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Water Induced Multi-Hazard Susceptibility Assessment of Rapti Rural Municipality, Dang

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Abstract

Due to its mountainous topography, fragile geology, seismically active areas, periodic Glacial Lake Outburst Floods (GLOFs), intense monsoon rainfall, and improper land management, Nepal is vulnerable to several hazards and the consequent disasters. These hazards pose a serious threat to the people and properties of the affected area. Similarly, water-induced multi-hazard assessment is very important in the context of the Nepal Himalaya. Rapti rural municipality, being located in the West Rapti Basin, is susceptible to different water-induced hazards. Therefore, water-induced Multi-hazard assessment in this context can help identify the susceptible areas and accordingly develop mitigation plans. The study has provided a Water-induced Multi-Hazard susceptibility mapping of Rapti Rural Municipality using Analytical Hierarchy Process (AHP), which includes developing susceptibility maps for each hazard, and overlaying them based on their weightage. The maps were obtained for landslide, flood, and debris flow hazards, which provide information on the susceptible zones and their characteristics. The heuristic approach for landslide mapping showed that around 64.2% of the study area had low susceptibility to the landslides, while 31.1% was in the medium susceptibility, and 4.69% was highly susceptible. The flood hazard map was prepared and inundation area was around 16.69%. 35 source areas for debris flows were identified in the study area, and runout was calculated based on direction and inertia algorithms. The percentage weights determined from the AHP method were for Landslide: 29%, Flood: 54%, and Debris Flow: 17% to create a multi-hazard map. Most of the study area has low susceptibility to multi-hazard (31.74%), while 6.16% of the area was very highly susceptible to water induced multi-hazard scenarios. The plains along the river are core residential and agricultural areas, and the high water-induced hazard susceptibility in those regions can pose a threat to the people residing in the area.

Keywords

Debris Flow, Flood, Landslides, Multi-Hazard, Susceptibility, Water-Induced

1. Introduction

Nepal is vulnerable to a number of natural hazards and disasters, which have a disastrous impact on the physical environment and lead to significant loss of life and property. Due to its mountainous topography, fragile geology, seismically active areas, intense monsoon rainfall, and improper land management, several water-induced disasters are prevalent in Nepal. Natural hazards such as landslides, debris flows, flooding, avalanches, GLOFs, drought, wildfires, and earthquakes have resulted in large economic and social implications, especially for low-income and vulnerable groups.

Every year, Nepal receives heavy rainfall during the monsoon season, which frequently result in severe flooding. Extreme precipitation events result in flooding and damage to the infrastructures, houses, and crops. Heavy rains that cause floods in areas with high slope may trigger mass movement and cause landslides [1]. Since the majority of landslide incidents in Nepal occur during the monsoon season each year, rainfall-induced landslides are common in Nepal . Heavy rainfall, along with seismic activity and poor land management, are some causes that could trigger landslides, which can result in fatalities and destroy residential areas [2, 3].

Among the types of landslides in hilly areas, debris flow is considered among the most destructive natural hazards [4]. Rainfall is a major contributor to the generation of a debris flow originating from the landslide. The hilly regions of Nepal are highly inhabited, and both life and property are exposed to the extensive debris flows caused by heavy rains. Rainfall-induced shallow landslides that develop into debris flows travel long distances across inclined terrain, and debris flows cover a larger region than their originating landslide source [2].

A significant technique for evaluating the potential risk of multiple hazards induced by rainfall, such as floods, landslides, and debris flow events, is water-induced multi-hazard mapping [5]. It offers an extensive process for identifying the areas that are susceptible to multiple hazards. It is therefore essential to establish effective means for the assessment and management of such hazards since water-related hazards pose severe risks to lives, properties, and infrastructures. A multi-hazard susceptibility assessment is a great resource in disaster and risk reduction since it highlights the scope of highly susceptible areas while taking into account the overall hazard events.

Various techniques have been employed in different studies to create multi-hazard maps, including heuristic approaches, Multi-Criteria Decision Making (MCDM), statistical methods, deterministic models, probabilistic models, and artificial intelligence. MCDM, a method for decision-making, can be implemented using tools like fuzzy logic, the weight overlay method, and the Analytical Hierarchy Process (AHP) [6]. AHP, introduced by Saaty in 1980, is a widely utilized approach in decision-making [7]. It proves effective in complex decision-making situations, assisting decision makers in setting priorities and making optimal choices. AHP has been used to develop Multi-hazard susceptibility maps around the world [7, 5, 6]. Water-induced multi-hazard susceptibility assessment allows the decision-makers to identify areas that are vulnerable to these hazards, prioritizing mitigation strategies, and establish contingency measures for responding to emergencies caused due to water-induced hazards.

The main objective of the study is to assess the susceptibility of the water-induced hazards in the study area, and determine the hazard type that influences the most. A comprehensive multi-hazard susceptibility map will be developed based on the individual susceptibility maps and the assigned weightage. The study also attempts to identify and understand the key geological, topographical, and anthropogenic factors that contribute to the susceptibility levels in different hazard types in the Rapti Rural Municipality.

