KDU Journal of Multidisciplinary Studies (KJMS)
Volume 3. Issue 1 July 2021

KJMS 2021 VOL.3 (1): 50-68

FLOOD HAZARD ASSESSMENT USING GIS-BASED MULTI-CRITERIA ANALYSIS: A CASE STUDY FROM DOWNSTREAM OF KELANI RIVER BASIN, SRI LANKA

K.K.E. Perera

Institute of Human Resource Advancement, University of Colombo, Colombo 07, Sri Lanka &

Department of Agrarian Development, Agrarian Services Centre, Homagama, Sri Lanka

ABSTRACT

Increasing the occurrence of extreme rainfalls due to climate change has become a common feature of the climate in Sri Lanka during the past decades. According to the study on national climate change adaptation strategy for Sri Lanka - 2011 to 2016 undertaken by the Environmental Ministry of Sri Lanka, increase in the intensity of rainfall in the wet-zone is expected to increase the propensity for flooding of the flood-prone rivers. Accordingly, the Kelani and Kalu rivers are recorded the highest flood frequencies and the accompanying flood damages among the river basins in the wet zone. In this respect, it is important to assess flood hazard in Sri Lanka.

Therefore, the aim of the study is to assess and map the spatial distribution of flood hazard in downstream of the Kelani River basin. Both primary and secondary data have been used for the study. As primary data, experts' and residents' opinions were collected to decide the important flood causative factors in the study area. As secondary data, rainfall data, GIS data layers such as land use, drainage network, contour data and soil type were used. GIS-based spatial multi-criteria analysis method was used for the study. Accordingly, the study mainly revealed that land use of the study area is the main flood hazard contributing factor among considered factors. The flood hazard assessment map illustrates that high and very high hazard zones are concentrated in the western side and low and very low flood hazard zones in the eastern and southern parts of the study area. The study identified that the spatial distribution of flood-affected areas in the inundation map of the 2016 flood and flood hazard zones of the study area are quite similar. This study, suggests that the GIS-based MCDA method can be very effective for mapping flood hazards and may be beneficial for decision-making in flood management.

KEYWORDS: *Floods, natural disaster, multi-criteria analysis, hazardous area, causative factors, downstream*

Corresponding Author: K.K.E. Perera, Email: *kumudikaerangi@gmail.com*

1. INTRODUCTION

The world is becoming increasingly susceptible to unexpected events due to climate change. As a result, these extreme weather or climate events leads to change in the magnitude, frequency, intensity, spatial extent, duration and timing of various natural disasters (Perera, 2017; Phillips, Cinderich, Burrell, Ruper, Will and Sheridan, 2015: Seneviratne, Nicholls, Easterling, Goodess, Kanae, Kossin, Luo, Marengo, McInnes, Rahimi, Reichstein, Sorteberg, Vera and Zhang, 2012). Accordingly, the frequency of the hydro-meteorological events has shown an increasing trend (Thomas & López, 2015). Among various hydro-meteorological hazards, flood hazard is one of the consequences of climate change-induced extreme events (Mirza, 2011).

Many scientific studies have revealed that the risk of floods in most humid Asian monsoon regions, tropical Africa and tropical South America have been increased whereas the risk of floods in non-negligible areas of the world such as most parts of northern North America have been decreased (Seneviratne et al., 2012: Dankers and Feyen, 2009: Hirabayashi, Kanae, Motoya, Masuda and Doll, 2008). However, according to Mirza (2011), South Asia is considered one of the world's most vulnerable regions to floods because the frequency, magnitude and extent of extreme floods have been increasing in South Asian countries.

Therefore, as a South Asian country, Sri Lanka is also frequently affected by natural disasters. Especially, floods and landslides are the most common and hazardous natural events in Sri Lanka than other natural disasters. According to International Water Management Institute (IWMI, 2018), the frequency of floods in Sri Lanka has steady risen over the past two decades. Therefore, the occurrence of flood events portrays an increasing trend in most regions of Sri Lanka. Especially, there is a significant spatial and temporal pattern of river floods in Sri Lanka. With an increase in the number of flood events, the associated flood damages such as human lives, property, crops and infrastructure damages have been also increased (Perera, 2017; Consortium of Humanitarian Agencies, 2016). However, there is a significant decline in loss of lives due to flooding since 2003 (Consortium of Humanitarian Agencies, 2016).

When considering the annual flood pattern in Sri Lanka, it can be characterized by two distinct monsoon seasons, specifically the South-west monsoon (SWM) from May to September, and the North-east monsoon (NEM) from December to February. The SWM brings heavy rains to the western and southern slopes of the central highlands while the NEM brings rains to the eastern side of the central hills and lowlands. Therefore, the country can be subjected to floods twice a year when received extreme rainfall in both seasons. In addition to these monsoon seasons, the country receives torrential rainfall because of the development of low-pressure systems or tropical cyclones frequently form in the Bay of Bengal. Accordingly, most of the cyclonic floods occur from October to December (Basnayake et al., 2019). As well, historical records prove that most cyclones hit the east, north, and north-central areas of the island (Yoshitani et al., 2007).

Among 103 river basins in Sri Lanka, the Kelani, Kalu, Nilwala, Gin, Walawe and Mahaweli rivers are vulnerable to floods (Gunasekara, 2008). These rivers are frequently subjected to floods triggered by the SWM that arrives in late May. Thus, only some parts of the districts such as Kalutara, Kegalle, Gampaha, Ratnapura, Colombo and Galle can be inundated (DMC, 1999). However, the Kelani and Kalu rivers are recorded the highest flood frequencies and the accompanying flood damages among the river basins in the wet zone (UNDP, 2011).

Kelani River basin has experienced several notable flood events in recent years (Ministry of Irrigation & Water Resource Management, 2018). Consequently, the Kelani River basin experienced a total of 350 mm of rainfall across three days from 15^{th} to 17^{th} May in 2016 after the devastating flood in 1989. Accordingly, 23 out of 37 Divisional Secretariat (DS) divisions in the Kelani River basin were affected by the 2016 Flood. Out of them, 15 DS divisions were affected significantly (Ministry of Disaster Management in Sri Lanka, 2016).

Therefore, a large area is inundated almost annually due to floods in the Kelani River. Especially, the gently gradients encountered in lower parts of the river mainly cause the floods in the Kelani River basin due to the extremely heavy and prolonged rainfall in the upper catchment areas (UNDP, 2011).

In addition to that, other indirect causes of flooding in the Kelani River basin are lack of investment for drainage projects, unplanned town development, lack of coordination among Agencies, and lack of public awareness. With this brief background, the main objective of the present study is to analyze the flood hazard and map the spatial distribution of hazardous areas in downstream of the Kelani River basin. Accordingly, hazard assessment using GIS-based multi-criteria analysis was conducted to identify the magnitude and spatial distribution of flood hazard.

2. METHODOLOGY

Description of study area

The Kelani River is the second largest river and the third largest watershed in Sri Lanka. It is also the fourth-longest river in Sri Lanka (Mallawatantri et al., 2016). This river basin is located totally in the wet zone of the country. The Kelani River starts from the Adams Peak and the Kirigalpotta areas, which is an elevation 2,200 m above MSL in the Central Hills. The Kelani River basin receives an average annual rainfall of 3,450 mm and corresponding to a volume of about 7860 MCM out of which nearly 43% discharges into the sea (Ministry of Irrigation & Water Resource Management, 2018). The river carries a peak flow of about 800-1500 m^3/s during monsoons to the sea (De Silva et al., 2016). The Kelani River basin is located at the coordinates between Northern latitudes 6° 46′ & 7° 05′ and Eastern longitudes 79° 52′ & 80° 13′ (De Silva et al., 2016). Administratively, the Kelani River spreads over three provinces, namely, Western, Sabaragamuwa, and Central.

