ENGINEER - Vol. LV, No. 01, pp. [23-30], 2022

DOI: http://doi.org/10.4038/engineer.v55i1.7483

Prioritization of Sub-basins of Nilwala River Basin for Flood Exposure using Multi Criteria Decision Analysis

B.M.L.A. Basnayake

Abstract: Morphometric analysis is useful to investigate flood proneness of a river basin. Prioritization of a river basin using relevant morphometric parameters and other causative parameters can be performed using Multi Criteria Decision Analysis (MCDA) method. Nilwala river basin is subjected to flooding every year. The aims of this research were to evaluate the morphometric parameters to understand the hydrological behaviour of the Nilwala river basin and to apply Technique of Order of Preference Similarity to the Ideal Solution (TOPSIS) for prioritizing its sub basins for flood exposure. This study considered morphometric parameters, climatic, geologic, and land use factors as causative factors for flooding. Geographic Information System of Environmental Systems Research Institute (ArcGIS) was used to extract parameters using Digital Elevation Model (DEM) of Shuttle Radar Terrain Mission (SRTM), soil map, and land use map of the river basin. TOPSIS was adopted for ranking the sub basins based on the causative factors. The Nilwala river basin was classified into three relative flood exposure zones as high, moderate, and low. The study indicated that analysis of morphometric parameters provides an intuitive information on sub basin characteristics related to flooding. Results showed that 20%, 54%, and 26% of the basin area have high, moderate, and low flood exposure, respectively. High and moderate flood exposure zones are mainly located along the main river course.

Keywords: Nilwala river basin, Morphometric parameters, Multi Criteria Decision Analysis (MCDA), Technique of Order of Preference Similarity to the Ideal Solution (TOPSIS), Flood exposure, Flood vulnerability index

1. Introduction

Morphometric analysis provides a quantitative description of the characteristics of a watershed. It has been applied to mass movement classification [1], watershed prioritization for soil and water conservation [2], identification of soil erosion prone areas [3] and for flood potential mapping [4]. Analysis of area, linear, and relief morphometric parameters of a watershed also provides a better understanding of its hydrological behaviour [5]. Floods occur as a result of topographical, geological, geomorphological, and hydrological factors. These multiple criteria/factors, of each sub basin of a watershed, contributing to flooding, can be evaluated to prioritize the sub basins or the alternatives. Multi-Criteria Decision-Analysis (MCDA) methods provide necessary tools for prioritizing multiple alternatives in case of collective contribution of multiple criteria. Prioritization of sub basins of a watershed is indicative to adopt different flood mitigation measures on priority basis. Different MCDA methods have been developed over time which differ from fundamental assumptions, calculation procedure, and in complexity such as Weighted Sum Model (WSM), Weighted Product Model (WPM), Analytical Hierarchy Process (AHP), Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE), and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), to name a few [6], [7]. Among those MCDA methods, TOPSIS is one of the widely applied MCDA methods to rank alternatives [8]. The advent of Geographic Information System (GIS) had made it easy to store, retrieve, and display spatial data providing a platform for extracting relevant criteria of the sub-basins. Application of GIS integrated MCDA falls into the category of vulnerability indicator method out of four distinct groups of flood vulnerability assessment methods: vulnerability indicator method; vulnerability curve method; disaster loss method; and modelling based method [9].

Nilwala river basin is considered as one of the flood hazardous basins in Sri Lanka. While flood elimination is not possible, attempts are made to mitigate the floods. The research studies on the Nilwala river basin were limited

*Eng. (Dr.) **B.M.L.A. Basnayake**, AMIE(SL), PhD (NUS, Singapore), B.Sc. Eng. (Hons) (Peradeniya), MIAHR, Senior Lecturer, Department of Civil and Environmental Engineering, University of Ruhuna, Sri Lanka.*
Email:arunoda@cee.ruh.ac.lk
https://orcid.org/0000-0002-4376-716X

to model based flood vulnerability assessments and flood forecasting. For example, Rathnayake et al. [10] incorporated the rainfall forecasts of Weather Research and Forecasting (WRF) model for predicting the floods of the Nilwala river basin using Hydrologic Engineering Center-River Analysis System (HEC-RAS) coupled with Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS). Lakmali et al. [11] also developed a flood inundation map for part of the Nilwala river basin using HEC-RAS hydraulic modelling software. This study considers index based flood vulnerability assessment using GIS integrated MCDA.