2. Materials and Methods

2.1 Study Area

Rapti Rural Municipality is located in Nepal's Dang district, Province No. 5 (Lumbini Pradesh). The elevation of Rapti Rural Municipality ranges from 193 meters to 1136 meters above sea level. The municipality is bounded by 82° 35' 52.97"- 82° 48' 43.71" due East, and 27° 48' 54.2"- 27° 55' 24.9" due North. The map produced by Department of Forest Research and Survey, 2018 indicates that around 65.5% of the total area is covered by forests [8]. The lowlands in the South are dominated by agricultural lands and settlements, while the Northern part is composed of rugged terrain with sparse settlements. The southern lands are at the right bank of Rapti river, making them prone to flooding; the rugged terrain in the North Siwaliks consist of weak young sedimentary rocks, which are at a risk for landslide.

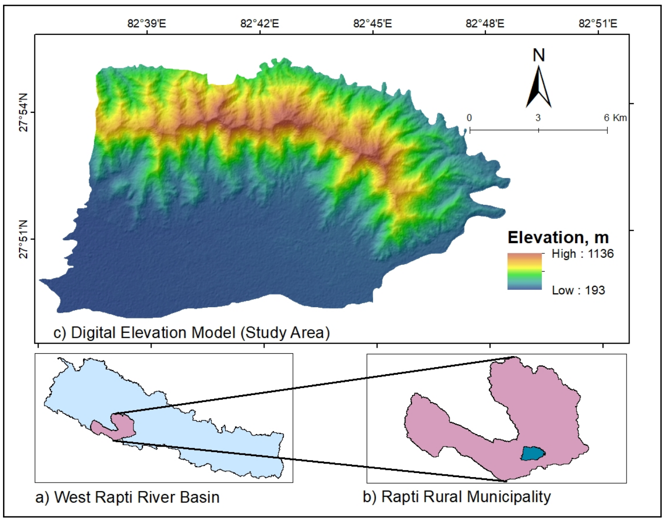

Figure 1: Study Area

2.2 Data Collection

The dataset for water-induced multi-hazard susceptibility assessment was carried out from different sources and tools. A high-resolution Digital Elevation Model (DEM) is the primary dataset for mapping the susceptibility of debris flow events. With the use of the high-resolution DEM, it is possible to accurately determine slopes, curvature, flow patterns, and probable source areas of the landslide and debris flow events.

A Digital Elevation Model (DEM) of 12.5m resolution ALOS Palsar data was downloaded from the from Earthdata website. The rainfall from the years 1985-2020, and discharge data from 1988-2019 was collected from the Department of Hydrology and Meteorology for flood hazard mapping.

Table 1: Input data used for the study

Input Parameters	Source	Scale/ Resolution
DEM	ALOS Palsar (https://search.asf.alaska.edu/#/)	30m
Road and Stream data	Government website (https://nationalgeoportal.gov.np/#/dataset)	1:1000000
Rainfall/ Discharge Data	Dept. of Hydrology and Meteorology	_
Land Cover	National Land Cover Monitoring System (http://rds.icimod.org/)	30m
Geology Map	Department of Mines and Geology (http://rds.icimod.org/)	1:1000000

2.3 Data preparation

2.3.1 Influencing Factors in Landslide Susceptibility

Aspect: Aspect can have a significant impact the susceptibility to landslides. South-facing slopes get more sunlight, and are typically dry. Similarly, North-facing slopes typically get less direct sunlight which could lead to a greater soil moisture content [9]. Insufficient moisture or water buildup can make slopes less stable and make landslides more susceptible.

Slope: Slope has a substantial impact on landslide vulnerability. Since gravity has a higher effect on weakening the slope-forming materials, the inclined slopes are more susceptible to landslides.

Geology: Different rocks have varying degrees of erodibility, water retention capacity, and load bearing capacity. The type of formation influences durability and permeability, which are important in determining the susceptibility of landslides in the area. Landslides are more likely to occur in geological formations that are susceptible to fast weathering, including some soft rock forms. Geology also influences the permeability of the soil.

Landuse: Landuse/land cover of an area is an important predisposing factor in landslide susceptibility assessment. Areas with forests and water bodies are less prone to landslides, while areas with bare soil or exposed slopes are more susceptible. Similarly, land use changes, including urbanization or agricultural activities can increase susceptibility.

Curvature: The land surface becomes steeper in regions with positive curvature, and as the curvature increases, it can increase stress and instability, which increases the risk of landslides in the region. Similarly, negative curvatures areas are susceptible to gully and channel erosion, and result in weakening the slope and increasing the risk of landslides.

Distance to drainage: Distance to drainage indicates how close a place is to a natural drainage system, including rivers, streams, or canals. Water flows from the surface and reaches the closest drainage system during rainfall. Surface runoff flow routes are shorter in areas that are adjacent to drainage systems, which reduces the amount of time that water may gather and potentially cause landslides.

Distance to roads: Sometimes, constructing roads on a rough terrain needs a great amount of cutting and filling. Due to budget constraints, the cut slopes can be improperly stabilized and fall apart during the monsoon. The further an area is from the road; the susceptibility of a landslide gradually decreases.

