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Flood Modelling of Madi River Using HEC-RAS by Rain on Grid Approach

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***Abstract*— Indispensable for prognosticating flood impact in areas with limited data availability, reliable flood models are crucial for the analysis and mitigation of flood hazard. This study provides insight to accurately analyse flood scenarios by preparing a well calibrated 2D hydraulic model in HEC-RAS along with the Rain on Grid approach, which is subsequently used for hazard map preparation of Madi River. Hazard classification of flood depth indicated that for a 20-year return period, Moderate hazard levels covered 16.499%, High hazard levels covered 14.831%, and Very High hazard levels covered 68.670% of the total inundated area with reference to the depth hazard categories. Since, significant portion of the inundated area is classified as Very High Hazard; the finding of this research emphasizes the need of effective mitigation measure and provides essential insights crucial for flood risk assessment.**

Keywords*— Floods, Flood modelling, HEC-RAS, Madi River, Rain on Grid

Introduction

Floods are one of the most catastrophic natural disasters that endanger lives and properties. In the present time, global warming has led flood to become more severe and unpredictable due to the occurrence of frequent and extreme precipitation, placing millions of people at risk [1]. The people living on flood-plains, non-resistant buildings or having no awareness about flood due to inadequate early warning systems are found to be more susceptible to flood [2]. Flood has caused the death of roughly 7,400 people across the globe in the year 2022 [3].

In Nepal, flood causes huge loss of life and damage in property throughout the monsoon season. Particularly, from June to September, there has been significant devastation due to continuous rainfall causing flood. As per study by UNDP, Nepal is ranked as 30th country with respect to vulnerability of flood [4]. Nepal has witnessed major flood in Tinau basin (1978), Koshi River (1980), Tadi River Basin (1985), Sunkoshi Basin (1987) and devastating cloud burst in Kulekhani area (1993) which alone resulted in fatalities of 1,336 people [5]. Similarly, the flood in Madi River (2021) created huge destruction in four hydropower projects in Madi Rural Municipality of Kaski district [6]. The Madi River is facing a risk of Landslide Dam Outburst Flood (LDOF), potentially causing property damage between USD 25 million to 68 million in estimation that suggests the requirement of immediate solution as 14 hydropower projects are proposed in the area [7].

With the increasing threat of lives and properties, flood modelling has become even more significant. Diverse research has been conducted for flood modelling widely that helped in various fields such as vulnerability and flood hazard analysis, urban flood risk management, flood risk prediction mapping as well as for the development of early warning systems [5], [8], [9], [10], [11]. These works demonstrate the variety of techniques employed in flood modeling research, such as hydrological modeling, hydraulic modeling, remote sensing, GIS analysis, and machine learning.

Existing researches about flood modelling has primarily focused on two modelling programs for hydrologic and hydraulic modelling. In particular, HEC-HMS or SWAT may be used to perform hydrologic calculations and generate hydrograph that serves as an input for hydraulic modelling in HEC-RAS [12], [13], [14]. However, Rain on Grid modelling combines both models by applying rainfall directly to 2D mesh through HEC-RAS [15], [16]. In Nepal, limited research has been carried out based on Rain on Grid approach that identifies clear research gap at present time.

Therefore, this study seeks to address the gap in implementation of ROG approach in flood modelling by analysing its potential benefits in unique context of the Madi River basin and hence, building a reliable flood model that captures hydraulic behaviour of the river at various circumstances. The scope of study covers flood modelling and hazard mapping. Additionally, the study will be applicable for infrastructure analysis, watershed management, and climate change impact assessments.

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Materials and Methods

A Study Area

Madi River is located in Kaski, Lamjung and Tanahu districts in Western, Nepal. It is a perennial river originating from the southern flank of the Annapurna Himalaya Range, and is notable as one of the seven tributaries feeding into the Gandaki River[17]. It is located at 27˚57'30" to 28˚32'15" North latitude and 84˚01'25" to 84˚20'27" East longitude with the area of 1123. 61 sq. km[17]. Madi River has total length of 50.36 km. The study area lies between Bhorletar to Damauli with approximate distance of 23 km and the co-ordinate extends from 28°08'52"N to 27°58'40"N and 84°13'18"E to 84°15'43"E.

