and migrations to the capital of the country may have resulted the significant increase of built-up areas downstream.

Furthermore, the most upstream of the basin (Norwood) also shows an increase in agricultural areas in addition to the slight increase of built-up areas. Population increase over the years might have impacted more agricultural lands in the fertile soil upstream.

Figure 3 shows the variations in percentages of area for each LULC class in each year considered. Notably, vegetation areas, bare lands, and agricultural areas have been reduced over time in most of the subbasins, except vegetation areas in Holombuwa and Deraniyagala subbasins show some increase in areas (refer to Figure 3c,d). The main explanation of the depletion of vegetation, bare land, and cultivated areas is the expansion of built-up areas; this expansion in the lower Kelani subbasin is significant. A study by Subasinghe et al. [56] revealed that the population of Colombo suburbs (lower Kelani basin) has drastically increased over time, and it could be the main reason for the expansion of built-up areas. Moreover, the end of 30 years of civil war also might have contributed to the expansion of built-up areas.

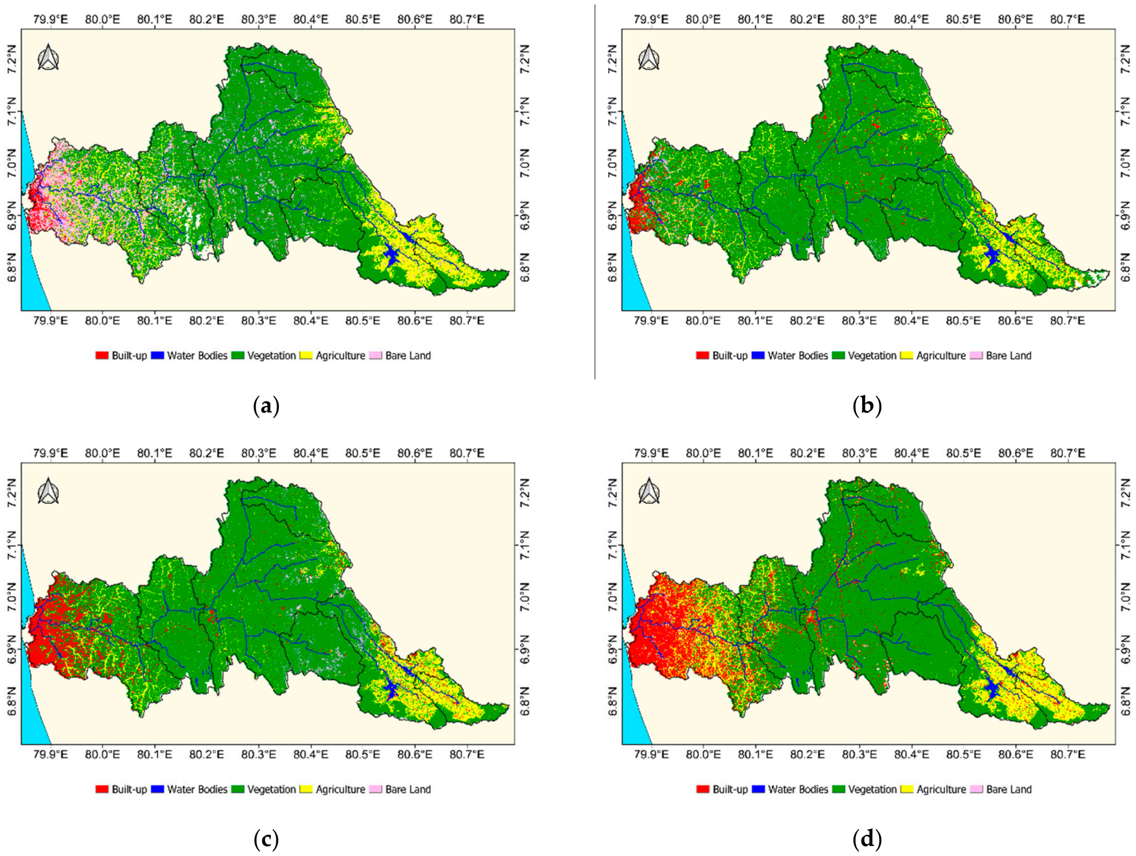


Figure 2. Land-use land cover maps of Kelani River Basin: (**a**) for 1988; (**b**) for 1998; (**c**) for 2008; (**d**) for 2018.

Table 2 presents the above variations numerically with respect to the baseline years of 1988, 1998, and 2008. Built-up areas of all the subbasins increased over time. Overall consideration of LULC change in the Kelani River basin reveals that the vegetation layer depleted over the last three decades and the rate of depletion from 1998 to 2008 was 0.178%/year. However, this rate significantly increased to 0.74%/year from 2008 to 2018. Similarly, bare lands in the river basin have also drastically reduced or occupied by other land-use classes. Interestingly, the built-up areas increased from 1988 to 2018, and the rate of increase remains steady (2.9%/year). Additionally, a fluctuation in vegetation is also observed. Most of the upper subbasins receive more precipitation than the lower basin, but it was also observed that some areas faced a reduction in rainfall. The main cause of the depletion of the canopy cover was the cutting down of artificial Pinus forests for timber. However, this was not applicable to the lower Kelani subbasin, as it was heavily urbanized over the years.

