Landslide susceptibility mapping of proposed reservoir of Budhigandaki Hydropower Project and its adjacent region

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Abstract: Detailed geological study and landslide susceptibility mapping are crucial aspects and critical components of any engineering project in tectonically active Himalayan region. The study area was characterized by the rocks of Nawakot complex with Lower Nawakot Group which comprises Kuncha Formation, Fagfog Quartzite, Dandagaon Phyllite, Nourpul Formation, Purebesi Quartzite and Dhading Dolomite and Upper Nawakot Group comprises the Benighat Slate only. Landslide susceptibility mapping was carried out by Weight of Evidence method and Frequency Ratio method using the combination of remote sensing and detailed engineering geological investigation of field. Data obtained from these methods were integrated and analyzed in Arc Map 10.8. During study sixteen landslide triggering factors were analyzed. These factors are slope, aspect, stream power index, topographic wetness index, distance from stream, normalized difference vegetation index, land-use and land cover, distance from shear zone, rainfall, plan curvature, profile curvature, distance from road, lithology, elevation, sediment transport index, terrain ruggedness index and all these factors were integrating into a map. The map was validated with an Area under curve (AUC). The Success Rate curve shows 72.54% accuracy for Frequency Ratio method and 76.04% for Weight of Evidence method.

Keywords: Landslide susceptibility map; Weight of evidence(WoE); Frequency Ratio (FR); Area under curve.

Introduction

Hilly terrains are subject to landslides due to their rough mountain topography, complicated fragile geology, heavy torrential rainfall, and frequent earthquakes. Landslides are common, especially during the monsoon, and can cause significant damage. For instance, a major landslide in 1968 blocked the Budhi Gandaki River [1] , damaging downstream areas.

In reservoir projects, landslide susceptibility assessment is vital to identify unstable slopes that could compromise the safety and functionality of the reservoir, including potential dam failure. The objectives of this research was to carry out detail geological investigation and preparation of geological map and to carry out landslide susceptibility mapping using Frequency ratio method and Weight of evidence method.

For this**,** Geological study was carried out from the area Benight in South to Arkhet in North along Budhi Gandaki River section in Gorkha and Dhading districts in Central Nepal Lesser Himalaya region, between latitudes 27°40'00" to 27°44'06" North and longitudes 85°21'06" to 85°23'00" East. Benighat is around 83 km west of Kathmandu, while Narayanghat and Pokhara are roughly 69 km west and 123 km South-West of Benighat, respectively. The location map of study area is shown in Figure 1.

Methods and Methodology

The study integrates GIS-based landslide susceptibility mapping using FR and WoE models. The methodologies

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and procedures (Table 1) used for software analysis, fieldwork validation of the research data and preparation of maps are discussed in this section.

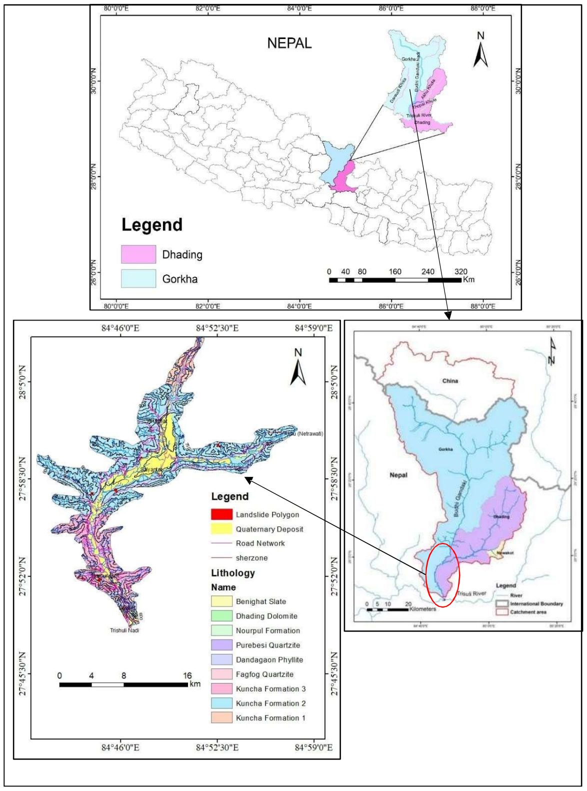

Figure 1: Location Map of Study area.