Geographically, the study area is situated 908 meters above sea level. The Madi River faces danger from landslide dam outburst flooding (LDOF) [6]. The lifetime of the bank protection works constructed over the last decades in Madi River is less than 10 years and often much shorter recommends initiating a bank protection pilot project to identify the cause of failure of the bank protection works and to test remedial measures for the sustainability enhancement of river protection works in the future [18]. The urgent need for flood protection measures in the Madi River basin has prompted our selection of the area for flood modeling research.

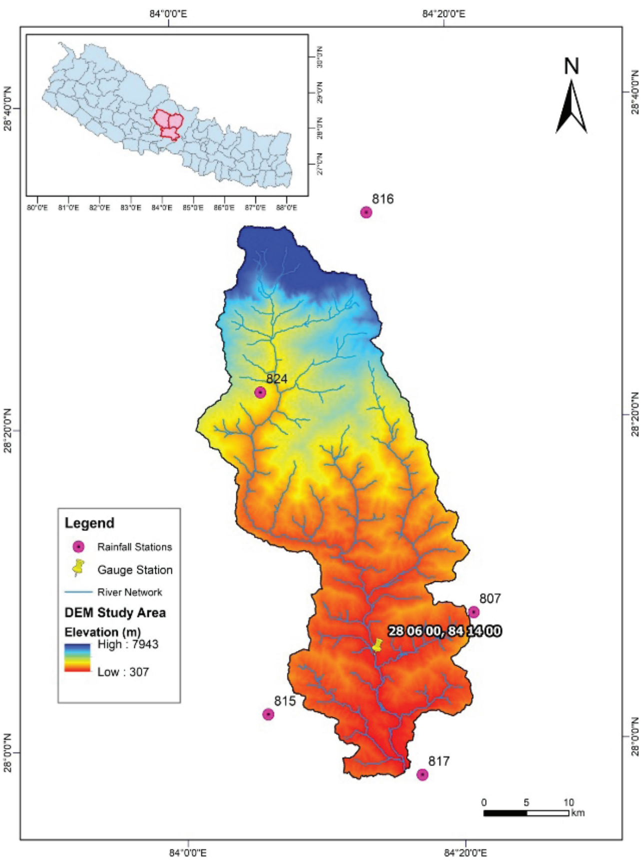

Fig 1 Madi River Catchment in Western Nepal

B Methodological Framework

The methodology of the research starts form collection of hydrological, meteorological and geo-spatial data from their respective sources. 30m DEM was extracted form AW3D which was then used for raster processing in ARC-GIS. The outlet point was assigned at the downstream and catchment area was formed. The streamflow in river network was then imported to HEC-RAS as a shape file and a Rain on Grid model was prepared. After proper calibration and validation, frequency analysis was performed for return period of 20 year in HEC-SSP. Lastly, flood hazard map was prepared. All the process involved are briefly presented stepwise in Fig 2.