Topographically, the Kelani River basin consists of two types of landscapes as a mountainous upper region and a flat coastal plain/ lower basin (Figure 1). The upper basin is mainly covered with the vegetation types such as tea, rubber, grass, and forest. The downstream of the Kelani River basin is highly urbanized. The lower basin is a flat terrain about 100 m MSL and about 500 km^2. Accordingly, this study is mainly focused on downstream of the Kelani River basin (Figure 2).

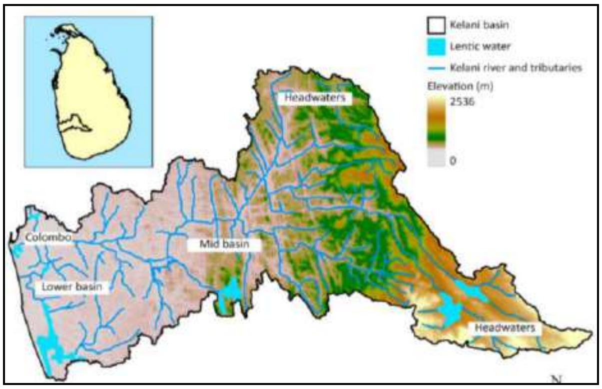

Figure 1: Topographic map of the Kelani River basin
Source: Mallawatantri et al., 2016

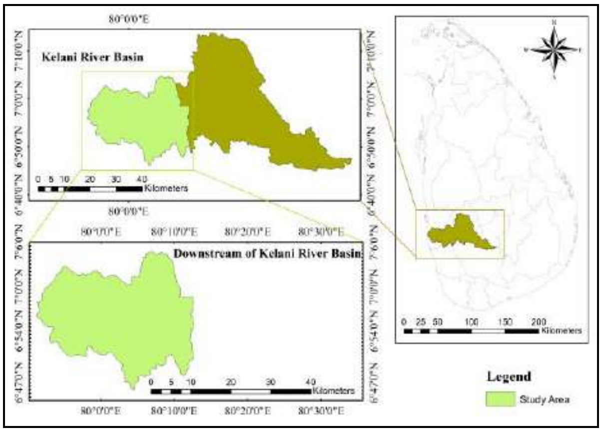

Figure 2: Absolute and Relative location of the study area

With the experience of the previous flood records of the Kelani River basin, the lower reach of the Kelani River basin was selected for the study area as mentioned before. The selected study area is in the Western and Sabaragamuwa provinces of Sri Lanka and located at the coordinates between Northern latitudes 6° 46′ & 7° 05′ and Eastern longitudes 79° 52′ & 80° 13′. When focused on the relative location, the study area is covered by four administrative districts. It is bounded by the Gampaha district in the North and the Kalutara district in the South. Kegalle and Ratnapura district lie in the East and the Indian Ocean lies in the West of the study area.

Accordingly, the study area covers the flood plains below Glencourse gauging station in Kegalle district up to the Nagalagam Street gauging station in Colombo district. The total length of the Kelani River in the study area is about 55 km. The total land area of the study area is about 810 km^2.

As mentioned before, the study area includes a part of two provinces out of three provinces in the Kelani River basin. Mainly, the western province covers 34% of the Kelani River basin with about 789 km^2. Sabaragamuwa province covers only 21 km^2 of the study area. Further, four out of the seven districts in the Kelani River basin are represented within the study area. The Colombo district represents the largest area with about 19% of downstream of the Kelani River basin, which is located within the district.

The study area is in the wet zone of Sri Lanka and it receives an annual rainfall varying from 500 mm to 4,000 mm with an average mean annual rainfall of around 2,440 mm over the elevation range of the basin. This large amount of annual rainfall becomes the main reason for flooding, as much of the total rainfall comes from intense storms or cyclones. Further, there is a significant variation in rainfall over the year. The highest rainfall in the study area has been recorded in October and May. The peak rainfall period coincides with the highest rainfall period in the main river. Since the study area is located within the wet zone, the flow of the main river, as well as its tributaries are significantly influenced by the rainfall and it tends to be torrential during the monsoonal periods (Ministry of Irrigation & Water Resource Management, 2018).

Data collection

The study was mainly based on primary and secondary data. As primary data, the opinions of experts and residents on flood factors regarding the study area were collected to decide the important flood causative factors in the study area. Therefore, primary data were collected by conducting structured interviews and a survey. The sampling method in data collection was the snowball sampling method and the sample size was 55. As the concerned key informants, 15 experts and 40 residents were interviewed and surveyed over the phone and conducting face-to-face interviews.

In addition to that, the following secondary data were used for the study and they were collected from different departments and institutes.

1. Meteorological data

Monthly rainfall data were obtained from the Department of Meteorology and Department of Agrarian Development of Sri Lanka. The rainfall data were collected for a period of 30-years from 1990 to 2019 at five rain gauge stations within the study area, namely Hanwella Group, Colombo, Kalatuwawa, Padukka Estate, and Angoda Mental Hospital to create the rainfall distribution map of the study area.

2. GIS data

GIS data layers were also used for the study. The flood hazard map was generated by using selected hazard factors. Therefore, vector datasets namely, land use, soil types, drainage network and sub-basins/watershed were obtained from the Department of Agrarian Development, Sri Lanka to generate basic thematic maps and hazard map for the study area. Further, 1:10,000 scale contour data with a contour interval of 5 m were obtained from the Department of Survey, Sri Lanka to create elevation and slope maps of the study area.

Data analysis

To assess and map the spatial distribution of flood hazard in the study area, Spatial Multi-criteria Decision Analysis (MCDA), image classification, Analytical Hierarchy Process (AHP) and weighted overlay analysis using pairwise comparisons were utilized as methods of analysis. Accordingly, the result of GIS-based multi-criteria hazard analysis was a map which allowed a ranking of hazard areas.

In this case, different areas were compared and evaluated with regard to different hazard criteria. Therefore, a new analysis method for flood hazard assessment was introduced by the current study. There are no widespread guidelines regarding the selection and ranked factors in flood hazard mapping. Therefore, the flood hazard factors related to the study area were determined by discussion with experts and residents, literature review, and personal observation (Ogato et al., 2020). Accordingly, the selected flood causative factors for this study were slope, elevation, soil type, land use, drainage density, and rainfall due to the nature of the study area.

The flood hazard analysis processes were employed with weighting flood causative factors according to their relative contribution to trigger the flood using the GIS-based MCDA method of AHP. MCDA is a commonly used approach for evaluating causative factors to determine and classify the flood hazard zonation (Wang, Tang, and Zeng, 2011; Zou, Zhou, Zhou, Song and Guo, 2013; Gigovi´c, Pamu´car, Bajic and Drobnjak, 2017; Rimba, Setiawati, Sambah and Miura, 2017; Ogato, Bantider, Abebe and Geneletti, 2020). AHP is applied to a wide variety of decisions (Saaty, 1980; Perera et al., 2018), and to solve multi-criteria decision problems by setting their priorities (Ogato et al., 2020).

In this study, flood causative factors exposed to series of pairwise comparisons using the existing literature and opinions of experts consist of academics, engineering experts, professionals, and residents concerning the above mentioned 9-point intensity of relative importance scale (Table 1) proposed by previous studies (Perera et al., 2018; Ogato et al., 2020).

The AHP in this study was mainly done in four steps: construct the decision hierarchy; determine the relative importance of attributes and sub-attributes; evaluate each alternative and calculate its overall weight regarding each attribute and check the consistency of the subjective evaluations (Ouma and Tateishi, 2014; Perera et al., 2018; Ogato et al., 2020).