Collection of necessary datasets: Necessary topographic maps, namely Malekhu (2784 04C), Gorkha (2784 03B), Jogimara (2784 03D), Salbas Chainpur (2784 04 A), Arughat (2884 16) with scales of 1:25,000, were obtained from the Survey Department of Nepal. Regional geological map of the study area was collected from the Department of mines and Geology. Rainfall data was sourced from Department of Hydrology and Metrology.

Landslide inventory mapping: Preliminary landslide inventory map was prepared using both topographic maps at scales of 1:25,000 for historic landslides, as well as high-resolution images from Google Earth Professional. The validation of the landslide inventory prepared with the aid of Google imagery is assessed with direct field observation landslide inventory prepared with the aid of Google imagery is assessed with direct field observation.

Detailed field investigation: Necessary in-situ test i.e. Unified Soil Classification System (USCS), infiltration test, penetration test, Schmidt hammer test, slake durability test etc. were carried out in the field. Previous studies [2] are consulted on the geology of the research area, and geological structures and boundaries were examined. In order to determine engineering soil types and to estimate soil depth, soil sampling and mapping was done. The research region was splitted into a number of topographical mosaics based on contour line orientation and comparable geomorphological environment. Each mosaic was designated with the USCS. Soils were evaluated in the field for soil domain categorization with the USBR 2001 field identification process.

Table 1: Methodological framework for landslide susceptibility assessment using FR and WoE models.

Phase	Main Activities	Output
Desk Study	Literature review, geological map review, secondary data collection	Base database
Landslide Inventory Mapping	Landslide identification from Google Earth and historical records	Preliminary landslide inventory map
Field Investigation	Reconnaissance survey, inventory verification, geological mapping, sampling	Validated landslide inventory and geological data
Geotechnical and Stratigraphic Analysis	Stratigraphic column preparation, lithostratigraphic classification	Geotechnical and stratigraphic database
GIS Database Preparation	Preparation of thematic layers (slope, aspect, lithology, land use, drainage, rainfall, etc.)	Spatial database
Susceptibility Modeling	Application of Frequency Ratio (FR) and Weight of Evidence (WoE) models	Landslide susceptibility maps
Model Validation	ROC–AUC and prediction accuracy assessment	Model performance evaluation
Interpretation and Reporting	Result interpretation, map preparation, manuscript writing	Final susceptibility zonation map and research paper

Preparation of landslide conditioning factors map: This begins with collecting relevant data, including Digital Elevation Models (DEMs), geological maps, land use/land cover data, soil characteristics, and climatic information such as rainfall. All together sixteen thematic layers were prepared in Arc Map 10.8 from different source. All these factors were selected based on the field observation as it is not universal but is site specific. These factors were derived from field surveys, remote sensing data, and GIS analysis.

Geomorphological factors

Slope, aspect, plan curvature, profile curvature, SPI, TWI, STI, TRI, elevation, NDVI were prepared from DEM NDVI is calculated by using the formula NDVI = (Band5-Band4)/(Band5+Band4). Band 4 and Band 5 image is downloaded from the Sentinel 8 satellite imageries. SPI and other parameters are prepared by using flow direction, flow accumulation, slope in percentage, raster calculator using following formula:

$STI = (\alpha/22.13)^{0.6} * (\sin ß/0.0896)^{1.3}$

$SPI = (\alpha * \text{cell size}) * \tan(ß * pi/180)$

$SPI = A \times \tan ß$

$TRI = \gamma \{\text{Sum} (x_{ij} - x_{00})^2 \}^{1/2}$

$TWI = \ln ((\alpha+1) * \text{cell size} / (\tan ß * pi /180) + 0.001))$

$TWI = \ln (A / \tan ß)$

α = flow accumulation, ß = slope in radian

A: Contributing drainage area per unit width of the slope (m^2/m). Tan (β): Local slope gradient, which represents the steepness of the terrain.

Geological factors: Features like faults, joints, bedding planes, and weathering zones can act as slip surfaces, increasing the likelihood of landslides. Three raster layers-geology; lithology, distance from shear zone is prepared based upon field observations.

Hydrological factors: Hydrological parameters such as river, streams and precipitation play great role on the slope stability. Higher the precipitation intensity, higher the possibility of landslide occurrences. The thematic layers: rainfall and distance from stream major rivers are suggested based on the field observation for susceptibility modeling. All these parametric layers are prepared, analyzed, processed, and extracted in cell size 20 m×20 m.