Flood vulnerability assessment comprises three factors, namely, exposure, a pre-flood activity; susceptibility, which involves pre-flood activities as well as activities during the flood; and resilience having both post-flood activities and activities during the flood. Exposure is defined as the "predisposition of a system to be disrupted a flooding event due to its location in the same area of influence" [8]. Susceptibility considers relative damageability to the system during floods while resilience is the capacity of the system to adapt. Further, generally, four components of a river system are suffered by floods: social, economic, environmental, and physical. These components of a river system are related to the vulnerability factors, i.e., exposure, susceptibility, and resilience, by vulnerability indicators. Flood vulnerability index (FVI) can be presented as [8]:

$$\begin{aligned} Total\ FVI = {} & Social\ FVI + Economic\ FVI \\ & + Environmental\ FVI \\ & + Physical\ FVI \qquad \ldots (1) \end{aligned}$$

This study considers physical component of the flood vulnerability comprising geo-morphological and climatic characteristics of the system, which mainly belongs to the flood exposure. Vulnerability can be geographically differentiated and can be thereby assessed at different spatial scales such as river basin, sub basin and urban areas. The FVI at sub basin scale will permit to identify hotspots related to flooding in a river basin and assist planners in prioritizing sub basins for further interventions. In this study, an attempt was made to evaluate morphometric parameters to understand the hydrological behaviour of the Nilwala river basin and to apply TOPSIS for prioritizing its sub basins for flood exposure as the first index based flood vulnerability assessment for the Nilwala river basin.

2. Methodology

2.1 Case Study

The Nilwala river basin has a catchment area of 1073 km^2. The river originates at Panilkanda at an elevation of 1050 m and falls into the Indian Ocean at Matara after traversing about 70 kms [11]. It discharges about 1500 MCM of water to the ocean annually.

The basin is located entirely in the wet zone of the country and receives mean annual rainfall of 3040 mm, varying from 1650 mm to 4000 mm. The basin has a bi-modal rainfall distribution and receives highest rainfall in May during South West (SW) monsoon and in October~November during second Inter Monsoon (IM2) period. According to the longitudinal profile of the Nilwala river, river gradient is very high upstream of Pitabeddara which is 40 kms away from the sea and flattens off thereafter. Water from up catchment of Pitabeddara comes with high velocity due to high elevation drop and releases into the downstream causing floods. Severe floods have been recorded in 1940, 1969, 1978, 1993, 1999, 2003, and 2017 [12].

The soil type is dominated by red-yellow podzolic. The river valleys and lower part of the basin are occupied by alluvial soils while poorly drained lower reaches of the floodplain contain bog soils. According to the land use map in year 2001, land use of the Nilwala river basin is dominated by home gardens (27%), forest (19%), tea (15%), and paddy (13%).

In this study, Nilwala river basin was divided into 11 sub basins considering its tributaries as shown in Figure 1.

2.2 Criteria and Alternatives

Decision matrix (X_{ij}) is the basis for MCDA. Particularly for flood potential analysis, it represents the score of different criterion (j) contributing for flooding for each alternative (i), i.e., sub basin. Figure 2 outlines the process of decision matrix preparation. Eleven sub basins of the Nilwala river basin as shown and named in Figure 1 were considered as the alternatives.

Variety of indicators has been used in flood vulnerability studies. The standard practice is to identify indicators, firstly based on suitability and usefulness using knowledge on the underlying phenomena and secondly based on the redundancy [8].