Accordingly, the pair-wise comparison matrix (Table 2) was normalized by Equation 1 (Perera et al., 2018; Ogato et al., 2020).

$$a_{ij} = \frac{1}{\sum_{i=1}^{n} a_{itj}} \quad \text{For all j = 1, 2, 3........ n}$$

…………. Equation (1)

To generate a weighted matrix (*W*), divide the sum of the normalized column of the matrix by the number of criteria used (*n*) based on Saaty's eigenvalue (*v*) using Equation 2 (Perera et al., 2018; Ogato et al., 2020).

$$W_{ij} = \frac{\sum_{j=1}^{n} a_{ij}}{n} \quad \text{For all i = 1, 2, 3........ n}$$

…………. Equation (2)

Table 1: Nine-point pairwise comparison scale

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one parameter over another
5	Strong importance	Experience and judgment strongly favor one parameter over another
7	Very strong importance	One parameter is favored very strongly and is considered superior to another: its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one parameter as superior to another is of the highest possible order of affirmation

Note: 2,4,6,8 can be used to express intermediate values for parameters that are very close in importance

Source: Ogato et al., 2020

Table 2: Pairwise comparison matrix of the flood hazard contributing

Flood Hazard Factors	Land use	Rainfall	Drainage Density	Elevation	Slope	Soil Type
Land use	1	5	2	2	2	2
Rainfall	1/5	1	2	2	2	2
Drainage Density	1/2	1/2	1	2	2	2
Elevation	1/2	1/2	1/2	1	2	2
Slope	1/2	1/2	1/2	1/2	1	2
Soil Type	1/2	1/2	1/2	1/2	1/2	1
Total	**3.20**	**8.00**	**6.50**	**8.50**	**8.50**	**11.00**

Note: λ_{max} represents the sum of the products between the sum of each column of the comparison matrix and the relative weights

Source: Ogato et al., 2020

Table 3: Normalized pairwise comparison matrix (Judgment matrix)

Flood Hazard Factors	Land use	Rainfall	Drainage Density	Elevation	Slope	Soil Type	Weight	Priority (%)
Land use	0.31	0.63	0.31	0.24	0.24	0.18	**0.32**	**31.6**
Rainfall	0.06	0.13	0.31	0.24	0.24	0.18	**0.19**	**19.1**
Drainage Density	0.16	0.06	0.15	0.24	0.24	0.18	**0.17**	**17.1**
Elevation	0.16	0.06	0.08	0.12	0.12	0.18	**0.12**	**11.9**
Slope	0.16	0.06	0.08	0.12	0.12	0.18	**0.12**	**11.9**
Soil Type	0.16	0.06	0.08	0.06	0.06	0.09	**0.08**	**8.4**
Total	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**100**

Note: The natural values were normalized by adding the column values and dividing the value of each cell by the total of column values Source: Ogato et al., 2020

Weight computed normalized pairwise comparison matrix is known as the Judgment matrix (Table 3). $[A]_{6\times6}$ is the judgment matrix. A relationship exists between the vector weights (W) and the judgment matrix $[A]_{6\times6}$ as shown in Equation 3 (Perera et al., 2018; Ogato et al., 2020).

$$AW = \lambda_{max} W \qquad \text{………… Equation (3)}$$

The λ_{max} value is an important validating parameter (Perera et al., 2018) in the pairwise comparisons in AHP. The quality of the output of the AHP is demanded to be severely related to the consistency of the pairwise comparison judgments (Ouma and Tateishi, 2014). In this situation, it is important to calculate the consistency ratio (*CR*) of the estimated vector (Perera et al., 2018; Ogato et al., 2020). To calculate the *CR*, the consistency index (*CI*) for each matrix of order *n* was obtained from Equation 4 (Perera et al., 2018; Ogato et al., 2020). The maximum threshold of *CI* is < 0.1 and *CR* < 10%.

CI = (λ_{max} – n) / (n – 1) ………… Equation (4)

The final calculation was the consistency ratio (*CR*) which is the ratio of the *CI* and random index (*RI*) as shown in Equation 5 (Perera et al., 2018; Ogato et al., 2020).

CR = $\frac{CI}{RI}$ ………… Equation (5)

The value of *RI* was suggested by Saaty (1980) which presents the value of the *RI* from matrices of order 1 to 10 (Table 4). Accordingly, the *RI* value for six parameters was 1.24 as suggested by Saaty.

Table 4: Random index (RI)

N	RI
1	0
2	0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

Source: Ogato et al., 2020; Perera et al., 2018

In this study,

λ_{max} = (3.20*0.32) + (8.00*0.19) + (6.50*0.17)+ (8.50*0.12) + (8.50*0.12) + (11*0.08)
= 6.60
n = 6
CI = (6.60 – 6) / (6 – 1) = 0.129
RI = 1.24
CR = (0.129 / 1.24) = 0.096 (9.6 %)

Accordingly, *CR* for the flood contributing factors in downstream of the Kelani River basin is 0.096 which is less than the standard 0.1 and 10%.

Hence, the pairwise matrix ranking is accepted. The order of normalized weight was land use (31.6%), rainfall (19.1%), drainage density (17.1%), elevation (11.9%), slope (11.9%), and soil type (8.4%).

Accordingly, the selected flood generating factors such as drainage density, elevation, land use, soil type, rainfall, and slope were combined for flood hazard assessment using ArcGIS/ ArcMap 10.4 software. Hence, the contour data converted into digital elevation model (DEM) and slope raster layers using the spatial Analyst tools in ArcGIS software. In this study, a drainage density map also created using the line density tool in ArcGIS software. The drainage density was calculated using the equation 6 (Ogato et al., 2020).

D = L/A ...…………………… Equation (6)

Where,
D = Drainage density of watershed
L = Total length of the drainage channel in the watershed
A = Total area of the watershed

Further, the rainfall distribution map generated using Inverse Distance Weighted (IDW) tool in ArcGIS. The selected factors were converted into the raster format and transformed to GCS Kandawala geographic coordinate system. To run MCDA and generate the final flood hazard map, the selected factors were developed using the weighted overlay tool in ArcGIS. Moreover, the main calculations in AHP have mainly done using Microsoft Excel 2010.

3. RESULTS AND DISCUSSION

In flood hazard assessment, slope, elevation, rainfall, drainage density, land use, and soil type were selected as the major flood-generating factors in the study area. The flood-generating raster layers have been classified based on the flooding capacity of the area. Accordingly, based on the susceptibility to flooding, all factors have been classified into five classes as very low, low, moderate, high and very high; and ranked from 1 to 5 respectively. The results of the flood hazard factor analysis can be summarized as follows.

Table 5: Scaled and weighted flooding hazard induced factors for the river basin

Parameter	Relative Weight (%)	Reclassified Parameter	Ranking	Hazard
Land use (based on water absorption level)	**31.6**	Forest/ Forest Plantation/ Scrub land	1	Very Low
		Barren land	2	low
		Coconut/ Rubber/ Tea/ Cinnamon/ Chena/ Home Garden/ Keera Vagawa/ Paddy	3	Moderate
		Residential Area/ Built up area	4	High
		Marsh/ Water Bodies	5	Very High
Rainfall (mm)	**19.1**	2392 – 2750 2750 – 3138 3138 – 3453 3453 – 3747 3747 – 4220	1 2 3 4 5	Very High High Moderate Low Very Low
Drainage Density (Sq. Km.)	**17.1**	2.5 – 4.4 1.7 – 2.5 1 – 1.7 0.5 – 1 0 – 0.5	1 2 3 4 5	Very Low Low Moderate High Very High
Elevation (m)	**11.9**	> 20 15 – 20 10 – 15 5 – 10 3 – 5	1 2 3 4 5	Very Low Low Moderate High Very High
Slope (percent)	**11.9**	> 12 9 – 12 6 – 9 3 – 6 0 – 3	1 2 3 4 5	Very Low Low Moderate High Very High
Soil Type (based on drainage capacity)	**8.4**	Bog and Half-Bog soils: high terrain	1	Very Low
		Red-Yellow Podzolic soils- steeply dissected	2	Low
		Red-Yellow Podzolic soils with strongly mottled subsoil & low Humic Gley soils	3	Moderate
		Red-Yellow Podzolic soils with soft or hard laterite: rolling and undulating terrain	4	High
		Alluvial soils of variable drainage and texture/ Bog and Half-Bog soils: flat terrain/ Regosols on the recent beach and dune sands	5	Very High

Analysis of Land use factor for flood hazard

The study mainly revealed that land use was the main flood hazard contributing factor in the study area. Land-use types of the study area were forests, forest plantation, coconut lands, rubber lands, tea lands, cinnamon lands, scrublands, residential areas, built-up areas, chena, home-gardens, Keera *vagawa*, paddy lands, barren lands, marshy lands and water bodies.