Anthropogenic factors: Human intervention and improper use of landmass can cause serious problem of mass movements in any stable area. Two major factors: land use and distance to road are used for susceptibility modeling. For these factors cell size of 20m×20m was maintained.

Landslide Susceptibility Mapping: This is the process of identifying areas that are likely to experience landslides based on various environmental and anthropogenic factors. WoE and FR approaches to landslide susceptibility mapping use statistical studies to pinpoint landslide-prone locations according to contributory variables.

Weight of Evidence (WoE): WoE is data-driven, statistical approach based on Bayesian probability, WoE method for landslide susceptibility mapping assesses the geographical link between landslip occurrences and causal variables [3]. By comparing the occurrence and non-occurrence of landslides in several classes of causative factors (such as slope, aspect, and lithology), this technique allocates weights to each class [4]. Negative weights imply a lesser chance of occurrence, whilst positive weights show a high correlation with landslides. WoE is computed by dividing the percentage of occurrences by the percentage of non-events, then taking the natural logarithm (log to base e).

WOE = ln (percentage of non-events / percentage of events)

WOE = ln (percentage of non-landslides area in terms of pixel / percentage of landslide area)

W^+ = ln [Npix landslide area in a class/ Npix total landslide area] / [Npix stable area in class/ Npix total stable area]

W^- = ln [Npix landslide area outside class/ Npix total landslide area] [Npix landslide area outside class/ Npix total stable area]

The contrast value, which is determined by the formula $W_f = C = W^+ - W^-$, provides a valuable indicator of the relationship between a certain class of causative variables and landslip occurrences.

Landslide Susceptibility Index = Slope×3.23 + Aspect×1.15 + SPI×2.06 + TWI×2.75 + Distance from Stream×2.37+ NDVI×2.05+ Land use and Land Cover×2.07+ Distance from Shear Zone×2.24+ Rainfall×4.05+ Plan Curvature×1.21+ Profile Curvature×3.3 + Distance to road ×1.0 + Lithology×3.17 + Elevation×2.49 + STI×4.79 + TRI×2.97

Frequency Ratio (FR): The frequency ratio for any given set of attributes is determined by dividing the likelihood of an occurrence by the chance of a non-occurrence [5]. A low frequency ratio indicates a poor correlation between the landslide's occurrence and the specified factor's characteristic. In This approach total landslide susceptibility score is based on each frequency ratio that relates to each contributing component [6]. The ratio of the individual class's landslip to its overall percentage is shown in the equation below:

FR = Percentage of particular class (Lc)/ Percentage of the specified class in the total area (Ac)

L_C = Number of landslide pixels in the class(N(A|L)/ total number of landslide pixels (N(A/L) *100

A_C = number of pixels of specific class N(A)/ total number of pixels (Nt) *100

Results

Major findings of this research are categorized into two section: detailed geological study and landslide susceptibility mapping as mentioned below:

Geological Study

Detailed geological study was carried out in the study area from Benighat in south to Arkhet Bazar in north and geological map on the scale of the 1:25000 was prepared (Figure 2). Different topo maps of the area in the scale of 1:25000 in southern part and in the scale of 1:50,000 in northern part were used as a base map for the preparation of final geological map of area. The study area comprises an autochthonous succession of low-grade metasedimentary rocks. The established litho-stratigraphy of the area published by Stöcklin and Bhattarai 1977 and Stöcklin 1980 [2,7] was adopted during the study.

Kuncha Formation: The Kuncha Formation was rocks consist of alternating grey to greenish-grey chloritic phyllite with crenulation cleavage (Photograph1), gritty quartzite, and psammatic schist in nearly equal proportions. The phyllite, which is argillaceous with silty or quartzitic characteristics, includes fine-grained laminated siliceous,varieties. Well developed crenulation cleavages are observed in the phyllite which indicates the different phase of metamorphism..

Fagfog Quartzite: The outcrops of Fagfog Quartzite were studied along Benighat Arughat road section 4 km north from the Benighat. In this area exposure is characterized by medium to thick banded, medium to coarse grained milky white ortho Quartzite with pale-orange tints intercalation of phyllite (Photograph 2). The rocks in this exposure are massive, highly fractured with three sets of joints. It forms a good marker in the study area.