3.2. Hydro–Climatic Characteristics

3.2.1. POT Analysis of Flood Characteristics

Figure 4 presents the results of the POT analysis. Based on POT analysis, the Norwood subbasin has faced the fewest floods over time (Figure 4a). The main cause for the above is its high elevation. Considering all the subbasins, the period from 1998 to 2007 can be considered the decade in which minimum floods occurred and the maximum occurrences were recorded from 1988–1998. Additionally, in the past two decades (1988–1997 and 2008–2017), the number of floods reduced in all the subbasins except the Lower Kelani subbasin (Figure 4a Nagalagam Street gauge), where flood occurrences were continuously increasing over last three decades. The possible reasons could be the recent development in the lower basin resulting in higher peaks and volume. The mean and maximum specific discharges of all the subbasins reduced over time except for the Hanwella subbasin. In other words, the magnitude of the floods from the other subbasins except Hanwella reduced over time. Thus, it indicates the amount of water coming from the floods is comparatively reduced.

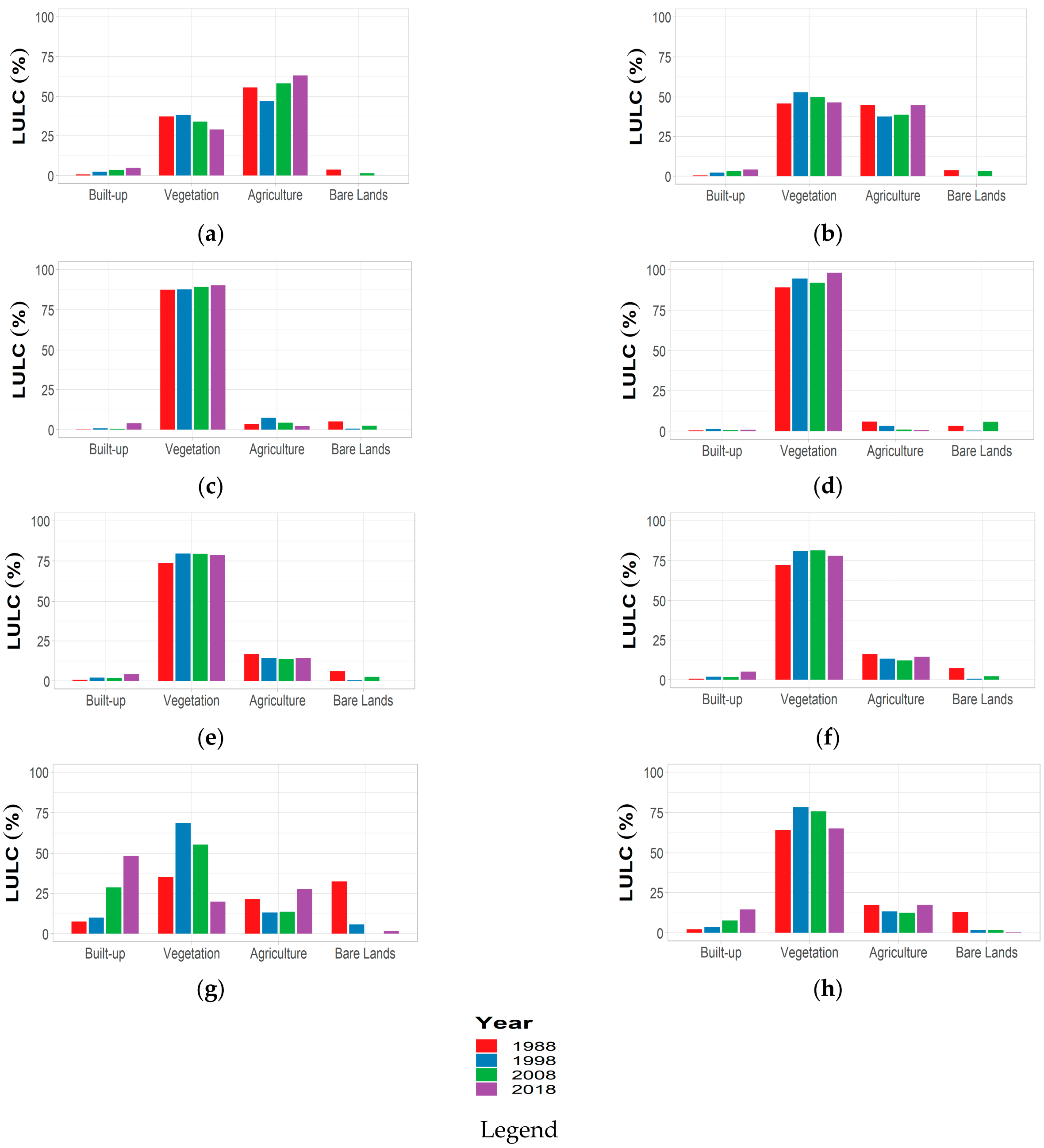


Figure 3. Percentage area of each LULC: (**a**) Norwood subbasin; **(b)** Kithulgala subbasin; (**c**) Holombuwa subbasin; (**d**) Deraniyagala subbasin; (**e**) Glencourse subbasin; (**f**) Hanwella subbasin; (**g**) Lower Kelani subbasin; (**h**) entire Kelani basin.