Rainfall: Rainfall that is particularly intense or persistent can saturate the soil, decreasing shear strength and making it more susceptible to landslides. Surface runoff and slope erosion of materials can also be caused by heavy rain. The eroded material may compromise the slope stability, resulting in slope failure and causing landslides or debris flows.

Internal Relief: The difference in altitude between an area's most and least elevation points is referred to as relief. Greater relief usually relates to steeper slopes in a given area. Steep hills are more inclined to have landslides. A landslide or slope failure is more likely to occur where there is high relief and steep slopes.

2.3.2 Influencing Factors in Debris Flow Susceptibility

Slope: Compared to flat lands and mild slopes, steep slopes are more likely to initiate debris flows, usually with angle greater than 15 degrees. Since steeper slopes have greater gravitational forces which can rapidly mobilize and carry loose soil and rock particles downward, they are more prone to debris flows.

Plan curvature: Concave downward surfaces can direct the flow of water and debris movement, which in a limited area can potentially increase the debris flow events. Similarly, natural channels can develop through water flow in areas with negative curvature over time, acting as a means of transportation of sediment and debris particles under certain conditions.

Flow Accumulation: Flow accumulation helps in identifying regions where debris as well as water are expected to accumulate during high precipitation or snow-melt. Large flow accumulation values correspond to the regions where high runoff may occur, possibly triggering a debris flow. Even though high flow accumulation values on their own do not cause debris floods, they do indicate regions in which runoff may rapidly build up.

Landuse: Debris flows are less likely to develop when vegetation, forests or grasslands retain water and increase infiltration. Alternatively, regions with little to no vegetation cover, including bare soil or urban areas, are more prone to erosion and the initiation of debris flows.

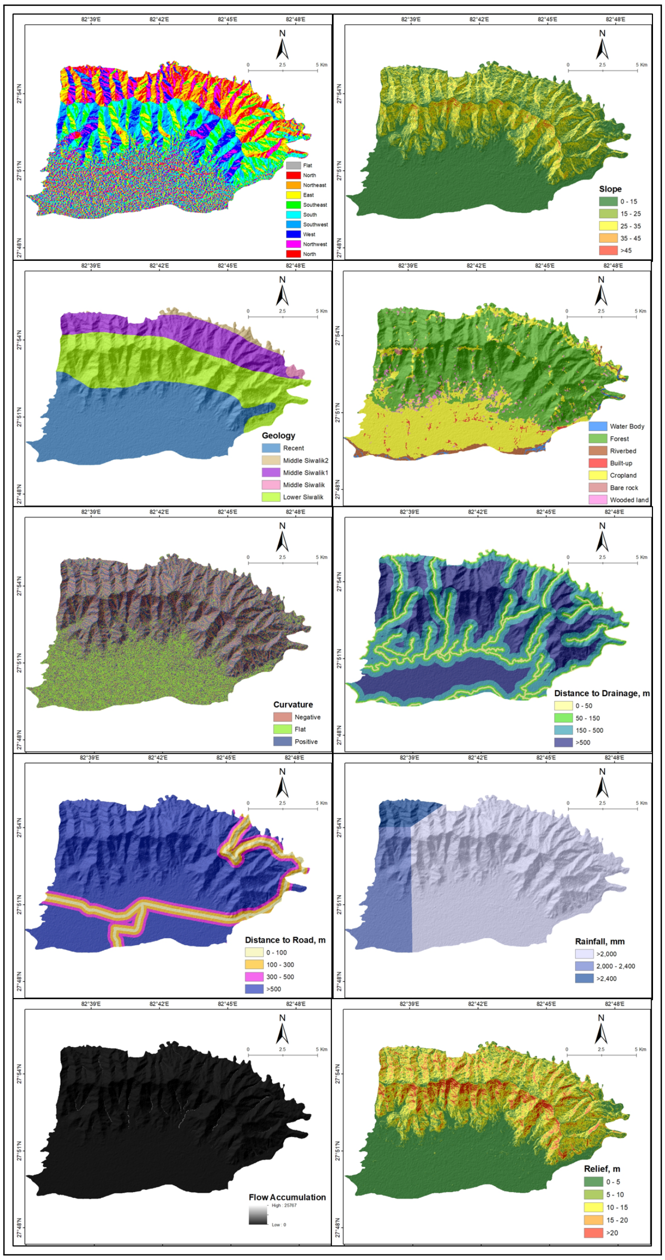

Figure 2: Influencing factors of Landslide and Debris Flow Susceptibility: a)Aspect ; b)Slope; c) Geology; d) Landuse; e) Plan curvature; f) Distance to drainage; g) Distance to roads; h) Rainfall; i) Flow accumulation; j) Internal Relief

2.4 Landslide Susceptibility Mapping

A landslide susceptibility map is generated based on numerous landslide hazard elements and the significant association between landslides and earth's surface data. The study used Heuristic approach to carry out the landslide susceptibility assessment.