Accordingly, those land-use types were rated as very low, low, moderate, high and very high flood hazard areas in order of their capacity to increase or decrease the rate of flooding (Table 5). The spatial distribution of different flood hazard zones portrayed that the Western portion of the study area and areas along the Kelani River basin belong to high and very high flood hazard zones (Figure 3). The map also depicts that the middle part and most of the eastern part of the study area were in the moderate hazard zone.

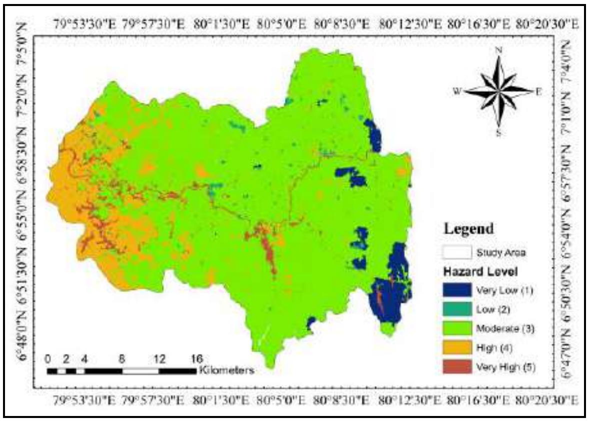

Figure 3: Susceptibility to flooding: rating of land use types

Many studies have revealed that a high rate of surface runoff is more likely on residential areas than on vegetated grounds (Fura, 2013; Mngutyo and Ogwuche, 2013). Especially, forest and scrublands highly reduce the impact of rainfall and the amount of water that ends up in the form of surface runoff. Water-resistant surfaces in the settlement areas such as buildings, concrete, paved areas, and roads decrease the infiltration of water into the soil and increase the amount of surface runoff (Tucci, 2007; Jha, Bloch and Lamond, 2012; Fura, 2013; Mngutyo and Ogwuche, 2013; Hall et al., 2014; Ogato et al., 2020). Hence, land use characteristics were significant parameters in evaluating the probable areas to flood hazard as well as vulnerability to flood risk (Ogato et al., 2020). Therefore, it can be identified that there is a significant change in the downstream of the Kelani River basin of which land-use type is the main flood hazard contributing factor in the study area based on their influence on floods.

The analysis also revealed that 4.17% (33.75 km^2), 1.19% (9.66 km^2), 77.25% (625.52 km^2), 13.86% (112.17 km^2), and 3.53% (28.62 km^2) of total land area in the study area falls under very low to very high flood hazard level respectively (Table 6). Therefore, it can be concluded that about 18% of the study area lies in high to a very high hazard zone of which residential/built-up areas and marsh/water bodies are most vulnerable to floods. The highest proportion (77%) of the study area was a moderate probability of flood hazard of which agricultural lands are more vulnerable to floods. However, the map of susceptibility to flooding also depicted that about 5% of the study area belongs to low and very low hazard zone of which forests and bare lands are least vulnerable to floods.

Table 6: The area covered by different flood hazardous levels subject to land use factor

Hazard Level	Area (sq. km.)	Percentage (%)
Very Low	33.75	4.17
Low	9.66	1.19
Moderate	625.52	77.25
High	112.17	13.86
Very High	28.62	3.53
Total	**809.76**	**100.00**

Analysis of Rainfall factor for flood hazard

The amount of runoff is correlated with the amount of rainfall experienced in an area. When the area receives heavy rainfall, the water level rises above riverbanks and commences overflowing leading to flooding (KRCS, 2013; Few, Ahern, Matthies and Kovats, 2004). The Kelani River floods are mainly due to the high flow rate and rainfall in upper catchment areas. Especially, the flood is mainly dominated by the rainfalls of the middle parts of the catchment and the areas on lower basin catchments are highly affected to floods (Hettiarachchi, 2020).

In this study, the average annual rainfall between 1990 and 2019 was ranged from 2392 mm to 4220 mm. According to the characteristics of the Kelani River basin, the lowest rainfall category (2392 mm – 2750 mm) of the study area was ranked as a very high flood hazard whereas the highest rainfall category (3747 mm – 4220 mm) was ranked as a very low flood hazard class (Table 5).

Accordingly, the highest proportion of the study area (34.31% and 277.80 km^2) was experienced moderate flood hazards of which these areas are close to the upper catchment area (Table 7).

Table 7: The area covered by different flood hazardous levels subject to rainfall factor

Hazard Level	Area (sq. km.)	Percentage (%)
Very Low	107.54	13.28
Low	132.02	16.30
Moderate	277.80	34.31
High	115.38	14.25
Very High	177.02	21.86
Total	**809.76**	**100.00**

The analysis also showed that about 30% of the study area belongs to low and very low hazard zone. Only 36% of the study area was in high to a very high hazard zone of which lower basin is most vulnerable to floods due to the behavior of water flow.

The spatial distribution of flood hazard levels by receiving the amount of rainfall indicated that the Eastern and Southern portions of the study area are lower hazard levels while the areas in the Western part is high hazardous levels (Figure 4). Because of the low-lying areas in the study area are inundated due to heavy rainfall which receives to the middle reach of the Kelani River. According to the opinions of experts and residents, the floods in the lower reach (below Avissawella) are more critical due to large areas of spread and longer durations of inundation. Those areas are highly developed, populated and susceptible to heavy damages during floods.

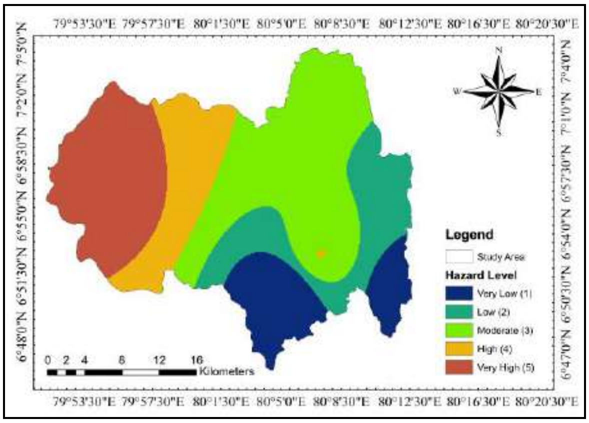

Figure 4: Susceptibility to flooding: rating of rainfall distribution

Analysis of Drainage density factor for flood hazard

Analysis of drainage density in the study area was indicated that the highest drainage density is 4.42 km^2 while the lowest drainage density is 0 km^2. Accordingly, the lowest drainage density category (0 – 0.5 km^2) was ranked as a very high flood hazard drainage density category, while the highest drainage density category (2.5 – 4.4 km^2) was rated as a very low flood hazard category (Table 5).

Frequently, the drainage system is related to the nature of the soil, rainfall amount, evapotranspiration rates, rock structure, and properties of the area (Ogato et al., 2020). Therefore, low drainage density areas have few channels to drain water and could end up as floodwater (McKnight & Hess, 2007; Ritter, 2010).

The results of the density analysis indicated that the poorly drained areas are highly affected to flood hazards whereas well-drained areas are less influence on flood hazards (Chibssa, 2007; Wondim, 2016; Ogato et al., 2020). The map on flood hazard zones under different drainage density was also indicated that the highest flood hazard areas in the study area are not mainly located along the river lines, and they are located at the periphery of the study area (Figure 5).