Photograph 1: Crenulation cleavage observed in the phyllite near Darbunphat in 2+7°51'30.25"N, 84°45'29.30" E photo facing towards North East.

Photograph 2: Milky white ortho quartzite observed in Fagfog Quartzite about 1.1 km North from Baseri village in 27°50'19.22"N, 84°46'30.87"E, 393 m Photo facing towards North East.

Dandagaon Phyllite: Exposure of Dandagaon Phyllite was observed about 1 km North West from Baseri village and 2.6 Km South East from Darbunphat. The exposure comprised of fine grained dark grey colored phyllite (Photograph 3), intercalated with lesser amount of quartzite and slate. Phyllites of this formation are quite darker than Kuncha Phyllite. Color of phyllite and slate is nearly same but can be distinguished only by the soapy nature of phyllite.

Nourpul Formation: Exposure of Nourpul Formation was studied along Benighat-Arughat road section about 2.8 km

North from Benighat and 3 km south from Baseri village. The exposure is comprising of mixed lithology of variegated phyllites, slates and quatzites (Photograph 4). The upper part of this formation shows dolomite and

Photograph 3: Thinly laminated Phyllite observed in Dandagaon Phyllite about 1 km North from Baseri village in 27°50'17.54"N, 84°46'10.72"E, and 476 m Photo facing towards South East.

dolomitic quartzite where as white to pink, strongly ripple-marked Purebesi Quartzite as a basal member.

Photograph 4: quartzite band observed in Nourpul Formation about 2.8 km North from Benighat at 27°49'45.77"N, 84°46'17.44"E, photo facing towards South East.

Purebesi Quartzite: Exposure of Purebesi quartzite was obsesrved in the test adit tunnel of Budhi Gandaki Hydropower Project in Kalleri village. The exposure consists of white and purple, fine to medium-grained quartzite (Photograph 5) with the parting of fine-grained, grey phyllite of the Nourpul Formation intercalated with highly jointed, grey, fine-grained,crystalline dolomite of the Dhading Dolomite.

Dhading Dolomite: Exposure of Dhading Dolomite was observed along Benighat Arughat road section about 1.8 km north from Majhitar village. lower part of this formation dolomite beds is strongly deformed forming brecciated structure (Photograph 6). middle parts of this rock

Photograph 5: Thick banded quartzite observed in Purebesi Quartzite in Kalleri village about 2.3 Km north from Benighat at 27°49'41.55" N, 84°46'27.83" E, 390m. (Photo facing towards North East).

succession along this road segment rocks are characterized by medium to thick-bedded (Photograph 14) monotonous sequence of siliceous dolomite with partings pelitic phyllite.

Photograph 6: Moderately deformed dolomite rock observed in 1.4 km North West from Majhitar at 27°49'08.12"N, 84°46'20.12"E, and 505 m photo facing towards South East.

Benighat Slate: Exposure of Benighat slate was observed about 1.8 Km north from the confluence of Budhi Gandaki River to Trishuli river near kalleri village. The outcrop consists of fine grained, dark grey to nearly black argillaceous phyllite containing intercalation of black carbonaceous highly cleaved slate (Photograph 7). Rocks consists of green-grey to dark grey, graphitic slate, calcareous slate and subordinate siliceous slate.

Landslide Susceptibility Mapping

Landslide susceptibility mapping involves identifying and analyzing factors contributing to landslides in a specific area. For the Budhigandaki Hydropower Project in Central

Photograph 7: Thinly to thickly foliated phyllite observed near the confluence of Budhi Gandaki to Trishuli Riverin the 27°4'54.46"N, 84°47'01.64"E.

Table 2: Lithostratigraphy of the study area prepared based upon field observation and modified after Stocklin and Bhattarai (1977)[7].