Heuristic methods require using professional expertise, experience, and judgment to determine a given area's susceptibility to landslides, and is usually based on qualitative or semi-quantitative methodologies [10, 11]. In this study, expert judgement was used to assign individual rank to all the classes of the thematic layers. Furthermore, a total rank was provided to all the factors based on their influence on landslide susceptibility.

The nine thematic maps were overlain and numerically added using the raster calculator in GIS to produce a Landslide Susceptibility Index (LSI) based on the weighted linear sum method.

$$LSI = \sum_{j=1}^{n} (W_j * X_{ij}) \quad (1)$$

Where, W_j is the weight value of parameter j, $X_i j$ is the rating value of class i of parameter j, and n is the parameters.

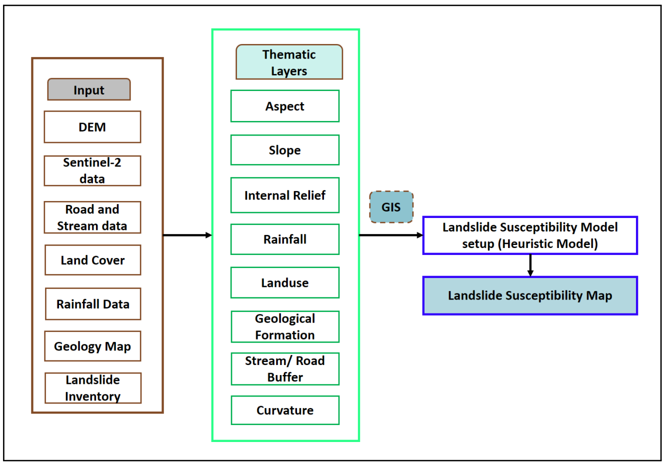

Figure 3: Methodology for Landslide Susceptibility Assessment

2.5 Debris Flow Susceptibility Mapping

Debris flow modeling for the study was carried out for the area using Flow-R (Flow path assessment of gravitational hazards at a Regional scale), which is a model for susceptibility mapping of debris flow events. Flow-R was developed at the University of Lausanne, Switzerland [12]. The program is useful in the identification of potential source areas for Debris Flow (DF) events, and also determines propagation extent of the Debris Flow. However, it does not take into account the Debris flow mass and volume [12, 13].

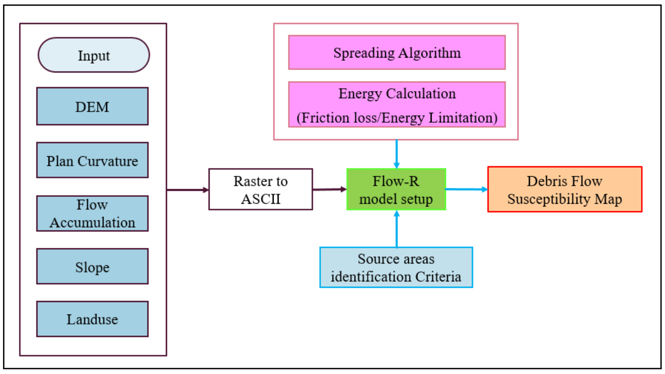

Figure 4: Methodology for Debris Flow Modeling in Flow-R

2.5.1 Source areas identification

The source areas in Flow-R are identified from the influencing factor maps input into the model. In the model, grid cells for each input map are classified as:

1. Favorable when debris flow initiation is possible,
2. Excluded when initiation is not likely,
3. Ignored when no deduction can be made.

A cell must have at least one favorable decision, and should never be excluded in order to qualify as a source area [12]. The sources areas can also be imported directly in the Flow-R as predefined sources, to include historical source areas or

Table 2: Heuristic table for Landslide Susceptibility Mapping

SN	Layer	Class	Weight	Total Rank
1	Aspect	F	1	
		N	1	
		NE	2	
		E	3	
		SE	8	
		S	9	10
		SW	6	
		W	4	
		NW	3	
		N	1	
2	Slope	0 – 15	1	
		15 – 25	2	
		25 – 35	5	13
		35 – 45	8	
		45 - 90	9	
3	Geology	Middle Siwalik2	1	
		Middle Siwalik1	1	
		Lower Siwalik	8	10
		Recent	3	
		Middle Siwalik	1	
4	Landuse	Waterbody, 1	1	
		Forest, 4	2	
		Riverbed, 5	2	
		Built-up, 6	1	13
		Cropland, 7	1	
		Grassland, 10	7	
		Other wooded land, 11	6	
5	Curvature	Negative	8	
		Flat	1	13
		Positive	4	
6	Distance to drainage	0 – 100	1	
		50 – 250	2	9
		250 – 500	3	
		500	4	
7	Distance to Road	0 – 100	4	
		100 – 300	4	10
		300 – 500	5	
		500	6	
8	Rainfall	0 – 1350	5	
		1350 – 1400	4	
		1400 – 1450	4	9
		1450 – 1500	2	
		1550	6	
9	Relative Relief	0 – 5	1	
		5 – 10	2	
		10 – 15	3	13
		15 – 20	4	
		20 – 68	5	

sourced identified by other methods.

In order to determine the source areas in this study, specific criteria were specified for all layers. The criteria were based on several literature and studies conducted around the world.