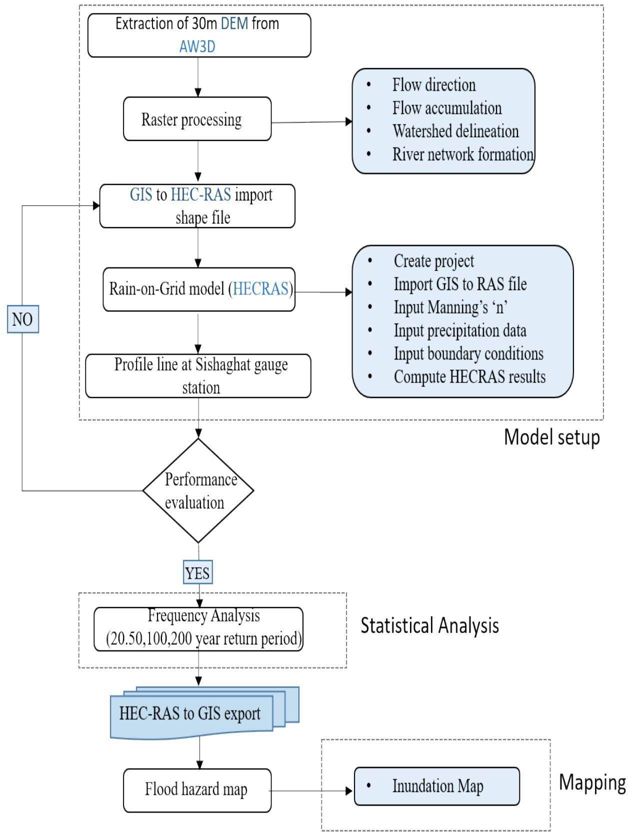

Fig 2 Methodological Framework

C Data Collection

The data was collected from Department of Hydrology and Meteorology (DHM). This includes daily discharge data of 40 years (1998-2019) from Sishaghat station, identified by station index 438. Additionally, daily precipitation data of five meteorological stations inside the study area and in its vicinity namely Kunchha, Khairinitar, Chame, Damauli and Siklesh identified by their respective station index of 807, 815, 816, 817 and 824. The DEM used for the study is of 30m×30m resolution from AW3D and the land use data was based on the ICIMOD value of 2010 Land use map. The respective resource and information of data utilized for the study is presented in TABLE I.

TABLE I

DATA USED DESCRIPTION

No.	Data	Information	Resources
1	Rainfall	1980-2019	DHM
2	Discharge of Madi River	1980-2019	DHM
3	Land Use Image	2010 LU map	ICIMOD (https://rds.icimod.org)
4	Digital Elevation Model (DEM)	30m×30m	AW3D (https://www.aw3d.jp)

D Frequency Analysis

The equation for Gumbel's distribution as well as to the procedure with a return period T is given as,

$$X_T = X_{av} + K \times SDV \quad (1)$$

Where,

X_T = value of variate with a return period, Xav = mean of the variate, SDV = Standard deviation of the sample, T = return period;

K = Frequency factor expressed as: K = (yT – 0.577)/1.2825; and

yT = reduced variate expressed by: yT (T – 1) = - (LN× LN).

E Flood Modelling

HEC-RAS uses Navier-Stokes equation for the 2D unsteady flow analysis with two governing equations [19]:

1) Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \quad (2)$$

2) Momentum Equations (in x and y directions):

$$\frac{\partial(\rho u)}{\partial t} + \frac{d(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}(\mu\frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(\mu\frac{\partial u}{\partial y}) + \rho g_x \quad (3)$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{d(\rho v^2)}{\partial y} = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}(\mu\frac{\partial v}{\partial x}) + \frac{\partial}{\partial y}(\mu\frac{\partial v}{\partial y}) + \rho g_y \quad (4)$$

DEM was used to prepare geometric data for the study site using GIS. The geometric data includes Stream Centerline, Flow Path Centerlines, Main Channel Banks, and perimeter. Manning's friction coefficient 'n' that varies highly on vegetation, channel alignment, surface roughness and other factors was extracted from land cover map and imported as basin characteristics into HEC-RAS.

For the simulation, initially used Manning's 'n' values were varied to give the downstream boundary condition. The area to be simulated was represented by a grid. A small portion of land is represented by each cell in the grid. Rainfall was simulated by randomly distributing rainfall intensity over the grid. Based on the intensity of the rainfall and land usage, the runoff from each cell was calculated. Model parameters were calibrated and the simulation results were validated.

After ensuring satisfactory calibration and validation of the model, frequency analysis was conducted employing the Gumbel distribution by using HEC-SSP. The model was run for return period of 20-year subsequently and the results were then imported to ARC-GIS for further processing.

Based on the reference of study conducted on the Pathariya Khola [19], the depth hazard level categories as shown in TABLE II were classified in this study.

TABLE II

DEPTH RANGES AND CORRESPONDING HAZARD CATEGORIES

Depth (meters)	Hazard
<0.8	Moderate
0.8-1.6	High
>1.6	Very High

Lastly, a hazard map for 20-year return period was prepared using ARC-GIS.

Result And Discussion

A. Calibration and Validation

The model was calibrated in the years 1996 AD and 2001 AD with the targeted correlation of 0.80 between simulated and observed data for the discharge and precipitation data as presented in Fig 3 and Fig 4. High correlation coefficient was obtained in the years 1996 AD and 2001 AD by correlating between simulated and observed data.