3.2.2. Precipitation and Temperature Trend Analysis

The average annual decadal precipitation trends (refer to Figure 5a) show the precipitation of Norwood, Kithulgala, and Deraniyagala decreases over time. Additionally, Hanwella and Lower Kelani River basins show an increasing trend over the decades. Furthermore, the precipitation of Glencourse and Holombuwa remains almost unchanged. But the long-term precipitation trend analysis was conducted using Mann–Kendall and Sen's slope estimator tests for each defined subbasin. None of the subbasins show positive or negative precipitation trends ($p = 0.05$) over the last 30 years except for the Kithulgala subbasin (−33.4 mm/year) (refer to Table 3). That further justifies the Kithulgala subbasin experience of a decrease in precipitation (refer to Figure 5a). Norwood also showcases a similar trend; however, it is not significant. Similarly, the spatial distribution of intensity of cumulative mean annual precipitation of Kelani River Basin decreased over time (see Figure 5b–d) and shifted to the centre. That further justified the statement of the Kithulgala subbasin has faced a reduction in rainfall. Norwood also showcases a similar trend; however, it is not significant.

Table 2. LULC changes in each subbasin with respect to the base year 1988, 1998 and 2008.

Subbasin	Period	Built-Up (Δ%)	Vegetation (Δ%)	Agriculture (Δ%)	Bare Lands (Δ%)
Norwood	1988–1998	58.6	1.2	−8.3	−97.5
	1998–2008	18.6	−5.7	10.6	93.5
	2008–2018	15.8	−8.0	4.1	**−100.0**
Kithulgala	1988–1998	58.1	7.2	−9.1	−85.9
	1998–2008	21.4	−3.0	1.4	84.2
	2008–2018	9.2	−3.5	7.5	**−100.0**
Holombuwa	1988–1998	60.1	0.1	33.7	−76.4
	1998–2008	−27.1	0.9	−25.4	55.6
	2008–2018	77.7	0.5	−29.5	**−100.0**
Deraniyagala	1988–1998	40.3	3.0	−29.5	−83.0
	1998–2008	−34.9	−1.4	**−50.4**	89.9
	2008–2018	16.3	3.1	−23.8	−99.9
Glencourse	1988–1998	52.4	3.8	−7.4	−83.2
	1998–2008	−8.1	−0.2	−2.8	65.4
	2008–2018	38.8	−0.4	2.9	−98.9
Hanwella	1988–1998	43.9	5.7	−10.0	−84.5
	1998–2008	−3.3	0.1	−4.2	56.6
	2008–2018	46.7	−2.1	8.6	−98.4
Lower Kelani	1988–1998	13.3	32.3	−24.1	−69.2
	1998–2008	48.3	−10.6	1.7	−99.9
	2008–2018	25.6	**−47.2**	34.2	99.8
Entire Kelani River Basin	1988–1998	24.2	10.0	−13.5	−75.7
	1998–2008	34.9	−1.8	−2.9	−0.6
	2008–2018	30.7	−7.4	16.4	−64.5

Note: (−) loss, (+) gain

Table 3. Precipitation trends.

Subbasin	Annual Scale	Significant (S)/Insignificant (IS)	Monthly (Summary)	Significant (S)/Insignificant (IS)
Norwood	−15.8	IS	−0.1	IS
Kithulgala	**−33.4**	S	−0.2	IS
Holombuwa	−4.9	IS	0.0	IS
Deraniayagala	−12.1	IS	−0.1	IS
Glencourse	0	IS	0.0	IS
Hanwella	8.4	IS	0.1	IS
N Street	5.4	IS	0.0	IS

Sri Lanka has a very limited number of temperature gauges. Therefore, the following comparison and estimations were conducted based on the temperature gauges located within and nearest to the KRB given in Figure 1. The results depicted in Figure 5e show that there were no significant changes in the temperature of each subbasin over the decades and remains unchanged. The average annual temperature varies from 24 °C in the upstream to 31 °C in the downstream of the basin.