Table 3: Source areas criteria

Input Parameters	Criteria	Sources
Slope	Above 15/degree	[12, 14, 13, 15]
Plan Curvature	-0.02	[13, 12, 15]
Flow Accumulation	DF Rare events for 10m DEM	[12, 14, 15]

2.5.2 Propagation calculation

The propagation calculation provides an assessment of all possible occurrences in a single execution and is performed after the previously identified source areas. Two main types of algorithms are used in the propagation assessment: spreading algorithms, which control the direction and movement of debris flows, and friction laws, which establish the runout distance of the flow.

Energy functions and flow direction algorithms control the spreading of the debris flow in an area. A modified version of the Holmgren (1994) method was employed in the study.

$$p_i^{fd} = \frac{(Tan\beta i)^x}{\sum_{j=1}^{8}(Tan\beta f)^x} \forall \{\tan(\beta > 0) \quad \text{if } x \in [1,\infty) \tag{2}$$

where, i and j are the flow directions, p_i^{fd} is the susceptibility proportion in direction $tan\beta i$ is the slope gradient between the central cell and the cell in the direction i, and x is the variable exponent [12, 13]. The spreading resembles the multiple flow direction when x = 1. When the value of x is increased, the divergence decreases up to the point where there is just one flow direction when x $\rightarrow\infty$. The spreading can be controlled using the parameter, and helps replicate a variety of other flow accumulations.

Depending on how the current direction differs from the previous direction, the persistence function modifies the flow direction. Replicating inertial behavior is the primary objective of inertial function. Weights (Gamma 2000) has been chosen as the study's inertial function. Furthermore, the friction loss function and the energy limitation have been determined to be travel angle (11°) and 15m/s, respectively [12].

2.6 Flood Hazard Mapping

To develop a flood hazard map, first step was to gather input data DEM, precipitations, land use/cover, and soil data of the study area. The flood susceptible areas were identified by analyzing the flood history of the area and using hydrologic and hydraulic models to simulate different scenarios of flooding. Flood mapping was done by analyzing using hydraulic models (HEC-RAS 2D) through rain on grid methods.

Rain on Grid methods in HEC-RAS modeling were used to simulate the rainfall-runoff process and generate flood hazard maps for a given study area. The method involved dividing the study area into a grid and estimating the amount of rainfall that would be converted to runoff based on land use/cover, soil type, precipitations and other factors. The runoff was then routed through the river network using the HEC-RAS model.

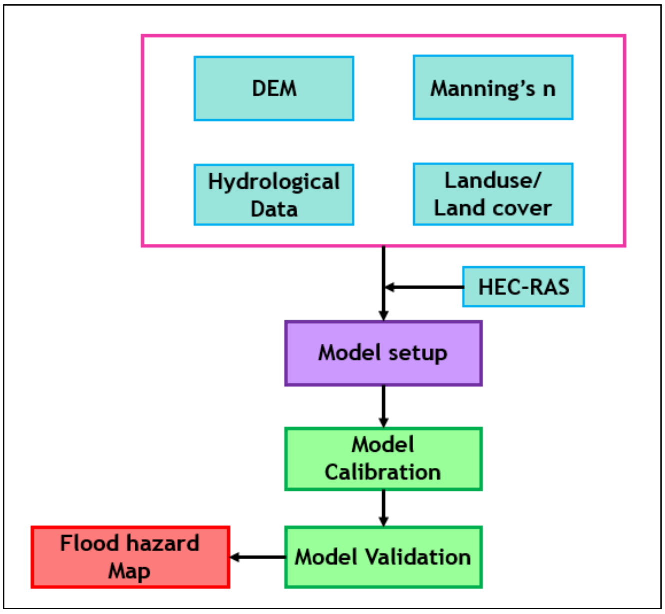

Figure 5: Methodology for Flood Hazard Mapping

The necessary layers were prepared in ArcGIS platform, and then exported to HEC-RAS platform. The projection was set up in the HEC-RAS workspace and geometry parameters were used to generate 2D flow area. The computational mesh of the 2D flow area was taken as 500 m in the whole basin, and 50 m along the river line. The landuse data was taken, and manning's roughness coefficients as well as impervious values were set based on the landuse classes.

Similarly, the meteorological stations of West Rapti Basin were set up and daily rainfall data was assigned to all stations based on the simulation dates. The boundary condition line was drawn along the outlet. Once all data were input, unsteady flow modeling was carried out. Courant conditions were utilized for the time step function with maximum and minimum courant values. The simulation was run for the model.

Calibration and validation of the models were performed by adjusting the values of manning's coefficient , along with the courant numbers. The simulated result was compared with the observed discharge data for Bagasoti station, where a profile line was drawn in the geometry. Once the model parameters were calibrated and validated, 100-yr return period flood map was generated for the study area.