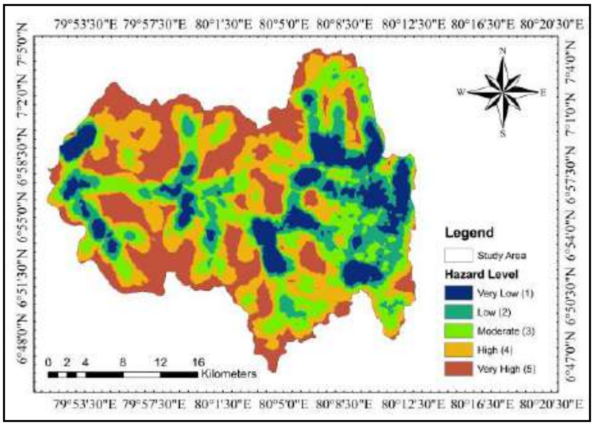

Figure 5: Susceptibility to flooding: rating of drainage density

Especially, 25.72% (208.26 km^2) of the total land cover in the study area was under the high hazard zones of floods while 25.36% (205.38 km^2) of the total land cover was under the very high probability of floods due to the low drainage densities (Table 8). Accordingly, only half of the study area (50%) was highly affected to flood hazards due to the poorly drained of the study area. However, high drainage density areas are well-drained as more permeable rock structures and soil allow more drainage and thus reduced the possibility of flooding (Waugh, 2009). Accordingly, only a quarter of the study area that is 12.12% (98.17 km^2), and 15.16% (122.79 km^2) of the total land area, were a very low and low probability of floods respectively.

Table 8: The area covered by different flood hazardous levels subject to drainage density factor

Hazard Level	Area (sq. km.)	Percentage (%)
Very Low	98.17	12.12
Low	122.79	15.16
Moderate	175.16	21.63
High	208.26	25.72
Very High	205.38	25.36
Total	**809.76**	**100.00**

Analysis of Elevation factor for flood hazard

Elevation has a significant role in controlling the movement of runoff direction and depth of the water level (Ogato et al., 2020; Gigovi´c et al., 2017). The highest elevation of the study area is 399 m while the lowest elevation is 3 m. Consequently, the lowest elevation class (3 m – 5 m) was ranked as a very high flood hazard elevation category while the highest elevation category (> 20 m) was ranked as a very low flood hazard elevation category according to their influence on flood hazard (Table 5).

Accordingly, the study area represented a high flood hazard level in the western and some middle parts of the study area due to the low elevation of those areas (Figure 6). Therefore, it can be identified that the elevation is also an important flood hazard contributing factor in the study area.

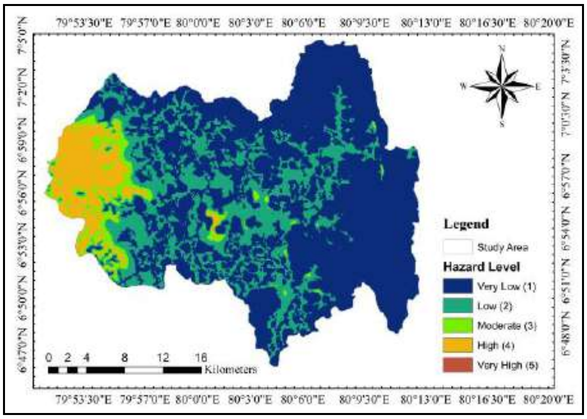

Figure 6: Susceptibility to flooding: rating of elevation

Further, the area covered by the highest elevation class (> 20 m) was under the very low hazard zone and that was 63.14% (511.28 km^2) of the study area (Table 9). The area covered by the lowest elevation (3 – 5 m) of the study area was under the highest probability of floods. Therefore, 0.01% of the study area was under the highest probability of floods. Accordingly, the study revealed that only 8% of the study area is highly susceptible to flooding.

Table 9: The area covered by different flood hazardous levels subject to elevation factor

Hazard Level	Area (sq. km.)	Percentage (%)
Very Low	511.28	63.14
Low	201.97	24.94
Moderate	34.43	4.25
High	62.07	7.66
Very High	0.01	0.01
Total	**809.76**	**100.00**

Analysis of Slope factor for flood hazard

The slope was also considered one of the main flood hazards contributing factors in the study area because the slope is a key factor in determining the rate and duration of water flow. For example, flat surface areas are more hazardous concerning the occurrence of floods with steeper surfaces (Gigovi´c et al., 2017; Ogato et al., 2020; Rimba et al., 2017).

The percent of the slope in the study area has displayed the range between the highest slope of 63% and the lowest slope of 0%. Therefore, in the classification process, the areas with the lowest slope values (0 - 3%) were considered as a very high flood hazard slope angle category and then ranked to class 5. In the case of the slope, the areas with the highest slope values (> 12%) were considered as a very low flood hazard slope angle category and then ranked as class 1 (Table 5).

The areas of a low percent of the slope were assigned to flat plains because of their ability to hold water and water spreads out of the wide area. Thus, such areas are more susceptible to flooding due to the intensive rainfall (Van Westen et al., 2011). However, the areas of high percent of the slope were assigned to the steep hill slopes because they have soils with low infiltration capacities and high speed of surface runoff. Thus, such areas are less probability of flooding (Hill & Verjee, 2010; Smithson, Addison & Atkinson, 2002).

Accordingly, the study area represented that a very low flood hazard level is in the eastern part due to the high slope angle in that area (Figure 7). However, a very high flood hazard zone was identified in the western and middle part of the study area due to the distribution of fewer slopes. Accordingly, the fewer slope areas lead to flooding due to the inundation with the influence of high-intensity rainfall (Gigovi´c et al., 2017; Rimba et al., 2017).

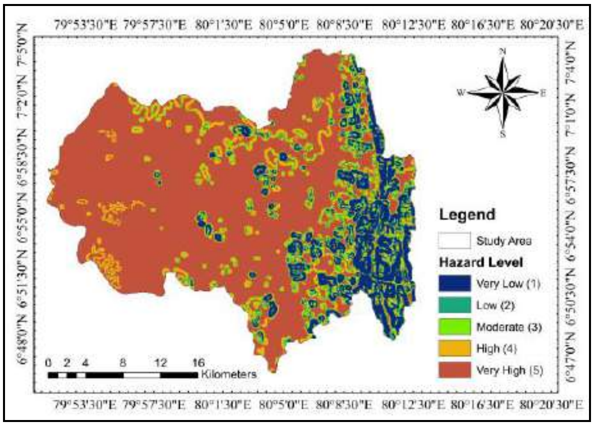

Figure 7: Susceptibility to flooding: rating of slope

On the other hand, 12.25% (99.20 km^2) of the total extent of downstream of the Kelani River basin was a very low likelihood of floods and 67.41% (545.85 km^2) of the total land area was a very high likelihood of floods (Table 10). However, 4.29% (34.75 km^2), 6.77% (54.79 km^2), and 9.28% (75.17 km^2) of land areas could be considered low, moderate, and high hazardous areas in the study area respectively.

Table 10: The area covered by different flood hazardous levels subject to slope factor

Hazard Level	Area (sq. km.)	Percentage (%)
Very Low	99.20	12.25
Low	34.75	4.29
Moderate	54.79	6.77
High	75.17	9.28
Very High	545.85	67.41
Total	**809.76**	**100.00**

However, the study indicated that the influence of slope and elevation factor to flood hazard of the study area are quite similar.

Analysis of Soil factor for flood hazard

The study also revealed that influence of soil type to flood hazard of the study area is the lowest contribution among all flood causative factors. Especially, floods can more likely occur over saturated soils, which mean that both soil moisture status and precipitation intensity play a significant role (Seneviratne et al., 2012).

The study revealed that the study area is mainly covered by the Red-Yellow Podzolic soils with soft or hard laterite: rolling and undulating terrain. This soil type was covered by 64% (522.03 km^2) of the total extent of downstream of the Kelani River basin. The study also revealed that this soil type lied in high (class 4) probability of occurrence of floods (Table 5 & Figure 8) of which surface runoff was more dominant in the hard laterite than the water infiltration (Ministry of Irrigation & Water Resource Management, 2018).