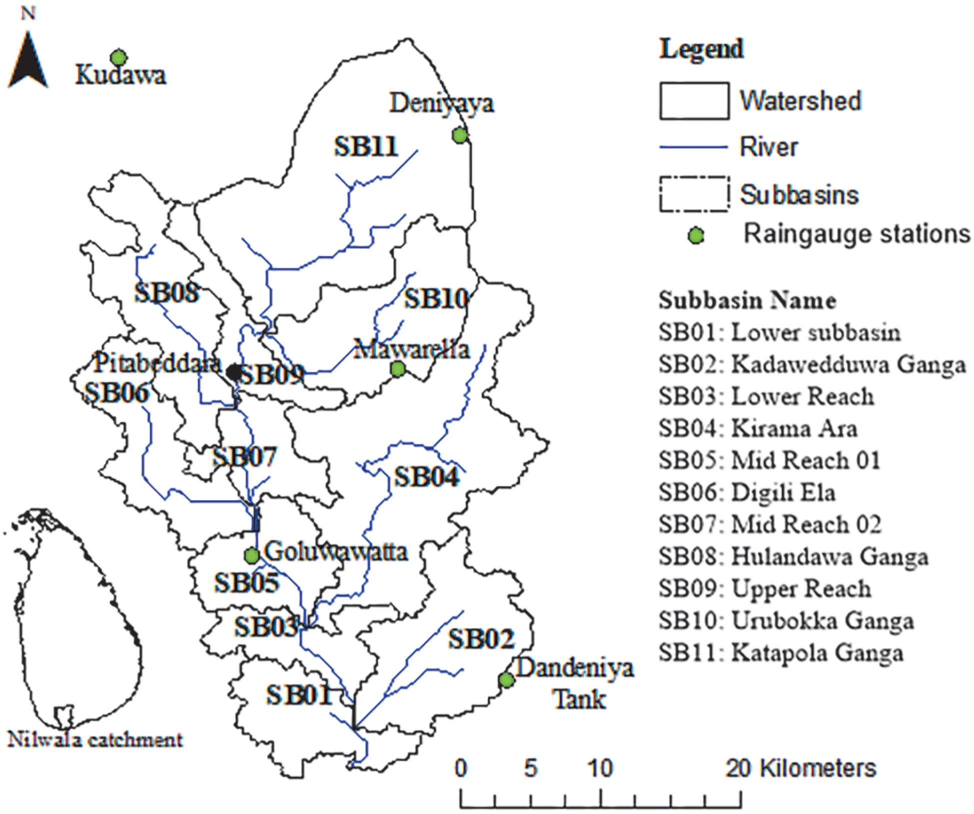

Figure 1 – Location of Nilwala River, River Network, its Sub-basins, and Raingauge Stations