2.7 Multi-Hazard Susceptibility Mapping

Individual hazard maps were generated and then merged to create a multi-hazard map for the hazards. The weightage of each hazard map was calculated using the Analytic Hierarchy Process (AHP) method. The AHP method uses a scale from 1 to 9 where 1 representing equal importance and 9 representing extreme importance [6]. After completing the pairwise comparison, a consistency ratio is determined to ensure that the weightings are logically and mathematically consistent. If the consistency check indicates that the weightings are inconsistent, adjustments are made to ensure consistency. The weightings from the pairwise comparison were developed to create hazard maps that show the relative importance of each hazard in each area.

The individual maps were normalized to make the susceptibility maps unit less and brought in the range of 0-1. A min-max, approach, as shown in the following equation was adopted for normalization of the values of the hazard maps.

$$xn_i = \frac{x_i - x_l}{x_h - x_l} \quad (3)$$

Where,
$x_n i$ is the normalized value of the landslide hazard map for the i^{th} pixel,
x_i is the original value of the landslide hazard map for i^{th} pixel,
x_h is the lowest value of the landslide hazard map, and x_l is the highest value of the landslide hazard map.
Raster calculator tool was used to assign the weights to the normalized maps, thus generating multi-hazard susceptibility map.

3. Results and Discussion

3.1 Landslide Susceptibility Assessment

The heuristic approach showed that around 64.2% of the study area had low susceptibility to the landslides, while 31.1% was in the medium susceptibility, and 4.69% was highly susceptible. The high and medium susceptible areas were found mostly on high elevation areas with high slope.

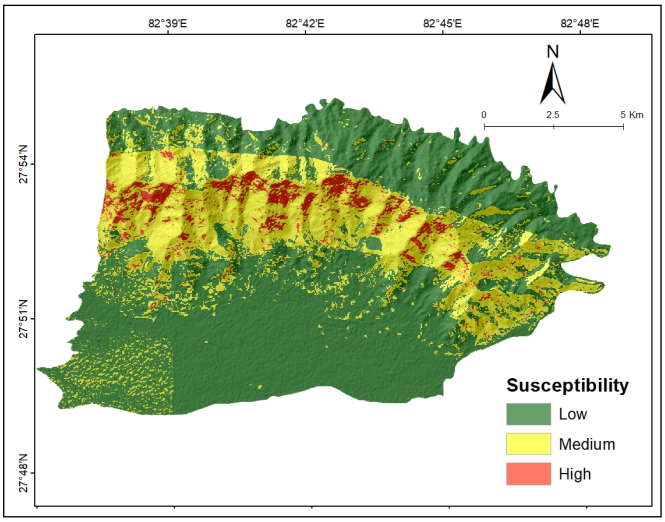

Figure 6: Landslide susceptibility map

Regions with little vegetation and those facing south and southeast are more prone to landslides. The slopes facing south direction in general receive more direct sunlight, as compared to the Northern slopes. The high exposure to sunlight usually results in greater fluctuations in temperature during the day and night, which increases stress in the slope-forming materials and make them weaker. Similarly, high slope can be linked with decreasing slope stability, which makes the area more susceptible to landslides. Aspect, distance to drainage, and road have comparatively less impact on the possibility of landslides than slope, curvature, and relief. The low susceptible areas are primarily on gentle slope and flat curvature, which have been used by the residents of the study area for farming and agriculture practices. Since the majority of settlements are in low-lying areas with less landslide susceptibility, there are not many landslide susceptibility zones that have an impact on human settlement.

3.2 Debris Flow Susceptibility Assessment

The results for Debris Flow susceptibility assessment were obtained as source areas and propagation extent in ASCII format, which were converted into raster and a coordinate system was assigned. The model identified 35 source areas, and resulting propagation extents were determined from the empirical equations. 11798 pixels were identified as debris flow susceptible regions, which accounted for 1.14% of the total study area. The susceptibility values obtained from 0.0003 to 1, which were then classified as very low, low, medium, high, and very high. The debris flow regions were prevalent on the Siwalik