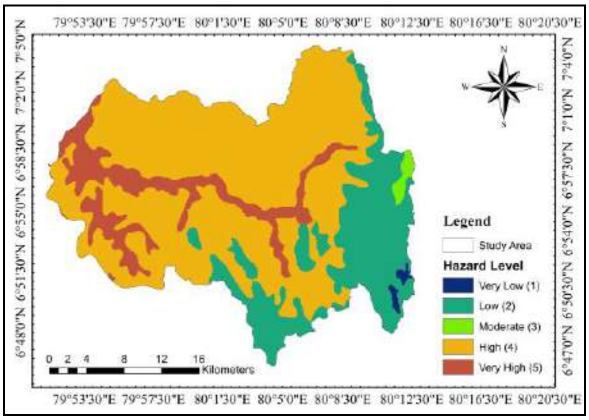

Figure 8: Susceptibility to flooding: rating of soil types

However, 12.12% (98.12 km^2) of the total land area was a very high likelihood of floods of which Bog and Half-Bog soils in flat terrain, Alluvial soils, and sandy Regosols of the dunes and elevated beach were dominant along the Kelani River banks and the river mouth. These soils mostly consist of fine-grained clay soils. Especially, alluvial soils are well developed in the lower regions of the river basin, especially from Kaduwela to Colombo by the previous floods (Ministry of Irrigation & Water Resource Management, 2018). Therefore, since clay soils have fine particles, these areas are more prone to the accumulation of surface runoff for a longer period (Ogato et al., 2020) because floods occur in areas where soils have low infiltration capacity (Ouma and Tateishi, 2014). However, sand deposits can be identified in the middle regions of the Kelani River and these sands are extensively developed in the river basin throughout the year (Ministry of Irrigation & Water Resource Management, 2018). Most of the finer sands also reach up to the Kelani River mouth. Especially, the alluvial and sand aquifers in the river basin are recharged by rainfall and seepage from the river. However, since groundwater levels of the above-mentioned soils are at a shallow depth, infiltration is limited. Therefore, these areas can highly hazardous to flooding during extreme rainfall events.

Table 11: The area covered by different flood hazardous levels subject to soil factor

Hazard Level	Area (sq. km.)	Percentage (%)
Very Low	3.91	0.48
Low	179.39	22.15
Moderate	6.31	0.78
High	522.03	64.47
Very High	98.12	12.12
Total	**809.76**	**100.00**

It also indicated that 0.48% (3.91 km^2) of the total extent of the study area is very low (class 1) likelihood of floods (Table 11). Only 22.15% (179.39 km^2) of land areas were low flood hazard of which saturation of Red-Yellow Podzolic soils (steeply dissected) are very low (Moormann and Panabokke, 1961). However, saturation of Red-Yellow Podzolic soils with strongly mottled subsoil and low Humic Gley soils are higher than Red-Yellow Podzolic soils with steeply dissected (Moormann and Panabokke, 1961).

Accordingly, only 0.78% (6.31 km^2) of the land area was identified as moderate flood hazardous areas.

Analysis of Flood hazard

Weighted overlay analysis was used as a Multi-criteria evaluation technique to assess the flood hazard or the probability of the occurrence of floods (Saaty, 1980; Perera et al., 2018) in the study area. From this analysis, the above-mentioned six factors were compared to each other in the contribution of flood hazard (Ouma and Tateishi, 2014; Gigovi´c et al., 2017; Ogato et al., 2020). In other words, the flood hazard assessment map was produced by flood generating factors such as slope, elevation, rainfall, drainage density, land use, and soil type in the downstream of the Kelani River basin using GIS along with multi-criteria AHP techniques and a weighted overlay.

Accordingly, the flood hazard assessment map shows that only 30% of the study area was under high and very high hazard zones (Table 12). The study also revealed that the highest proportion of the study area (53.94%) lies in moderate hazard zone. Only 1.75% (14.20 km^2) of the study area was a very low probability to the occurrence of flood hazard.

Table 12: The area covered by flood hazardous levels subject to all causative factors

Hazard Level	Area (sq. km.)	Percentage (%)
Very Low	14.20	1.75
Low	114.66	14.16
Moderate	436.79	53.94
High	237.23	29.30
Very High	6.88	0.85
Total	**809.76**	**100.00**

Therefore, the non-flooded extent of the study area was relatively small (only 16%) and thus most of the study area was relatively more flooded due to the contribution of above-mentioned six parameters.

When considered to the spatial distribution of flood hazard in the downstream of the Kelani River basin, the flood hazard map indicated that the very high flood hazard areas are concentrated in the western side of the downstream of the Kelani River basin of which build up/ residential and low-lying flat areas are most vulnerable to floods (Figure 9).

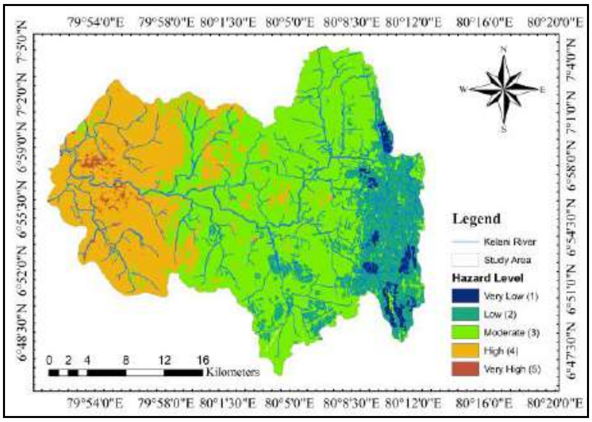

Figure 9: Flood hazard map of downstream of the Kelani River basin

Further, high hazardous areas are also concentrated in the western side and some areas in the middle part of the study area. However, the study revealed that many areas in the middle part of the study area are at moderate hazard level.

Moreover, the flood hazard map presents that there were low and very low flood hazard probability in the highlands which is in the eastern and southern parts of the study area. Therefore, it can be identified that slope angle less than 6% with terrain elevations less than 10 meters; low infiltration capacity of soils; low infiltration of water into the soil and high rate of surface runoff of land uses; drainage density less than 1 km^2 plus less than 2750 mm of average annual rainfall in the study area is considered highly hazardous. Accordingly, the flood hazard map of the study area represented the magnitude of flood events of downstream of the Kelani River basin.

In this study, an actual inundated map of recent flooding event in the Kelani River basin was used to validate the flood hazard map of downstream of the Kelani River basin. Accordingly, the inundation map of the 2016 flood shows that some parts of Colombo, Kelaniya, Kolonnawa, Sri Jayawardanapura Kotte, Biyagama, Kaduwela, Homagama, Hanwella, Padukka and Dompe DS divisions were inundated (Figure 10). When compared these inundated areas with flood hazard map of downstream of the Kelani River basin, the flood hazard map of the study area revealed that some parts of Kelaniya, Sri Jayawardanapura Kotte, Kaduwela and Kolonnawa belong to high and very high hazard zones. The flood hazard map also shows that some parts of Biyagama, Kaduwela, Homagama, Hanwella, and Dompe were moderately hazardous. Therefore, the study identified that the distribution of flood-affected areas in the inundation map of the 2016 flood and flood hazard zones of the study area are quite similar.