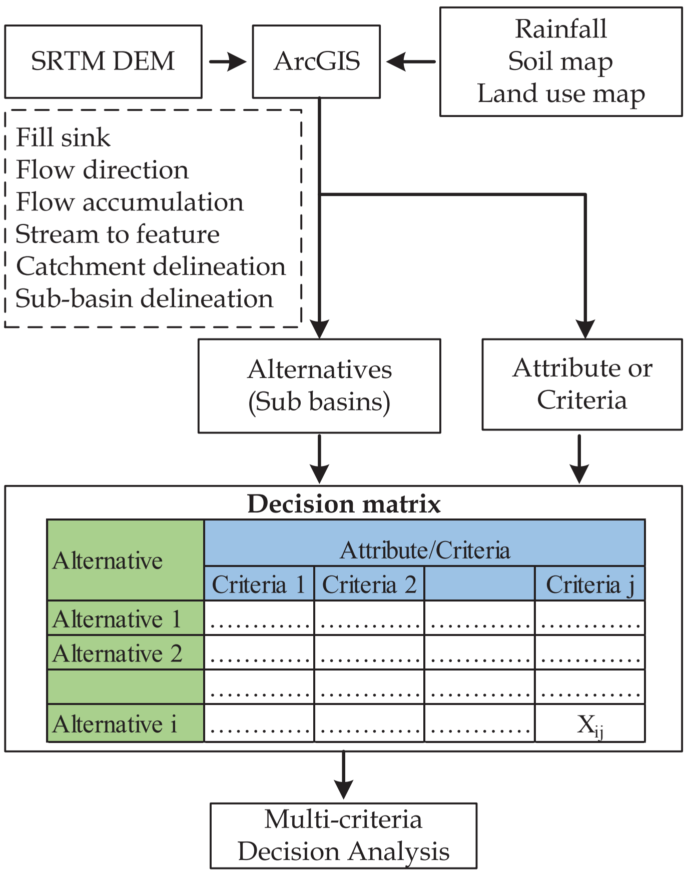

Figure 2 – Process of Decision Matrix Preparation

This study followed standard approach in selecting appropriate criteria. As the morphometric parameters, bifurcation ratio ($R_b = N_u/N_u + 1$: ratio of the number of streams of a given order to the number of streams of next higher order), elongation ratio ($R_e = 2\sqrt{A/\pi}/L$), relief ratio ($R_h = R/L$; R- Elevation difference between the river's source and the river's mouth), drainage density (D), ruggedness number (RxD), and texture ratio (total stream number/P) were considered, where A, P, and L are area, perimeter, and length of the sub basins, respectively. Total rainfall in May was taken as the runoff generating climatic parameter and curve number (CN) was considered to represent the contribution of soil and land use on runoff generation. Raingauge data were spatially interpolated using inverse distance weighting method and then sub basin averaged rainfall was obtained. The CN mainly depends on the hydrologic soil group and land cover. Soils are categorized into four hydrologic soil groups as, A, B, C, and D based on the infiltration rates. The CN was obtained by referring USDA-NRCS [13] for corresponding hydrologic soil group and land cover. Based on the relationship between soil type and land use, CN map was prepared for the entire basin. Area weighted CN value was calculated for each sub basin.

Morphometric parameters and sub basin averaged rainfall and CNs were derived using ArcGIS software. Shutter Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with 90 m resolution was used to delineate the Nilwala river basin and its sub basins (Figure 1). Land use maps and rainfall data were obtained from the Survey Department of Sri Lanka and Department of Meteorology, respectively.

2.3 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

The TOPSIS was developed by Hwang and Yoon [14] based on the concept that the best alternative should have the shortest Euclidean distance from the ideal solution. In this study, sub basins were prioritized for flood exposure using the TOPSIS method.

First, the decision matrix $\left(X_{ij}\right)$ was normalized using vector normalization to transform it into a dimensionless matrix allowing the comparison between different criteria. Score in the normalized decision matrix $\left(\bar{X}_{ij}\right)$ can be represented as:

$$\bar{X}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{ij}{}^2}} \quad \text{... (2)}$$

Then, weighted normalized matrix $\left(V_{ij}\right)$ was calculated by multiplying the normalized decision matrix by its associated weights$\left(w_j\right)$. Weights were found using the entropy method.

$$V_{ij} = w_j \bar{X}_{ij} \quad \text{... (3)}$$

From the weighted normalized matrix, ideal best solutions $\left(V_j^+\right)$ and ideal worst solutions $\left(V_j^-\right)$ were identified for each criterion.

Fundamental concept in TOPSIS is related to the calculation of Euclidean distance from the ideal best solution and ideal worst solution. The distance of alternative i from the ideal best solution (D_i^+) and the distance of alternative i from the ideal worst solution (D_i^-) were calculated by using the equations given below.

$$D_i^+ = \left[\sum_{j=1}^{m}\left(V_{ij} - V_j^+\right)\right]^{0.5} \quad \text{...(4)}$$

$$D_i^- = \left[\sum_{j=1}^{m}\left(V_{ij} - V_j^-\right)\right]^{0.5} \quad \text{...(5)}$$

Finally, performance score (P_i) of each alternative was calculated as follows.

$$P_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad \text{...(6)}$$

The value of P_i lies between 0 and 1. The alternative with highest P value, which is distance from the negative ideal solution, has high flood exposure.

The above procedure was implemented in MATLAB.

3. Results and Discussion

Figure 3 presents the linear dependency between criteria. It is generally considered that parameters with a correlation coefficient greater than 0.8 are very strongly correlated. Based on this guideline, it can be interpreted that ruggedness number and drainage density have very strong correlation.

3.1 Contribution for Flooding

Morphometric parameters indicate runoff behaviour of each sub basin. Figure 4 shows the variation of these parameters in the sub basins of the Nilwala river basin.