Lithologic units	Main Lithology	Approximate thickness (m)	Age	Occurrence
Colluvium	originated from landslides debris of boulder to silt	upto 50 m	Quaternary	on the slopes and at the toe of old landslides in Rampur and Dhodeni
Debris Fan deposits	rounded to angular shaped boulder to sand and silt	upto 50m		in the Darbunphat deposited by Khani Khola
Residual soil	Brown to reddish soil with gravel to clay	Upto 10 m		on hilltops of Rampur, Ratmata
Benighat Slate	Black slate	400-500	Paleozoic	1 km NW from the confluence of Budhigandaki to Trishuli
10-20 cm weathered zone indicating to erosional unconformity about 1.02 km North-West from the confluence of Budhi Gandaki to Trishuli				
Dhading Dolomite	Grey silicious dolomite	500	Late - Precambrian	Left and Right bank of Budhi Gandaki
Nourpul Formation	Phyllite, Quartzite and silicious dolomite	400		1 km SE from Baseri village
Purebesi Quartzite	Quartzite with phyllite Intercalation	300		600 m SE from Baseri village
Dandagaon Phyllite	Grey phyllite	1100		Appears in Baseri Village
Fagfog Quartzite	Milky white quartzite	650		left and right bank of Budhigandaki 1 km NW from Baseri
Kuncha Formation	Almost equal proportion of chloritic phyllite / and gritty quartzite	3000+		Left bank of Khani khola 280 m SW from Darbunphat

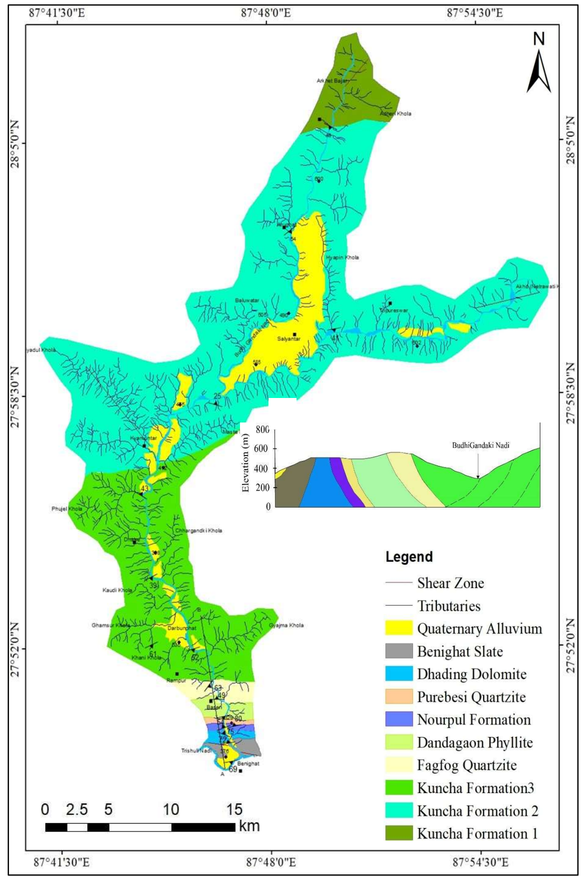

Figure 2: Generalized geological map of the study area prepared based on the field observation and modified after Stocklin and Bhattarai (1977) and Feasibility and detail design of BGHPP 2015 (Unpublished report).[8]

Nepal, several geophysical, geological, hydrological, and human-induced factors play significant roles in landslide susceptibility. Causative factor of landslide has been selected on the basis of desk study, field verification and using conditional independence test.

For the landslide susceptibility mapping sixteen landslide conditioning factors were analyzed. The sorting of these factor is wisely decided according to literature review and researcher expertise. The designated factors were assigned into raster format having cell size 20 m x 20 m. Then, these raster data were further processed by overlaying the landslide raster to model the landslide susceptibility [9]. The proposed factors for landslide susceptibility analysis are explained in detail as follows:

Slope: Land units with slope angles less than 20 degrees make up the majority of the study area and ranges from 0 to

88°, which was later categorized into four different classes: (0-22°), (22°-44°), (44°-66°), (66°-88°). Positive weight of index (W_i^+) for these slope angles are -1.168, 0.429, 0.862, and 1.428 respectively. While weight for FR method is -1.17, 0.43, 0.86 and 1.43 respectively. Highest (62%) and lowest (1%) landslides are clustered in (22°- 44°) and (66°-88°) slope angle respectively.

Aspect: Aspect layer was categorized into ten classes: Flat, North, Northeast, East, Southeast, South, Southwest, West, Northwest and North. The North-facing and South- facing slopes dominate due to the East-West running hill. Highest (16%) landslides are clustered in North east (22.5°-67.5°) slope aspect while lowest (0.7%) landslide are clustered in flat aspect. Positive weight of index (W_i^+) for these classes are -0.876, 0.764, 0.422, 0.022, -0.144, -0.618, -0.772, -0.345, 0.094 and 0.54 respectively. While weight for FR method is 0.88, 0.76, 0.42, 0.02, 0.14, 0.62, 0.77, 0.35, -0.09, -0.54 respectively.