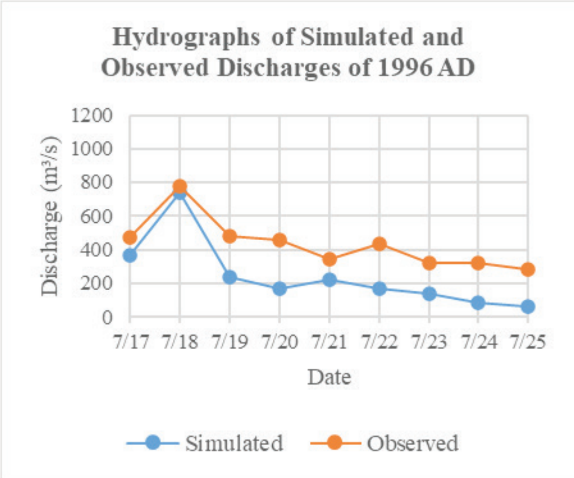

Fig 3 Hydrographs of Simulated and Observed Discharges of 1996 AD

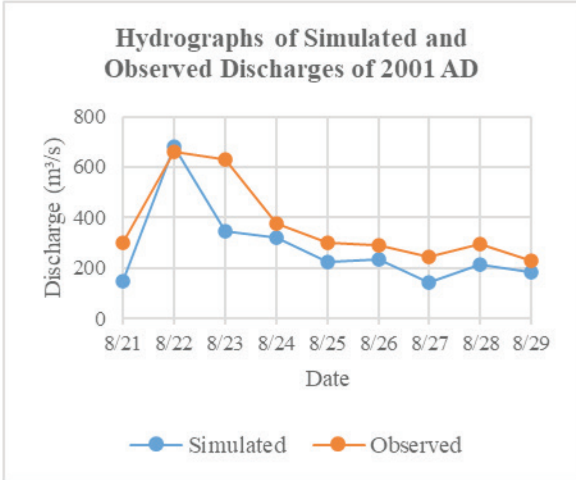

Fig 4 Hydrographs of Simulated and Observed Discharges of 2001 AD

Similarly, the model was validated on the highest discharge of 877 m^3/s which occurred on 9th July of 2003 AD as shown in Fig 5 with correlation coefficient of 0.8142.

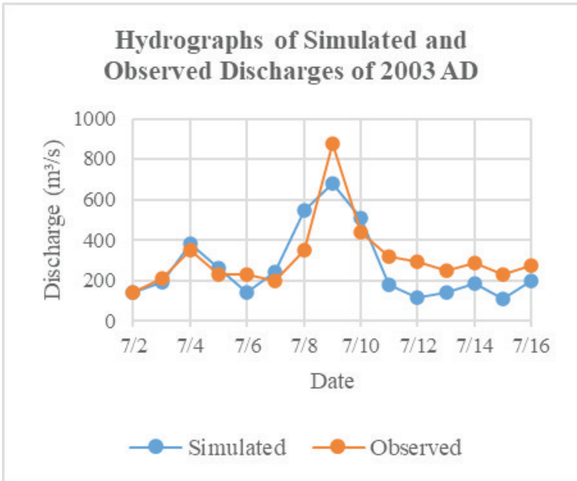

Fig 5 Hydrographs of Simulated and Observed Discharges of 2003 AD

B. *Frequency Analysis*

The maximum rainfall amounts expected to occur for four return periods of the 5 stations after performing the analysis is displayed in TABLE III.

TABLE III

RETURN PERIODS AND MAXIMUM RAINFALL AT 5 STATIONS

Return Period (Years)	**Precipitation in mm**				
	Kunchha (807)	**Khairinitar (815)**	**Chame (816)**	**Damauli (817)**	**Siklesh (824)**
20	197.937	193.783	95.816	200.673	215.875

The Gumbel Distribution curve of stations Kunchha, Khairinitar, Chame, Damauli and Siklesh are shown in Fig 6, Fig 7, Fig 8, Fig 9 and Fig 10 respectively.