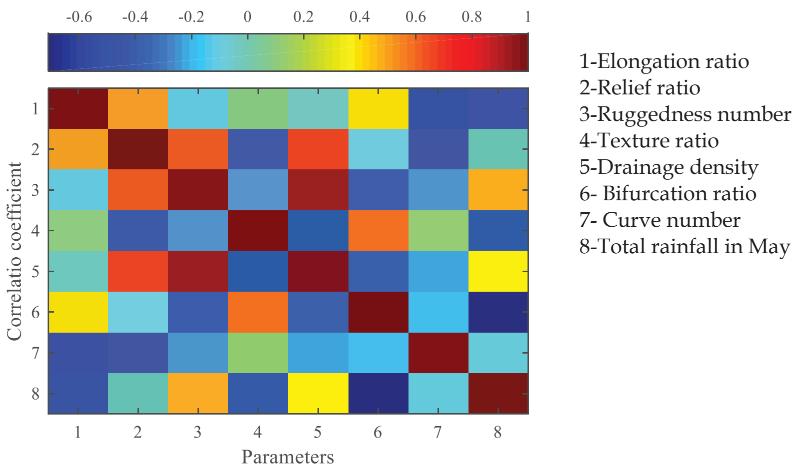

Figure 3 – Correlation Coefficient Among Criteria

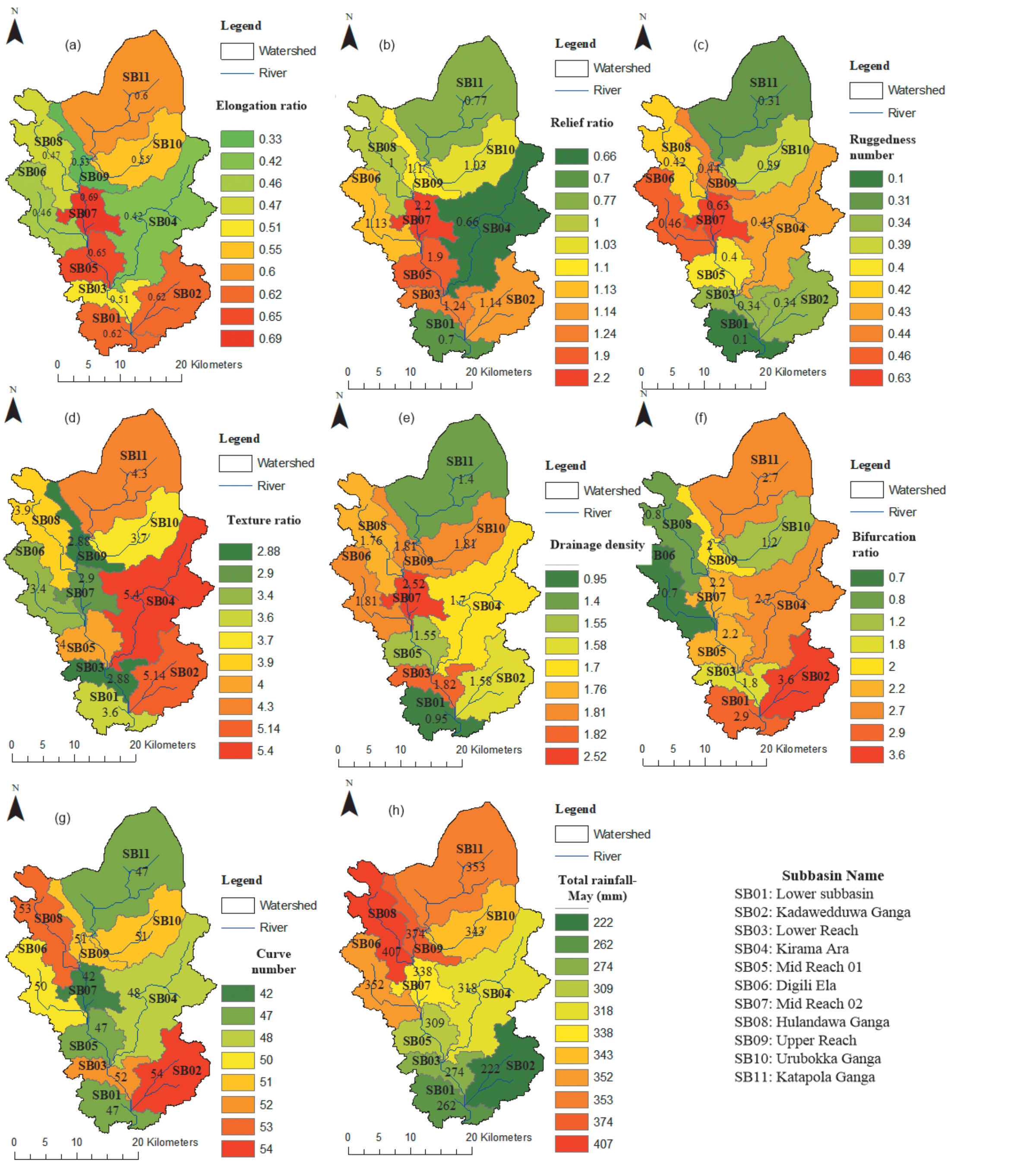

Figure 4 – (a)-(f) Morphometric Parameters, (g) Curve Number, and (h) Total Rainfall (mm) in May of the Nilwala Sub-basins