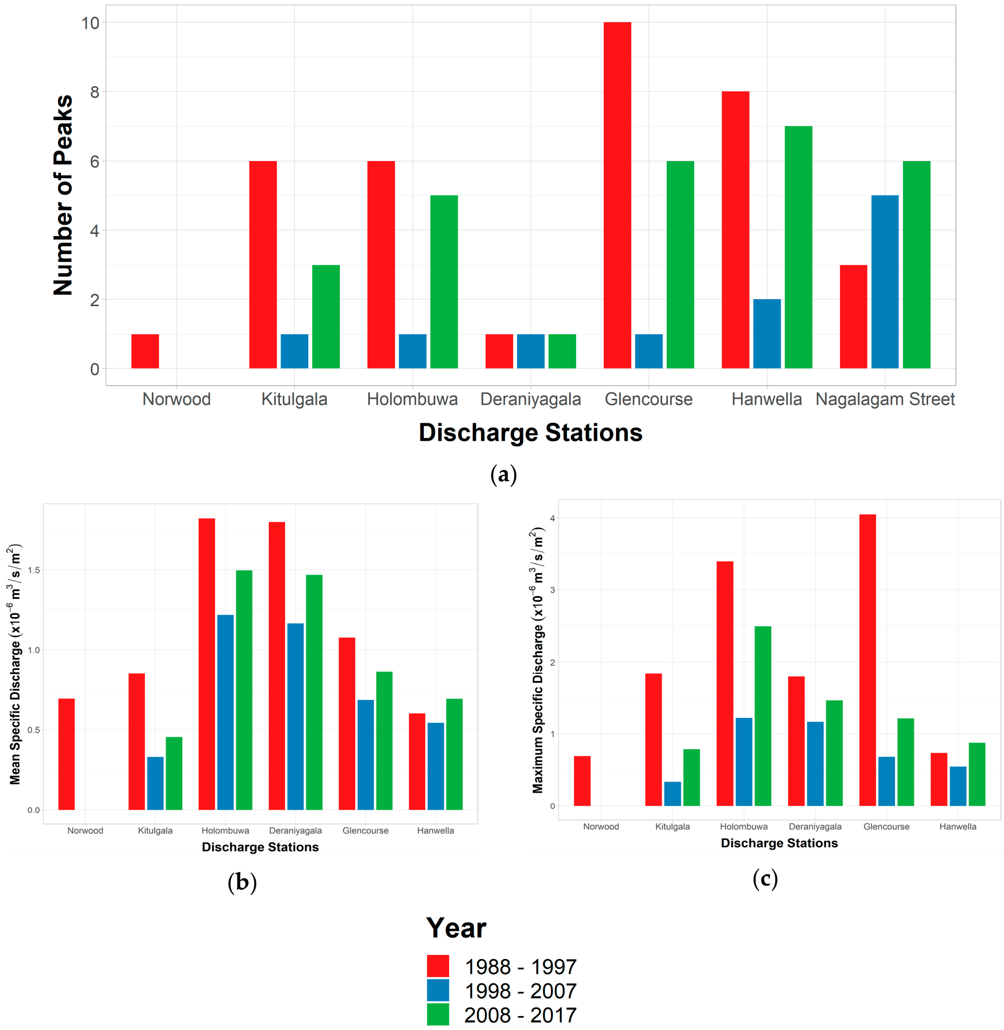


Figure 4. Results of the POT analysis: (**a**) Number of peaks recorded in each subbasin; (**b**) Mean specific discharge; (**c**) Maximum specific discharge.