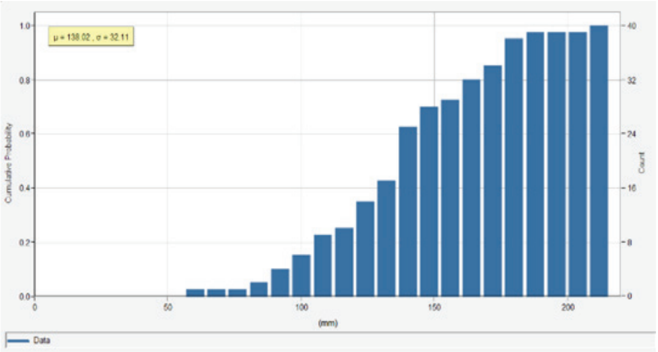

Fig 6 Gumbel Distribution Curve of of Kunchha Station

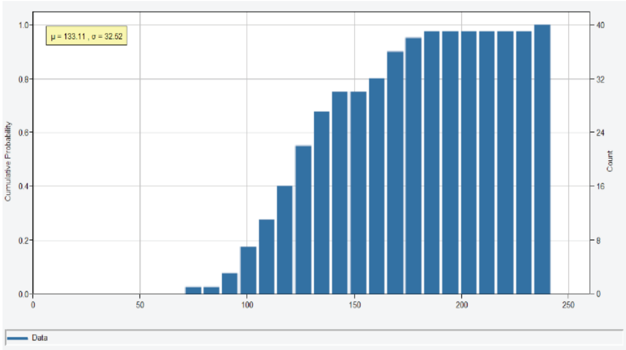

Fig 7 Gumbel Distribution Curve of Khairinitar Station

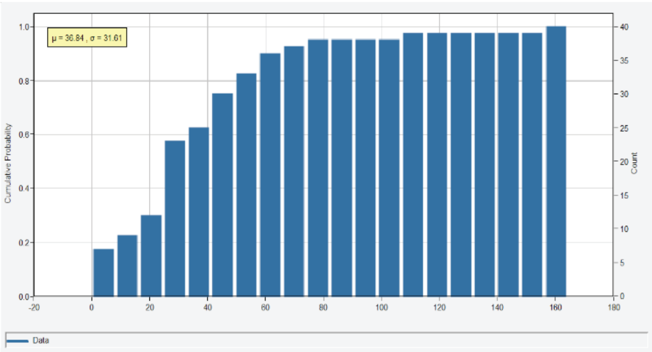

Fig 8 Gumbel Distribution Curve of Chame Station

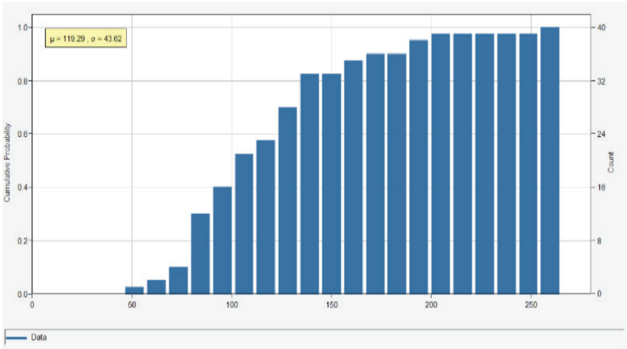

Fig 9 Gumbel Distribution Curve of Damauli Station

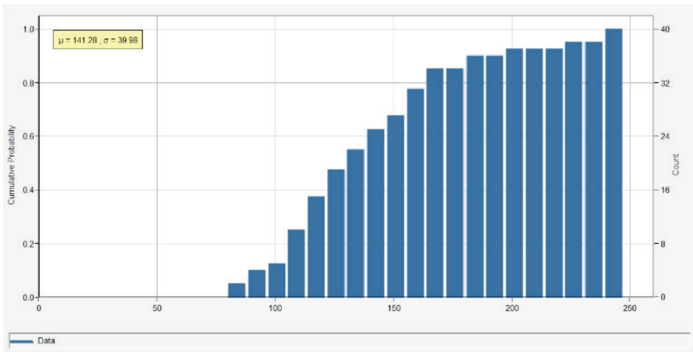

Fig 10 Gumbel Distribution Curve of Siklesh Station

The discharges obtained for return periods, measured at the Sishaghat station are represented by the hydrograph as shown in Fig 11.