Elongation ratios of the sub basins were in the range of 0.33 - 0.69. High value of elongation ratio indicates high peak flow within a short duration. The catchment shape is classified based on the elongation ratio as circular (1~0.9), oval (0.9~0.8), less elongated (0.8~0.7), elongated (0.7~0.5), and more elongated (<0.5). According to this classification, sub basin shape falls into the categories of more elongated and elongated, indicating low or flatter peak flow with longer duration. Kirama Ara, Digili Ela, Hulandawa Ganga, and Upper Reach sub basins are more elongated and peak flood intensity is reduced owing to the distribution of discharge over time. In contrary, in other sub basins, greater discharge is produced as there is no greater difference in time taken to reach the flow from tributaries to the main stream.

The relief ratio is a measure of a steepness of the watershed and higher relief conveys fast runoff. In the Nilwala basin, relief ratio varies from 0.65 to 2.23. Mid reach sub basins have high relief ratios and contribute more water in a short time causing floods in the lower regions of the basin. Kadawedduwa Ganga, Lower Reach, Urubokka Ganga, Digili Ela, and Hulandawa Ganga sub basins have moderate relief ratio, while Kotapola Ganga, Kirama Ara sub basins, and Lower sub basin provide low relief.

The drainage density indicates closeness of channels. The low drainage density values represent permeable subsurface material, good vegetation cover, and low relief which causes low flood volumes and vice versa. In the Nilwala river basin, drainage density was within the range of 0.95 to 2.52 km/km^2.

Mid Reach 2 sub basin has the highest drainage density, contributing more runoff while lowest is recorded by the Lower sub basin with low contribution for flooding. High and moderate drainage densities are evident in the middle of the river basin.

The watershed's mean bifurcation ratio was 2.1 and that of sub basins was within the range of 0.7~3.6. Kadawedduwa Ganga sub basin has the highest bifurcation ratio indicating high runoff generation potential with minimum time lag. Hulandawa Ganga and Digili Ela sub basins have bifurcation ratios of 0.8 and 0.7, respectively, with comparatively low runoff generation. All the sub basins located along the main river course have high and moderate bifurcation ratios.

The CN has a range of 30 to 100 and lower numbers indicate low runoff potential. CN values of the Nilwala sub basins lie in between 42 to 54 indicating moderate runoff potential. The basin receives high rainfall (>200 mm) in the month of May. The upper watershed receives the highest rainfall and it decreases in the direction of Southeast.

Table 1 provides the order of contribution of each criterion for flooding.

3.2 Flood Exposure Mapping

Flood exposure mapping was achieved by integrating criteria through ranking and weighting process. Bifurcation ratio, relief ratio, and ruggedness number were the most influential factors on ranking while elongation ratio, rainfall and texture ratio had moderate influence on the decision.

Table 1 – Ordering of Sub Basins for each Criterion Based on the Contribution for Flooding, Performance Score of Sub Basins and their Priority for Flood Exposure

Sub basin	Area (km^2)	*Re*	*Rh*	*Rr*	*Rt*	*D*	*Rb*	CN	Rainfall	PS	Rank	Priority
SB01	60	3	10	11	6	11	2	10	10	0.44	7	M
SB02	106	4	4	9	2	8	1	1	11	0.63	2	H
SB03	48	7	3	8	10	2	8	3	9	0.39	8	M
SB04	210	10	11	4	1	7	3	7	7	0.49	4	M
SB05	60	2	2	6	4	9	5	9	8	0.59	3	H
SB06	82	9	5	2	8	3	11	6	4	0.30	10	L
SB07	47	1	1	1	9	1	6	11	6	0.69	1	H
SB08	97	8	8	5	7	6	10	2	1	0.27	11	L
SB09	45	11	6	3	11	4	7	5	2	0.44	6	M
SB10	105	6	7	7	5	5	9	4	5	0.30	9	L
SB11	224	5	9	10	3	10	4	8	3	0.47	5	M

Re: Elongation ratio; *Rh*: Relief ratio; *Rr*: Ruggedness number; *Rt*: Texture ratio; *D*: Drainage density; *Rb*: Bifurcation ratio; CN: Curve Number; PS: Performance Score

Elimination of CN and drainage density slightly changed the score. This might be due to the insignificant variation in CN within the sub basins and the very strong interdependency between ruggedness number and drainage density values of the sub basins.