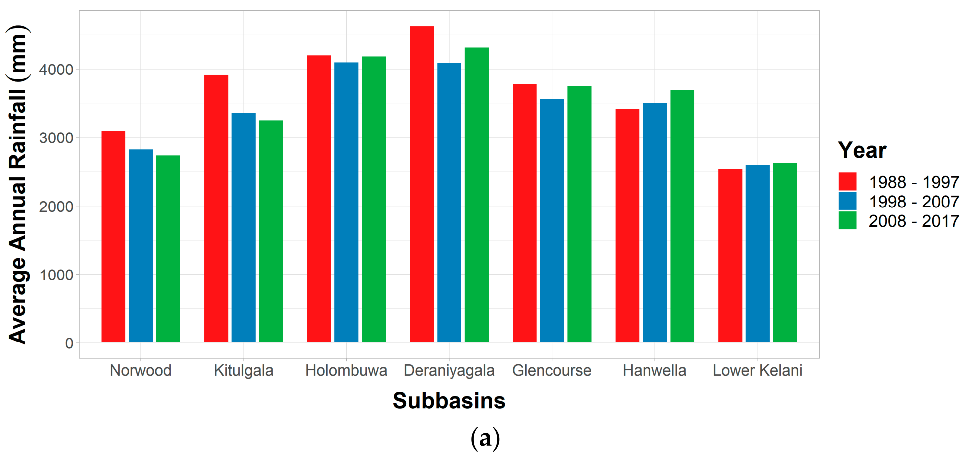
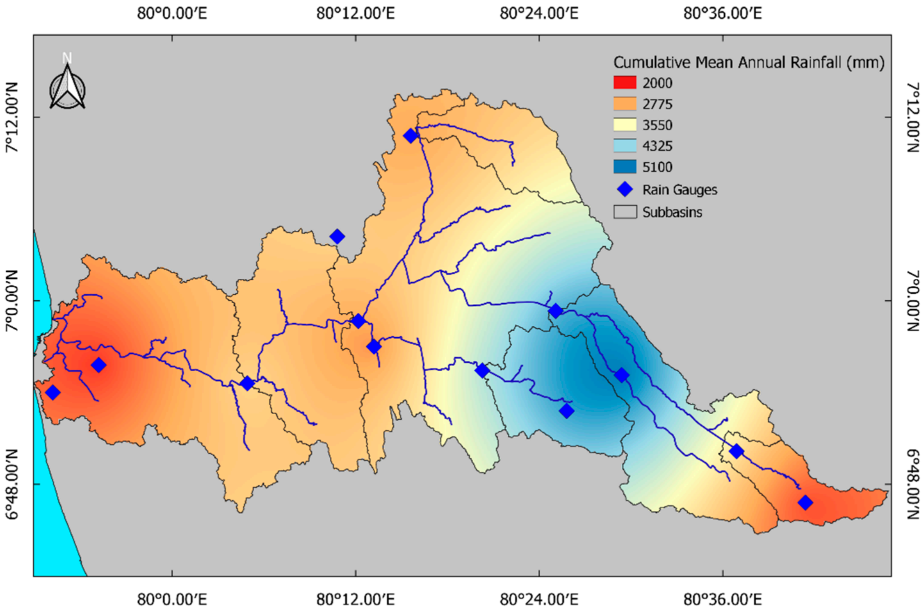
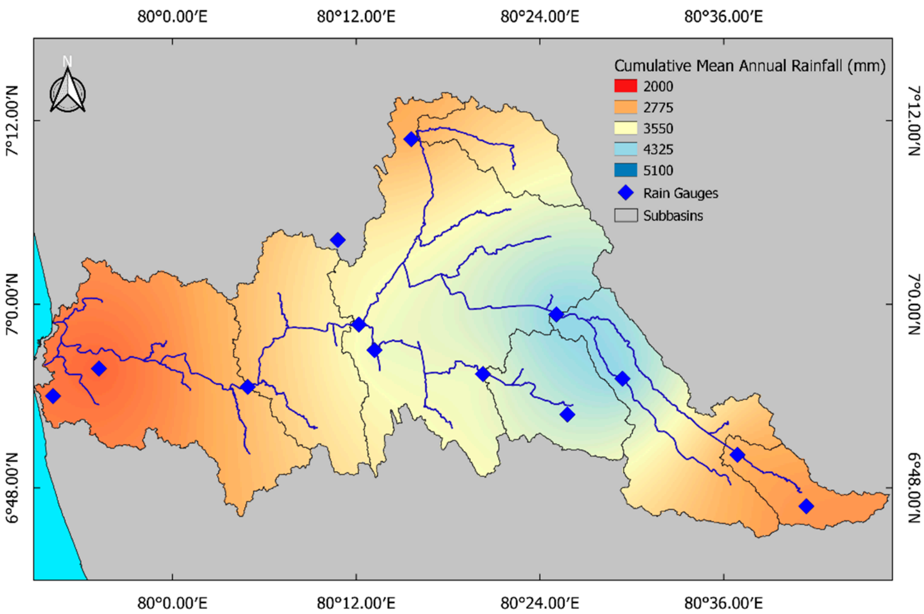


Figure 5. *Cont.*

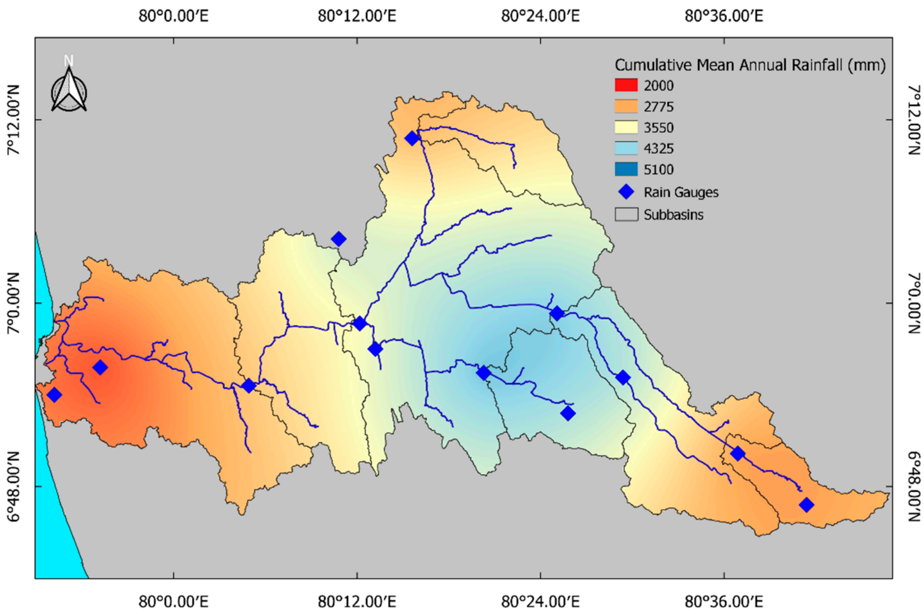


(**b**)