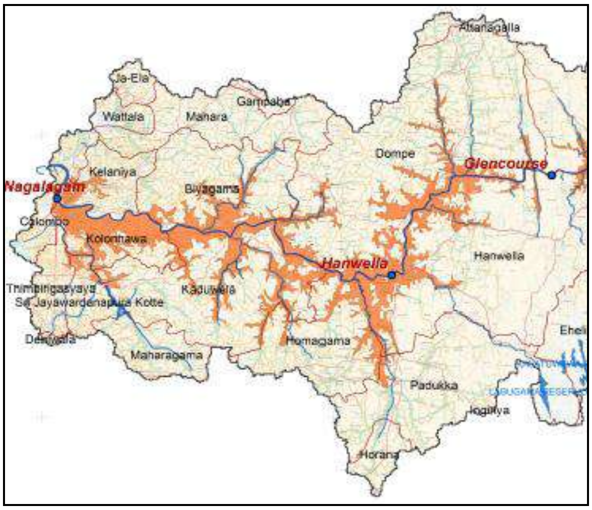

Figure 10: Flood inundation areas in 2016 Flood (Source: Irrigation Department, 2020)

Hence, the present study suggests that flood hazard map of the study area can be fundamental to the entire mapping process particularly in the beginning as well as a flood hazard map forms the basis for flood emergency maps and other related maps for the downstream of the Kelani River basin. The study also suggests that the GIS-based MCDA method can be very effective for mapping flood hazards that may be beneficial for decision-making in flood management. The methodology employed here can also be applied for data-limited areas anywhere in the world. Furthermore, the study is recommended to conduct a flood risk assessment for identifying the exposure and vulnerability of different types of element-at-risks.

4. CONCLUSIONS

The study was carried out to identify the spatial distribution of flood hazard in downstream of the Kelani River basin using the GIS-based spatial multi-criteria analysis method. The study tried to incorporate AHP-based criteria weights and parameter rankings for decision-making in complex relations. Six parameters related to hydro-geomorphological characteristics were prepared in ArcGIS software and clustered into five classes as very low, low, moderate, high and very high for assigning ratings based on their influence on floods. The criteria and their weights were combined linearly to obtain the final hazard map.

The study mainly revealed that land-use is the main flood hazard contributing factor among considered flood causative factors in the study. The analysis also presented that around 18% of the study area lies in high to a very high hazard zone of which residential/built-up areas and marsh/water bodies are most vulnerable to floods.

According to the perceptions of the experts, the Kelani River floods are mainly due to the high flow rate and rainfall in the upper catchment areas. Especially, the flood is mainly dominated by the rainfalls of the middle parts of the catchment and the areas on lower basin catchments are highly affected by floods. The spatial distribution of flood hazard levels by rainfall distribution of the area showed that the eastern and southern portions of the study area are low hazard levels while the areas in the western part are high hazardous levels. According to the experts and residents, the floods in the lower reach (below Avissawella) are more critical due to large areas of spread and longer durations of inundation. Those areas are highly developed, populated and susceptible to heavy damages during floods.

The results of the density analysis have indicated that the poorly drained areas are highly affected to flood hazards whereas well-drained areas are less influence by flood hazards. The map on flood hazard zones under different drainage densities has also indicated that the highest flood hazard areas in the study area are not mainly located along the river lines, and they are located at the periphery of the study area. Accordingly, only half of the study area (50%) was highly affected to flood hazards due to the poorly drained of the study area.

The study identified that elevation is one of the less important flood hazard contributing factors to the study area. Accordingly, the study revealed that only 8% of the study area is highly susceptible to flooding. The study also indicated that there is a similar contribution of slope and elevation factors to the flood hazard of the study area. Besides, the study has revealed that influence of soil type to flood hazard of the study area is the lowest contribution among all considered flood causative factors.

The flood hazard assessment map shows that the highest proportion of the study area (53.94% or 436.79 km^2) lies in the moderate hazard zone. Only 16% (129 km^2) of the study area was a very low and low probability of the occurrence of flood hazard. Therefore, the non-flooded extent of the study area was relatively small and most of the study area was relatively more flooded due to the contribution of the above-mentioned six parameters.

The flood hazard map also indicated that the very high flood hazard areas are concentrated in the western side of the downstream of the Kelani River basin of which build-up/residential and low-lying flat areas are most vulnerable to floods. Further, high hazardous areas were also concentrated in the western side and some areas in the middle part of the study area. There was low and very low flood hazard probability in the highlands which is in the eastern and southern parts of the study area. Further, the study has identified that the distribution of flood affected areas in the inundation map in the 2016 and flood hazard zones of the study area are quite similar.

Hence, the present study suggests that the GIS-based MCDA method can be very effective for mapping flood hazards that may be beneficial for decision-making in flood management. Furthermore, the study is recommended to conduct a flood risk assessment for identifying the exposure and vulnerability of different types of element-at-risks.

5. ACKNOWLEDGEMENT

I wish to express my gratitude to Institute of Human Resource Advancement (IHRA), University of Colombo for supporting me throughout MSc degree programme. I also highly appreciate Water Management Branch in Department of Agrarian Development, Computer Division in Department of Meteorology and Survey Department for their valuable help in acquiring the necessary data and information for my research. Further, I would like to thank anonymous reviewers for comments on this manuscript.

6. REFERENCES

Basnayake, S., Punyawardena, B.V.R., Jayasinghe, S., Gupta, N., Shrestha, M.L., & Premalal, K.H.M.S. (2019). Climate Smart Disaster Risk Reduction Interventions in Agriculture Sector – Flood hazard – A Report.
Available:
http://www.adpc.net/igo/category/ID1578/doc/2020-cHxj0N-ADPC-Report_Climate_Smart_DRR.pdf
[Accessed: 3rd Dec. 2020].

CHA. (2016). Impacts of Disasters in Sri Lanka, The Consortium of Humanitarian Agencies, Sri Lanka.

Chibssa, A.F. (2007). Flood Hazard Assessment Using GIS in Bacho Plain, Upper Awash Valley, Southwest of Addis Ababa. (Master of Science Thesis), University of Addis Ababa.

Dankers, R. & Feyen, L. (2009). Flood hazard in Europe in an ensemble of regional climate scenarios, Journal of Geophysical Research – Atmospheres, 114 pp 16-28.

De Moel, H., Van Alphen, J., & Aerts, J.C. (2009). Flood maps in Europe – methods, availability, and use. Natural Hazards and Earth System Sciences, 9: pp 89-301.

De Silva, M.M.G.T.D., Weerakoon, S.B., & Herath, S. (2016). Event-Based Flood Inundation Mapping Under the Impact of Climate Change: A Case Study in Lower Kelani River Basin, Sri Lanka, Hydrology, 7(228), pp 1-24. Available: DOI:10.4172/2157-7587.1000228 [Accessed: 3rd Dec.2020].

Disaster Management Centre. (1999). Sri Lanka Country Report. Available: https://issuu.com/suzanne_brady/docs/sri_lanka_country_report [Accessed: 25th Nov 2020].

Few, R., Ahern, M., Matthies, F., & Kovats, S. (2004). Floods, Health, and Climate Change: A Strategic Review. Tyndall Center Working Paper No. 63. Tyndall Centre for Climate Change Research, Norwich.

Fura, G.D. (2013). Analyzing and Modeling Urban Land Cover Changes for Run-off Modeling in Kampala, Uganda. (Master of Science Thesis), University of Twente, Netherlands.

Gigovi´c, L., Pamu´car, D., Baji´c, Z., & Drobnjak, S. (2017). Application of GIS-Interval rough AHP methodology for flood hazard mapping in urban areas. Water, 9(360), pp 1-26.

Gunasekara, I.P.A. (2008). Flood Hazard Mapping in Lower Reach of Kelani River, ENGINEER, 41(5): pp 149 – 154. Available: https://pdfs.semanticscholar.org/1f85/93b04767a3dfa6c97bf4b87d6367641aa1f4.pdf [Accessed: 30th June 2021].

Hall, J., Artheimer, B., Borga, M., Brazdil, R., Claps, P., Kiss, A., Kjeldsen, T.R., Kriauciuniene, J., Kundzewicz, Z.W., Lang, M., Liasat, M.C., Macdonald, N., Mcintyre, N., Mediero, L., Merz, B., Merz, B., Molnar, P., Montanari, A., Neuhold, C., Parajka, J., Perdigao, R.A.P., Plavcova, L., Rogger, M. Salinas, J.L., Sauquet, E., Schar, C., Szolgay, J., Viglione, A., & Bloschl, G. (2014). Understanding flood regime changes in Europe: A state of the hazard assessment. Hydrol. Earth Syst. Sci. Discuss, 18: pp 2735-2772.