The performance score provides the physical flood vulnerability index (PFVI) for the sub basins. The flood exposure map of Nilwala river basin classifies the basin into different zones and consists of three major classes: low, moderate, and high as shown in Figure 5.

4. Conclusions

The study of watershed characteristics derived using ArcGIS helps in understanding the hydrologic behaviour of the Nilwala River basin. A flood exposure map was prepared using eight flood contributing factors. The results showed that bifurcation ratio, ruggedness number and relief ratio dominate the causes for flooding in the lower regions of the basin. The low, moderate and high flood potential regions occupy 26%, 54%, and 20% of the Nilwala river basin, respectively.

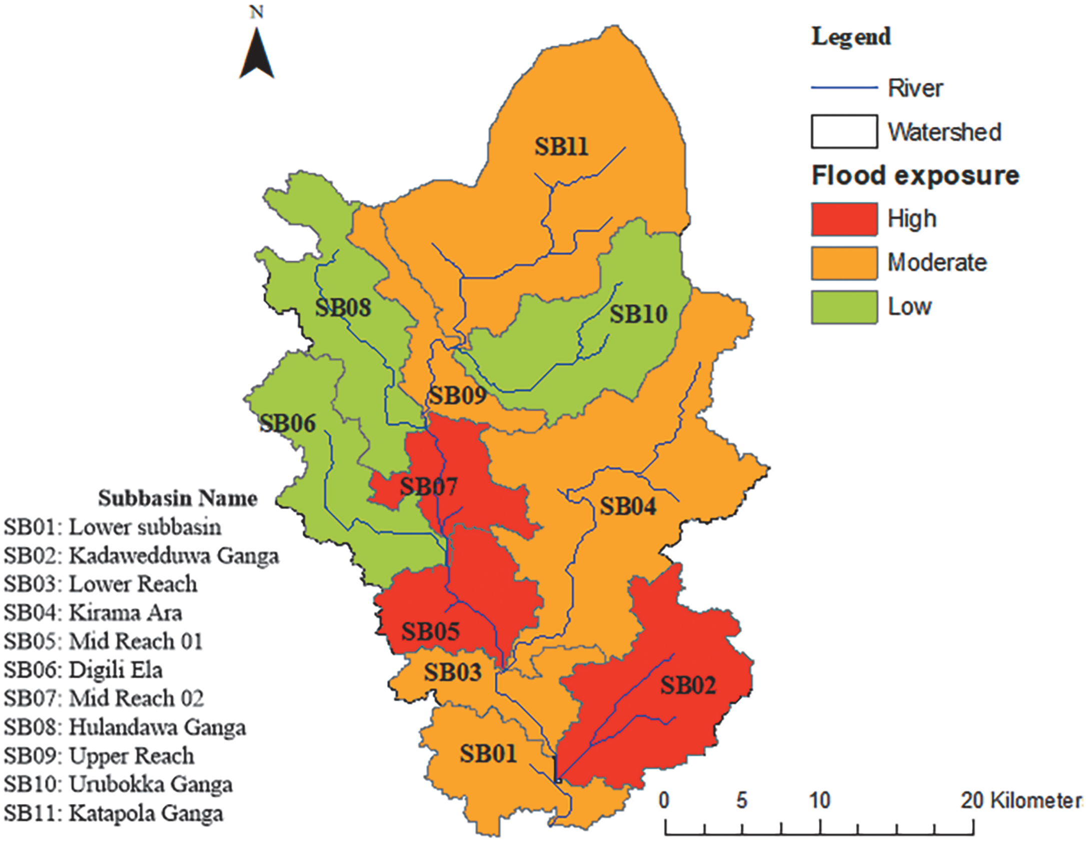

Figure 5 – Flood Exposure Map of the Nilwala River Basin

The sub basin belonging to the river reach between the confluences of Hulandawa Ganga and Digili Ela recorded the highest PFVI of 0.69. Further, this is located downstream of Pitabeddara where ponding of water starts due to significant change of elevation gradient. Two downstream adjacent sub basins of Pitabeddara and Kadawedduwa Ganga sub basin were categorized as having high flood exposure. Kirama Ara and Kotapala Ganga main tributaries and other sub basins along the main river belong to the category of moderate flood exposure. Hulandawa Ganga, Digili Ela, and Urubokka Ganga sub basins showed low flood exposure.