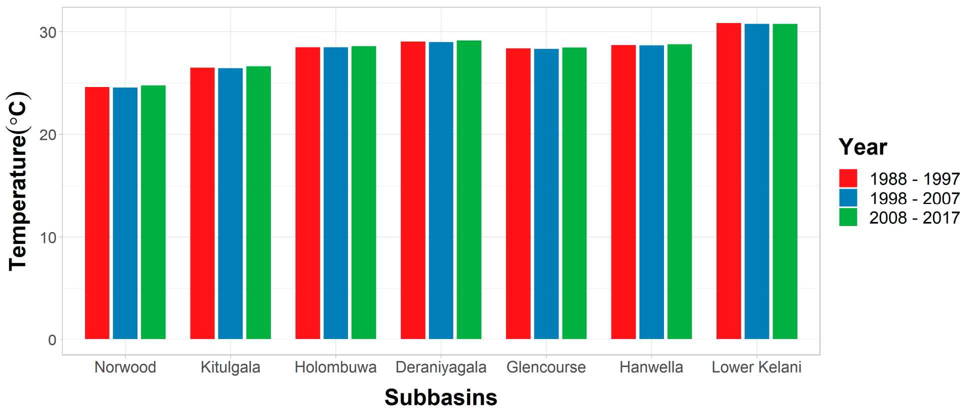


(**c**)

Figure 5. *Cont*.



(**d**)



(**e**)

Figure 5. Average annual climatic variables of subbasins: (**a**) rainfall; (**b**) spatial distribution of rainfall 1988–1997; (**c**) spatial distribution of rainfall 1998–2007; (**d**) spatial distribution of rainfall 2008–2017; (**e**) temperature.

3.3. Comparison of Flood Inundation Areas Based on Historical Flood Events

According to written evidence, the Kelani River basin has faced severe floods since 1837. Floods that happened in the years 1947, 1989, and 2016 are considered the most destructive floods [47]. Therefore, comparisons for inundation areas of the lower Kelani Basin were conducted only for two historical flood events in 1989 and 2016 as they are within the study period. The flood magnitude comparison indicates that the two flood events are different from each other and the 1989 flood was more extreme than the 2016 flood (water levels of 2.74 m in 1989 and 2.27 m in 2016 at high flood levels).

Figure 6a,b clearly show the inundation areas for the 1989 and 2016 flood events. The reddish patches are for the inundation areas from the floods. It can be clearly observed that the 1989 flood had higher inundated areas compared to the flood in 2016. Approximately, 102.9 km^2 and 69.7 km^2 area were inundated during the flood events in 1989 and 2016, respectively. The overlaps of floods and the comparisons can be seen in Figure 6c.