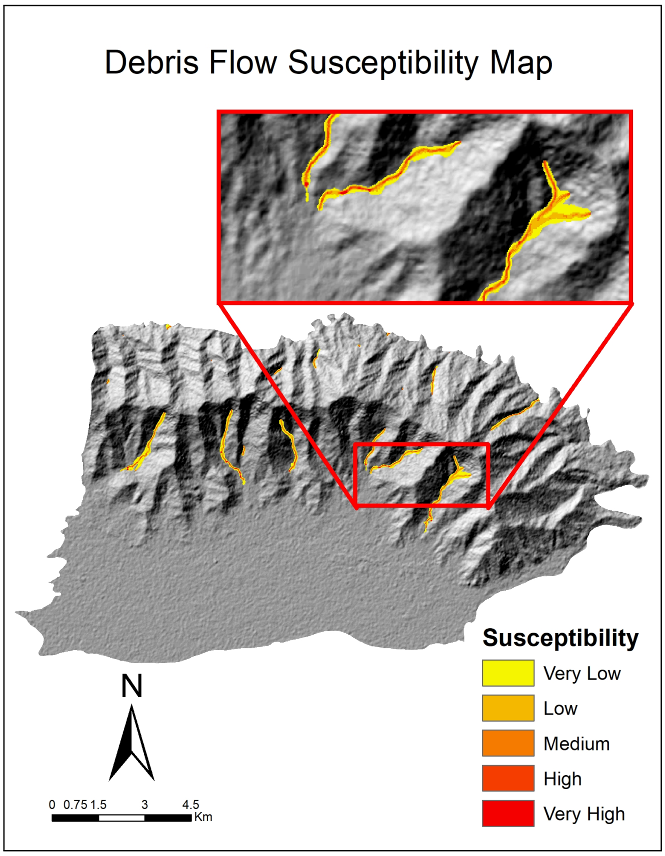

Figure 7: Debris Flow Susceptibility map

regions with a rugged terrain and high elevation. The Siwalik is typically made up of poor consolidated rock materials like sandstones, siltstones, and mudstones. Such rocks weather and erode easily, which results in fine-grained and loose soil and debris particles and elements that are easily mobilized after heavy rains. The rugged terrain of the Siwalik areas, consisting of high slopes and valleys, speeds up the weathering and erosion process, contributing to slope instability. Siwalik areas in the Rapti Rural Municipality frequently get extreme rainfall during the monsoon season. During the extreme rainfall events, it causes the eroded material to travel rapidly down the slope, resulting in debris flows.

3.3 Flood Hazard Map

The HEC RAS model for flood hazard mapping was setup using the rain-on-grid approach. The model was calibrated for the year 1999, and validated for 2014. The model was calibrated and validated by using Nash-Sutcliffe efficiency (NSE), and Coefficient of determination (R^2). The obtained NSE values were 0.878 for the year 1999, and 0.748 for 2014, both of which are acceptable ranges in terms of model performance [16].

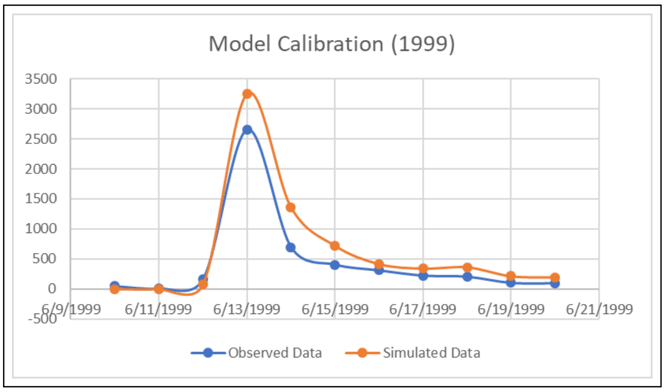

Figure 8: Model Calibration

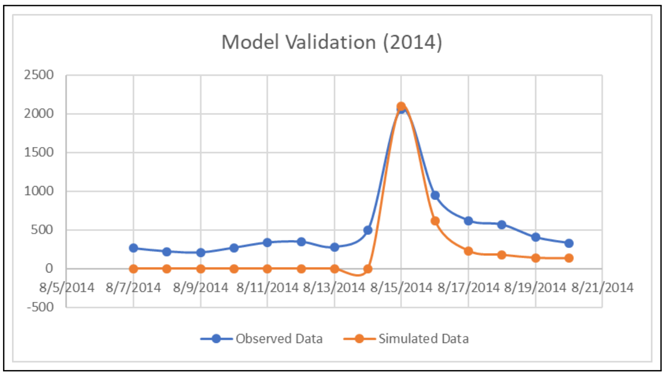

Figure 9: Model Validation

The calibration and validation results of flood hazard model provide an acceptable performance. However, in the model calibration in the year 1999, a significant difference in the peak discharges of observed and simulated values can be observed. Similarly, the NSE value of the validated data (in the year 2014) is lesser than that of the calibrated data, but the peak discharge is better simulated in the validated model.

100-yr return period rainfall was determined based on the model results, and then flood hazard map was developed for 100-yr return period. The classes were then divided as: Very Low, Low, Moderate, High, and Very High. For 100-yr return period, classification was done as Very low (0-0.5), low (0.5-1), moderate (1-2), high (2-3), and very high (> 3). The map shows that around 16.69% of the area was inundated, which accounts for 26.9 km^2 area in Rapti Rural Municipality.

The outcomes of flood hazard mapping indicate that the external banks of the meanders along Bagasoti have high hazard level, implying an increased likelihood of future erosion. Furthermore, the inner banks of these meanders have lower hazard level, which increase the possibility of deposition. The downstream river segment, characterized by a broader and flatter profile, is shown evenly distributed flow with relatively less hazard level. The areas near the floodplain are dominated by agricultural and croplands. These areas are used by the residents for agricultural practices, and may be at a risk for flooding during extreme rainfall event.