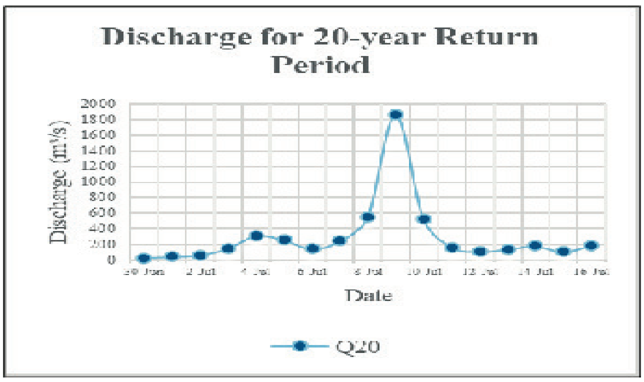

Fig 11 Hydrograph of 20-year return period

A Hazard Mapping

The hazard map for 20-year return period created from ARC-GIS shown in Fig 12.

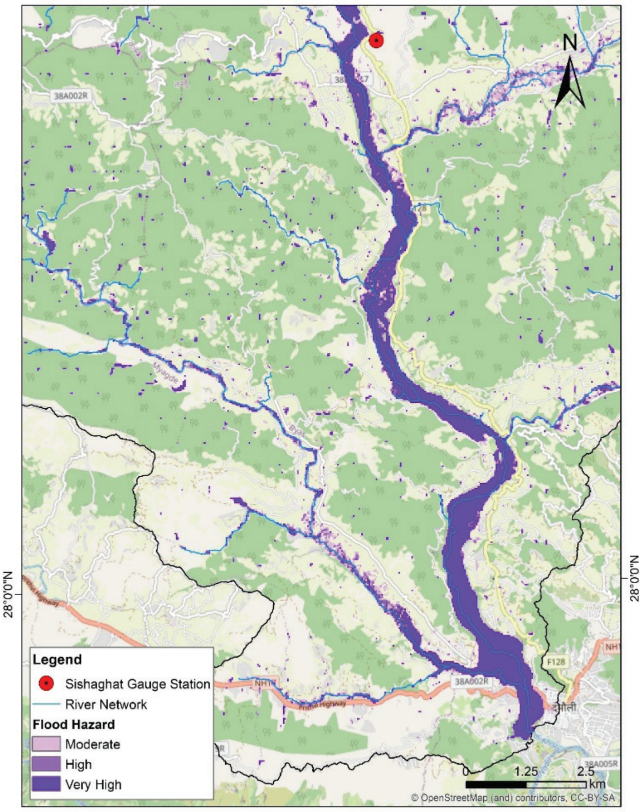

Fig 12 Hazard Map of Madi River for 20 year return period

On the basis of reference values used on a study conducted on the Pathariya Khola [19], the depth hazard level categories were classified in this study by analyzing TABLE II . The floodplain is categorized as having a moderate hazard when the water depth is less than 0.8 meters, a high hazard between 0.8 to 1.6 meters, and a very high hazard for water depths exceeding 1.6 meters. The flood inundation area was classified into moderate, high, and very high categories.

From the analysis, it was found that for a 20-year return period, Moderate hazard levels covered 16.499%, High hazard levels (0.8-1.6m) covered 14.831%, and Very High hazard levels covered 68.670% of the total inundated area. This shows that most of the area is prone to high flood risk and emphasizes need of proper mitigation measure for the prevention of potential damage in people's lives, property as well the surrounding topography of Madi river basin.

Conclusions

In conclusion, the flood modeling was conducted using HEC-RAS through Rain on Grid approach combining data from various sources including DEM from AW3D, land use data from ICIMOD and precipitation data from DHM. The discharge data for return period of 20-year was calculated. The simulations generated hazard maps based on depth results for various flood events. Analysis revealed that for a 20-year return period, Moderate hazard levels (<0.8) covered 16.499%, High hazard levels (0.8-1.6m) covered 14.831%, and Very High hazard levels (>1.6) covered 68.670% of the total inundated area. These findings can serve as a basis for creating risk assessment maps. The input parameters used in this model were the average value of 24-hour interval. Using a Real-time hourly data can further improve the accuracy of the result obtained. The models described here are preliminary in nature, reflecting the nature of this new field of study, and should be regarded as a place to start for future improvements. Further studies using this model can provide valuable insights for future Land Use development or other Infrastructure Developments as well as formulation of mitigation and evacuation plans.

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