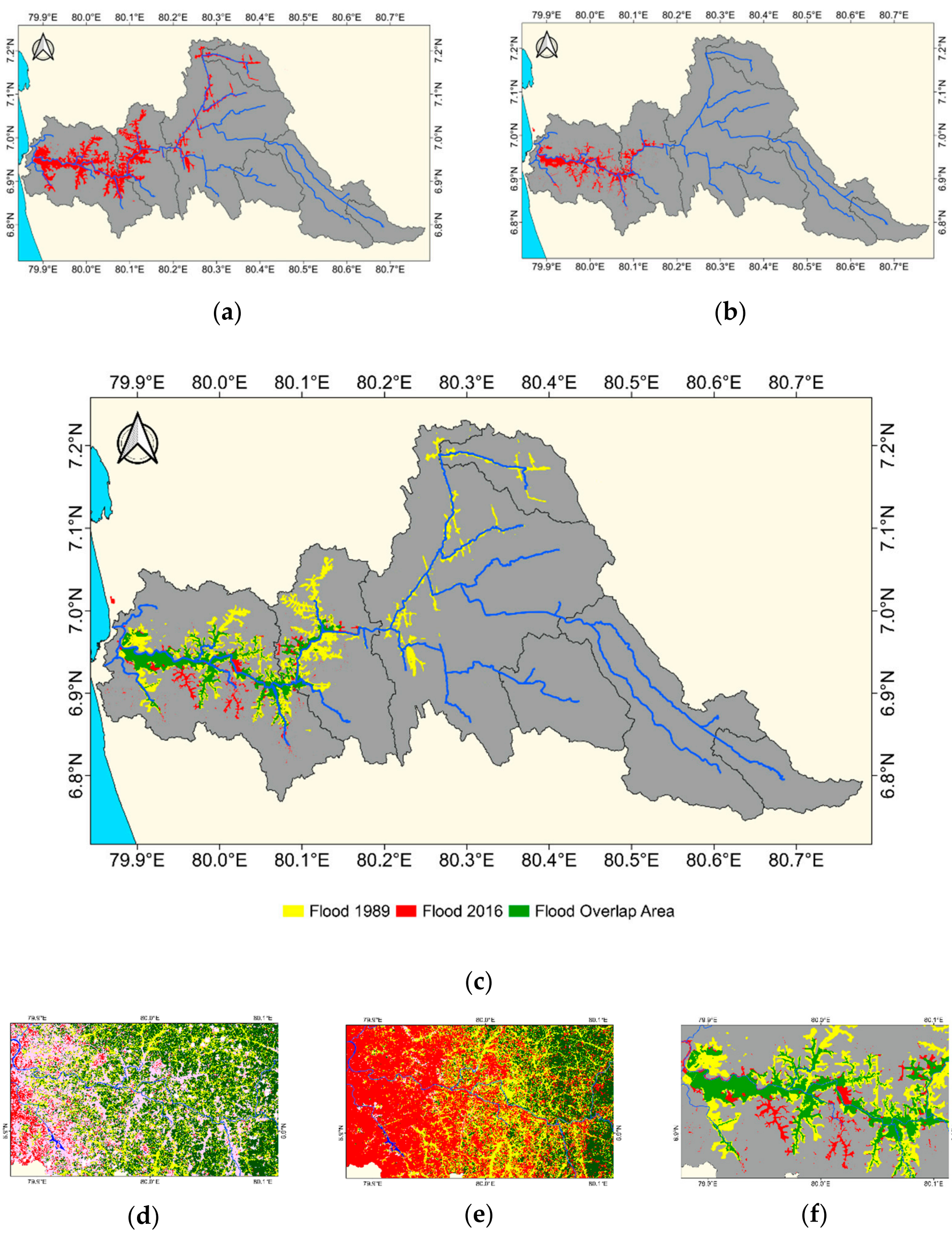


Figure 6. Historical flood inundations of Kelani River Basin: (**a**) For 1989 flood; (**b**) for 2016 flood; (**c**) comparison of inundated areas from two floods; (**d**) 1989 LULC; (**e**) 2016 LULC; (**f**) flooded area comparison.

However, the zoomed-in views in Figure 6d–f showcase the newly inundated areas in the flood event of 2016: the newly flooded areas in 2016 were barren lands in 1989. This can be understood from the LULC maps. Even though the 2016 flood had a smaller magnitude, it impacted many built-up areas. Therefore, the relationship between LULC changes to floods can be clearly understood. Dammalage and Jayasinghe [67] also stated that precipitation in the year 2016 was less than in 1989, which demonstrates that urbanization has a significant impact on floods.

3.4. Relationship between Flooding and Hydro-Climatic Characteristics and LULC in the Basin

The impacts of climatic characteristics and LULC on the flood characteristics (i.e., mean peak, maximum peak, and flood frequency (number of peaks)) were evaluated with a statistical approach that included determining the partial correlation coefficient (ρ) (refer to Table 4 and Figure 7). The partial correlation coefficient is useful for determining the relationship between two variables affected by the third variable [36]. In other words, if the third variable is removed, the relationship between the other two variables changes. Analysis reveals the precipitation has a moderate positive correlation ($\rho > 0.45$) with the mean and maximum peaks of the Kithulgala and Deraniyagala subbasins. However, the flood frequency only shows a moderate positive correlation with the Kithulgala subbasins. That implies the increase in precipitation in Kithulgala and Deraniyagala subbasins can result in floods. Other than that, the correlations with the rest of the subbasins are minimal. The temperature and the flood characteristics do not have a defined relationship (low correlation coefficients, i.e., $\rho < \pm 0.25$). Table 3 showcases the comprehensive list of partial correlation coefficients from the analysis.

Table 4. Correlation coefficients of climatic factors and LULC for subbasins.

Subbasin Name	Precipitation and Mean Peak	Precipitation and Maximum Peak	Precipitation and Frequency	Temperature and Maximum Peak	Temperature and Mean Peak	Temperature and Frequency	LULC and Mean Peak	LULC and Maximum Peak	LULC and Frequency
Norwood	0.27	0.27	0.27	−0.05	−0.05	−0.05	−0.82	−0.82	−0.82
Kithulgala	0.51	0.5	0.47	0.16	0.14	0.19	−0.6	−0.55	−0.46
Holombuwa	0.08	0.09	0.1	−0.13	−0.15	−0.11	−0.53	−0.42	−0.22
Deraniyagala	0.45	0.45	−0.14	0.19	0.19	−0.1	−0.45	−0.45	0.29
Glencourse	0.17	0.16	0.24	0.2	0.2	0.11	0.62	0.66	−0.44
Hanwella	0.18	0.14	−0.1	0.18	0.19	0.06	0.5	0.33	−0.63
Lower Kelani	−0.04	−0.04	0.07	0.25	0.25	−0.27	−0.55	−0.54	0.93