Hettiarachchi, S. (2020). Hydrological Report on the Kelani River Flood in May 2016, ResearchGate. Available: https://www.researchgate.net/publication/342865359_Hydrological_Report_on_the_Kelani_River_Flood_in_May_2016 [Accessed: 4th Nov.2020].

Hirabayashi, Y., Kanae, S., Motoya, K., Masuda, K. & Doll, P. (2008). A 59-year (1948-2006) global meteorological forcing data set for land surface models, Part II: Global snowfall estimation. Hydrological Research Letters, 2: pp 65-69.

IWMI (2018). Getting ahead of disaster risks. Available: https://www.iwmi.cgiar.org/2018/08/getting-ahead-of-disaster-risks/ [Accessed: 30th June 2021].

Jha, A.K., Bloch, R., & Lamond, J. (2012). Cities and Flooding: A Guide to Integrated Urban Flood Risk Management for the 21st Century. Washington DC: The World Bank.

Kenya Red Cross Society. (2013). Status of Floods in Kenya, KCRS.

Mallawatantri, A., Goonatilake, S.D.A., Perera, N., Silva, G.D., & Weerakoon, D. (2016). Natural Resource Profile of the Kelani River Basin. Colombo: International Union for Conservation of Nature Sri Lanka Country Office and Central Environment Authority. Available: https://portals.iucn.org/library/sites/library/files/documents/2016-012.pdf [Accessed: 4th Nov.2020].

McKnight, T.L., & Hess, D. (9th Ed.). (2007). Physical geography: A Landscape appreciation. New Jersey: Prentice-Hall.

Ministry of Irrigation & Water Resource Management. (2018). Strategic Environmental Assessment of Development of River Basin Level Flood and Drought Mitigation Investment Plans-Kelani River Basin. Kotte: Sri Lanka. Available: http://documents1.worldbank.org/curated/fr/844811547109856952/pdf/Kelani-River-SEA-Study-Final-Report.pdf [Accessed: 16th Nov.2020].

Mirza, M.M.Q. (2011). Climate change, flooding in South Asia and implications, Regional Environmental

Change, 11(1): pp 95-107. DOI: 10.1007/s10113-010-0184-7 [Accessed: 30th June 2021].

Mngutyo, I.D., & Ogwuche, J.A. (2013). Urban development, flood, and disaster management: challenges of contemporary urban planning perspectives. International Journal of Innovative Environmental Studies Research, 1(1): pp 1-6.

Moormann F.R. & Panabokke, C.R. (1961). Soils of Ceylon. Available: https://edepot.wur.nl/482354 [Accessed: 30th June 2021].

Nandalal, H.K., & Ratnayake, U.R. (2010). Setting up of Indices to Measure Vulnerability of Structures during a Flood, Paper presented at International Conference on Sustainable Built Environment (ICSBE-2010).

Ogato, G.S., Bantider, A., Abebe, K., & Geneletti, D. (2020). Geographic information system (GIS)-based multi-criteria analysis of flooding hazard and risk in Ambo Town and its watershed, West Shoa zone, Oromia Regional State, Ethiopia, Journal of Hydrology: Regional Studies, 27: pp 1-13.

Ouma, Y.O., & Tateishi, R. (2014). Urban flood vulnerability and risk mapping using integrated multi-parametric AHP and GIS: methodological overview and case study assessment. Water, 6: pp 1515-1545.

Perera, E.N.C., Jayawardana, D.T., Ranagalage, M., & Jayasinghe, P. 2018. Spatial Multi-Criteria Evaluation (SMCE) Model for Landslide Hazard Zonation in Tropical Hilly Environment: A Case Study from Kegalle, Geoinformatics & Geostatistics: An Overview, 3: pp 1-7. Available: DOI: 10.4172/2327-4581.S3-004 [Accessed: 15th Nov. 2020].

Perera, K K.E (2017). The Socio-Economic Impacts of Flood Disaster in Sri Lanka, NeelaHaritha – the climate change magazine of Sri Lanka, 2: pp 8-16.

Phillips, M.C.K., Cinderich, A.B., Burrell, J.L., Ruper, J.L., Will, R.G. & Sheridan, S.C. (2015). The Effect of Climate Change on Natural Disasters, Weather, Climate, and Society, 7(1): pp 60-68. Available: https://www.jstor.org/stable/24907417 [Accessed: 30th June 2021].

Rimba, A.B., Setiawati, M.D., Sambah, A.B., & Miura, F. (2017). Physical Flood Vulnerability Mapping Applying Geospatial Techniques in Okazaki City, Japan. Urban Science, 1(7): pp 1-22.

Ritter, M.E. (2010). The physical environment: An introduction to physical geography. Stevens Point: University of Wisconsin. Available: http://www.uwsp.edu/geo/faculty/ritter/geog101/textbook/title_page.html [Accessed: 7th Dec.2020].

Saaty, T.L. 1st Ed. (1980). Analytic hierarchy process, New York: McGraw-Hill, USA.

Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C. & Zhang, X. (2012). Changes in climate extremes and their impacts on the natural physical environment, Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC), New York, USA, pp 109-230. Available: https://www.ipcc.ch/site/assets/uploads/2018/03/SREX-Chap3_FINAL-1.pdf [Accessed:30th June 2021].

Thomas, V., & López, R. (2015). Global increase in climate-related disasters. Asian Development Bank Economics Working Paper Series, p.466. Available: http://hdl.handle.net/11540/5274 [Accessed: 30th June 2021].

Tucci, C.E.M. (2007). Urban Flood Management. Geneva: World Meteorological Organization.

United Nations Development Programme. (2011). Practitioners' Guidebook on the Best Agricultural Practices for Drought and Floods in Sri Lanka, UNDP: Sri Lanka.

Van Westen, C.J., Alkema, D., Damen, M.C.J., Kerle, N. & Kingma, N.C. (2011). Multi-hazard risk assessment Distance education course Guidebook, Twente: United Nations University-ITC School on Disaster Geoinformation Management (UNU-ITC DGIM).

Waugh, D. (2009). Geography, an integrated approach. Cheltenham: Nelson Thornes.

Weerasinghe, K.M., Gehrels, H., Arambepola, N.M.S.I., Vajja, N.M.S.I., Herath, J.M.K. & Atapattu, K.B. (2018). Qualitative Flood Risk assessment for the Western Province of Sri Lanka, Procedia Engineering, 212: pp 503-510.

Wondim, Y.K. (2016). Flood Hazard and Risk Assessment using GIS and Remote Sensing in Lower Awash Sub-basin, Ethiopia. Journal of Environment and Earth Science, 6(9): pp 69-86.

World Meteorological Organization. (2013). Integrated Flood Management Tools Series.20: Flood Mapping. Geneva: Switzerland. Available from: https://library.wmo.int/doc_num.php?explnum_id=7341 [Accessed: 3rd Nov.2020].

Yoshitani, J., Takemoto, N., & Merabtene, T. (2007). Factor Analysis of Water-related Disasters in Sri Lanka, The International Centre for Water Hazard and Risk Management: Japan.

Zhiyu, L., Xiaotao, C., Zuhua, C., Haotao, W., Li, Z., Lai, E.S., Kunitsugu, M., Kim, Y., Cheong, T.S., Chung, G., & Espinueva, S.R. (2013). Guidelines on Urban Flood Risk Management. Macao: China.

Zou, Q., Zhou, J., Zhou, C., Song, L., & Guo, J.(2013). Comprehensive flood risk assessment based on set pair analysis variable fuzzy sets model and fuzzy AHP. Environ. Res. Risk Assess. 27: pp 525-546.