3.4 Multi-Hazard Susceptibility Map

The weights for each hazard were defined by identifying the hazards that are most important in assessing the risk associated with them. In the context of Rapti Rural Municipality, flood was found to be the biggest issue as

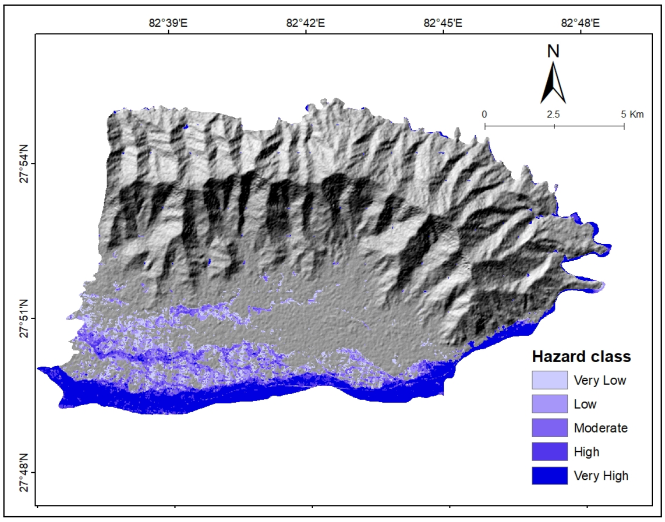

Figure 10: Flood Hazard Map for 100-yr return period

suggested by different literature, followed by landslides and debris flows. Flood was also a significant cause for landslide and debris flow events. The percentage weights determined from the AHP method were for Landslide: 29%, Flood: 54%, and Debris Flow: 17%. The multi-hazard map thus obtained was further reclassified into five classes: very low, low, moderate, high, and very high by using the natural break method.

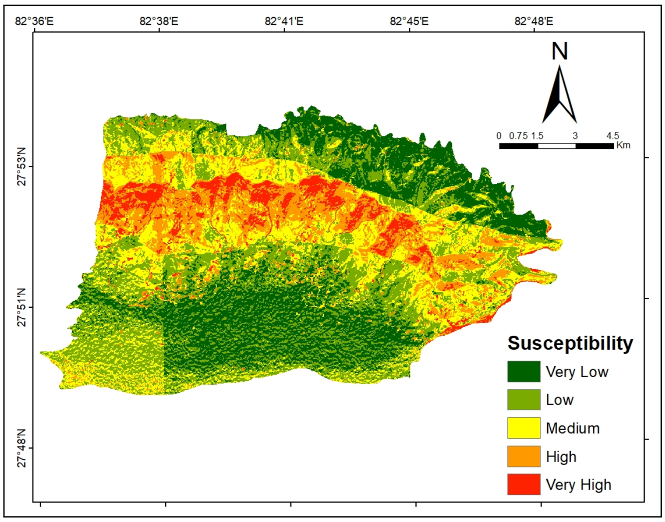

Figure 11: Water-Induced Multi-Hazard Susceptibility Map

The percentages of the susceptibility classes in the study area is provided in Table 4.

Table 4: Percentage distribution of multi-hazard classes

Susceptibility Class	Percentage
very low	23.94
Low	31.74
Moderate	22.65
High	15.49
Very High	6.16

Most of the study area has low susceptibility to multi-hazard scenarios (31.45%), while only 6.16% of the area was very highly susceptible. The areas along Rapti River in Bagasoti area have

shown more susceptibility to the multi-hazards, due to the high flood risk in the area which can trigger potential water-induced hazards. Similarly, the gentle slopes and forest hills have high susceptibility. These areas are characterized by steep slope and high elevation, which makes them more prone to landslide and forest fire based hazards. The plains along the river are core residential and agricultural areas, and the high water-induced hazard susceptibility in those regions can pose a threat to the people residing in the area.
The results show that topography and geology play a significant role in the susceptibility of water-induced multi hazards in the Rapti Rural Municipality. Other than rainfall, slope, relief, and curvature are the primary causative factors of landslide and debris flow hazards, as they have the most influence in the susceptibility. Slope and relief are interrelated, as higher slope usually indicates higher relief. The higher slope areas, when coupled with higher relief and a negative curvature, have a higher possibility of being affected by multi-hazard scenarios during extreme rainfall events.

4. Conclusion

In this way, the study has conducted a susceptibility assessment of water-induced hazards including flood, landslide, and debris flow, and developed a multi-hazard map based on the individual hazards. The study used AHP in order to determine weights of the hazards prevalent in the area, which uses Multi-Criteria Decision Making (MCDM) in order to make complex decisions. It proves effective in complex decision-making situations, helping decision makers in setting priorities and making optimal choices. The landslide map was developed based on Heuristic approach, and showed that the rugged terrains with steep slopes in the Siwaliks are highly susceptible to landslides and debris flow events. Similarly, the plains and agricultural areas along the river are more prone to flooding.The percentage weights for each hazard were determined from the AHP method were, Landslide: 29%, Debris flow: 17%, and Flood: 54%, based on their priority. Flood was assigned the highest weightage among the three hazards, based on its impact on the study area over the years. The multi-hazard map thus obtained was further reclassified into five classes: very low, low, moderate, high, and very high. The geology, and topographic factors such as slope, relief, and curvature were found to be the key factors in contributing to the susceptibility levels. The areas along Rapti River in Bagasoti area have shown more susceptibility to the multi-hazards, due to the high flood risk in the area which can trigger potential water-induced hazards. Similarly, the Middle Siwaliks are also more prone to water-induced multi-hazards. Therefore, steps need to be taken to decrease the risk of the multi-hazards in the municipality.

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