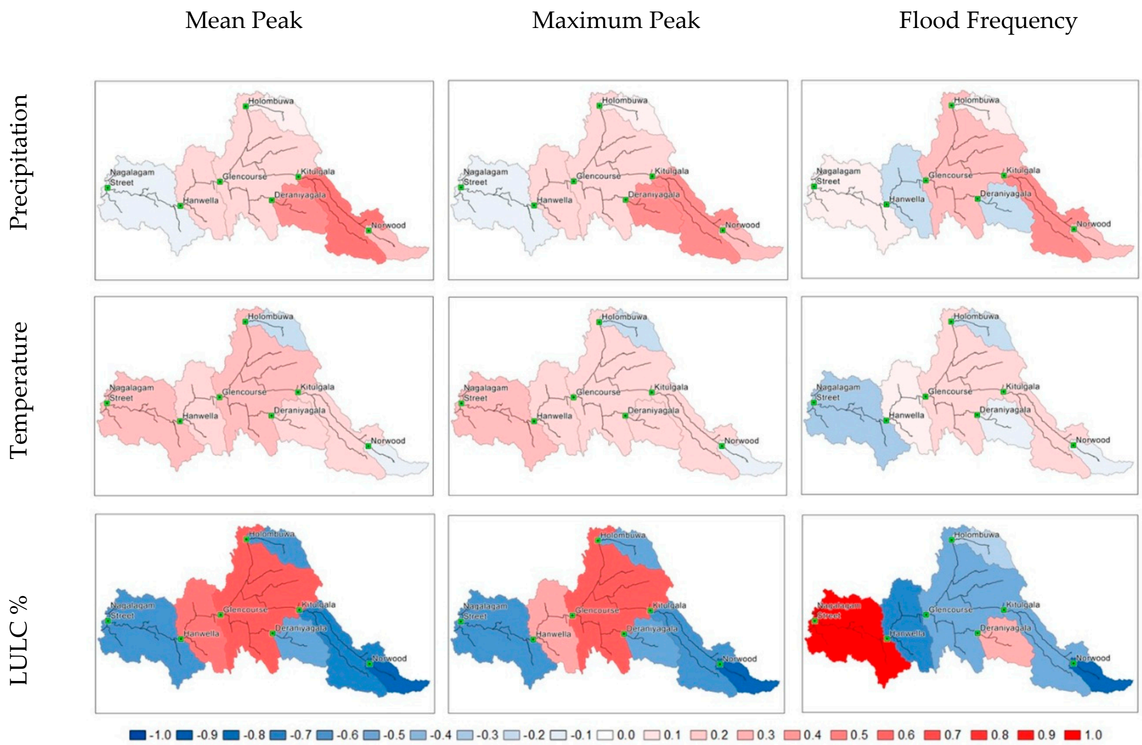


Figure 7. Hydro-Metrological and LULC correlation with each subbasin.

As was earlier stated, precipitation has a high impact on floods. However, there is no significant contribution from the temperature of the subbasins (refer to Figure 7). Hollis [68] and Zhou et al. [33] stated that floods are enhanced with rapid urbanization. Therefore, LULC change was evaluated with changes in built-up areas over time. LULC and the flood characteristics of all the subbasins have a significant relationship (in terms of values). Except for the changes of LULC in Glencourse and Hanwella subbasins, all the other subbasins have a moderate to high negative correlation with mean and maximum peaks. Similarly, flood frequency and LULC change have a moderate to high negative correlation with Norwood, Kithulgala, Glencourse, and Hanwella subbasins. However, the lower Kelani subbasin shows a strong positive correlation for the flood frequency against LULC change. That implies the changes to the land use increased the floods in the Lower Kelani River basin from 1988 to 2017.

4. Summary and Conclusions

The current study evaluates the impact of climate change and changes in land use/land cover (LULC) on flood characteristics in the Kelani River basin, Sri Lanka. The peak over threshold (POT) method was employed for identifying the mean, maximum, and number of peaks in subbasins of the Kelani River basin. Additionally, the specific discharge was used for identifying the above flood characteristics as it removes the effect of the subbasin size. The long-term hydro-meteorological and climatic trends were assessed with non-parametric tests. The LULC maps were derived from Landsat satellite missions and classified under different land use classes, for the years 1988, 1998, 2008, and 2018. The conclusions of the present study can be summarized as follows:

- LULC of the Kelani River basin reveals that the vegetation and bare land have depleted over time, and the built-up areas have grown rapidly.
- The flood frequency of all the subbasins except the lower Kelani basin was reduced. Similarly, the mean and maximum flood peaks were also reduced in all the subbasins except for the Hanwella subbasin.
- The long-term precipitation trend analysis reveals that the Kithulgala subbasin is undergoing a reduction in rainfall that is significant compared with other subbasins, but Norwood and Deraniyagala subbasins also showed a decreasing trend. However, Hanwella and lower Kelani basins are experiencing an increasing trend but are not significant.
- The temperature does not have a significant increase or decrease over the decades in any of the subbasins.
- The inundation comparisons for two extreme flood events with different magnitudes showed newly inundated areas in the Lower Kelani basin. That was a result of urban developments.
- The meteorological characteristics and LULC of all subbasins with flood characteristics showed significant correlations.

The lower Kelani River Basin is frequently flooded during the southwestern monsoon (from May to September) of the year. The government of Sri Lanka has proposed a framework for identifying solutions for these floods as they cause severe socioeconomic losses. The conclusions of this research have clearly identified the reasons for these frequent floods, and therefore, the solution framework can be oriented on the basis of the findings of this research work. For instance, the conversion of barren land to built-up areas in the lower Kelani River Basin is significant. Some of these barren lands were temporary flood retention areas decades ago but are now converted into urban or built-up areas. Therefore, the flood water is expected to do more damage in these converted areas. These conclusions can be considered by the local authorities and the government in seeking a sustainable solution to the problem of floods in the lower Kelani River Basin.

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