High and moderate flood potential zones are located along the main river course except the Kirama Ara and Kadawedduwa sub basins.

The results of this study provide new avenues for developing flood management plans. It is understood that elevation is of prime importance in deciding the flood inundation area. This research can be extended at more fine spatial scale including criteria such as distance to river and elevation for direct comparison with flood inundation areas.

References

1. Ochoa-Tejeda V., Jean-François P., & Monique F., "Mass Movement Classification Using Morphometric Parameters (Puebla, Mexico)". In: *Landslide Science and Practice*. Margottini C., Canuti P., Sassa K. (Eds.), Springer, Berlin, Heidelberg, 2013.

2. Kottagoda, S. D., & Abeysingha, N. S., "Morphometric Analysis of Watersheds in Kelani River Basin for Soil and Water Conservation", *Journal of National Science Foundation Sri Lanka*, Vol.5, No.03, 2017, pp. 273-285.

3. Kadam, A. K., Jaweed, T. H., Kale, S. S., Umrikar, B. N., & Sankua, R. N., "Identification of Erosion-Prone Areas using Modified Morphometric Prioritization Method and Sediment Production Rate: A Remote Sensing and GIS Approach", *Journal of Geomatics, Natural Hazards and Risk*, Vol. 10, No.01, 2019, pp. 986-1006.

4. Abuzied, S. M., & Mansour, B. M. H., "Geospatial Hazard Modelling for the Delineation of Flash Flood-Prone Zones in Wadi Dahab Basin, Egypt", *Journal of Hydroinformatics*, Vol. 21, No. 01,2019, pp. 180-206.

5. Rai, P. K., Chandel, R. S., Mishra, V. N., & Singh, P., "Hydrological Inferences through Morphometric Analysis of Lower Kosi River Basin of India for Water Resource Management Based on Remote Sensing Data". *Journal of Applied Water Science*, Vol. 8, No.15, 2018, https://doi.org/10.1007/s13201-018-0660-7.

6. Celikbilek, Y., & Tuysuz, F., "An In-Depth Review of Theory of the TOPSIS Method: An Experimental Analysis", *Journal of Management Analytics*, Vol. 7, No. 02, pp. 281-300,DOI: 10.1080/23270012.2020.1748528.

7. Hajkowicz, S., & Higgins, A., "A Review of Multiple Criteria Analysis for Water Resource Planning and Management", *European Journal of Operational Research*, Vol. 184, 2008, pp. 255–265.

8. Balica, S., & Wright, N., "A Network of Knowledge on Applying an Indicator-Based Methodology for Minimizing Flood Vulnerability", *Hydrological Processes*, Vol. 23, 2009, pp. 2983-2986.

9. Nasiri, H., Yusof, M. J. N., & Ali, T. A. M., "An Overview to Flood Vulnerability Assessment Methods", *Sustainable Water Resources Management*, Vol. 2, 2016, pp. 331-336.

10. Rathnayake, U., Sachindra, D. A., & Nandalal, K. D. W., "Rainfall Forecasting for Flood Prediction in the Nilwala Basin", *Proc. of the International Conference on Sustainable Built Environment,* 2010, pp 355-362.

11. Lakmali, U. W. U., Navarathne, C. M., & Fowze, J. S. M., "Development of Flood Hazard Map for the Selected Areas of Nilwala Downstream using HEC-RAS", *Proc., 5th International Symposium on Advances in Civil and Environmental Engineering Practises for Sustainable Development (ACEPS)*, 2017, pp 316-322.

12. Japan International Cooperation Agency (JICA)., *Comprehensive Study on Disaster Management in Sri Lanka,* JICA, Japan, 2009.p216.

13. United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS), *Urban Hydrology for Small Watersheds. Technical Release No. 55 (TR-55)*, USDASCS, Washington DC, 1986.

14. Hwang, C. L., & Yoon, K., (1981). "Methods for Multiple Attribute Decision Making", In *Multiple Attribute Decision Making*, Beckmann, M. & Künzi, H.P. (Eds.), Springer, 1981, pp. 58–191.