Stream Power Index (SPI): Study area is categorized into low erosive (-51.11--2.62), high erosive (-2.62-1.01) and very high erosive (1.01-51.93). Calculated data shows that maximum landslide (39%) is located in the very high erosive region and minimum landslide (26%) is associated with low erosive region. Positive weight of index (W_i^+) for these classes are 0.452, -0.562 and 0.532 and weight for FR method are -0.45, 0.56 and -0.53 respectively.

Topographic Wetness Index (TWI): In the region TWI are categorized into four values 1.3-6.3, 6.3-11.24, 11.24-16.16 and 19.16-21. Among these value maximum landslides (70%) are concentrated in 1.3-1.6 value range and minimum 0.008% landslide in 19.16-21 value range. Positive weight of index (W_i^+) for these classes are 0.1 -0.174, -0.758 and -2.18 and weight for FR method 0.17, 0.76, 0.67 and 2.18 are respectively.

Distance from stream: River is responsible for the erosion as well as added water to the nearby slope and it can cause slope instability by undercutting the slope. Area is categorized into four regions; (0-238 m), (238-477 m), (477-715 m) and (715-954 m) in which most of the landslide lies in the range of 0-238m and lowest (0.65%) landslide are associated with 715-954 m from the range of streams.

Normalized Difference Vegetation Index (NDVI): In the research region area NDVI was separated into water (-0.035-0.015), settlement area (0.015-0.14), barren land (0.14-0.18), shrub and grassland (0.18-0.27), sparse vegetation (0.27-0.36), and dense vegetation (0.36-0.5). Among these division most of the landslide (42.8%) are associated with sparse vegetation and minimum of landslide (0%) are associated with water. Positive weight of index (W_i^+) for these classes are 0.0, -2.22, -0.24, -0.022, 0.131 and -0.132 and weight for FR method 0.0, 2.23, 0.25, 0.02, -0.13 and 0.13 respectively. High NDVI values correlate with lower susceptibility zones, while low NDVI values mark higher-risk areas. NDVI values range from -1 to +1.

Land use land cover (LULC): Land use of the area was categorized under river with sand deposit, settlement area, cultivation land, vegetation cover, sparse forest and dense mixed forest. Bushy vegetation covers the milder slopes of the Budhi Gandaki riverine corridor in Borlang, Sallyantar, Salang, and Ghylchok. Maximum landslides (50%) are concentrated in sparse forest followed by vegetation cover and dense mixed forest. W_i^+ for these classes are 0.0, -1.81, 0.346, -0.356, 0.226 and 0.218 and weight for FR method are 0.0, 1.81, -0.35, -0.23, -0.22 and 0.19 respectively.

Distance from shear zone: Study area is categorized into four regions of distance from shear zone; (0-2430), (2430-4975), (4975-7641), (7641-10854). Among them most of the landslide 35% are concentrated into the distance range of 2430-4975 m. Positive weight of index (W_i^+) for these classes are 0.0, -1.81, 0.346, -0.356, 0.226 and 0.218 and weight for FR method are 0.0,1.81, -0.35, -0.23, -0.22 and 0.19 respectively.

Rainfall: Rainfall map is prepared and separated into three regions; (1184-1461), (1461-17190), and (1719-2190). Calculation shows that most of the landslide (68%) lies in the high rainfall region i.e. 1719- 2190. Positive weight of index (W_i^+) for these classes are -0.43, 1.25, -0.25 and weight for FR method are 0.43, -1.26 and 0.25 respectively.

Plan Curvature: Plan curvature map was prepared with the values of (-3.1-0), (0-1.340), (1.34-2.51) and (2.51- 5.34). Among the classified value most of the landslide (79.9%) are concentrated in the range of 2.51-5.34. Positive weight of index (W_i^+) for these classes are -0.673, 0.132, 0.007 0.001 and weight for FR method are 0.67, -0.13, -0.001 and 0.00 respectively.

Profile curvature: Profile curvature map was prepared with the values of -5.63-0, 0-2.61, 2.61-5.32, 5.32-7.92 respectively. These four ranges are categorized into linear, concave and convex. Maximum landslides lie in the range of 2.61-5.32. Positive weight of index (W_i^+) for these classes are 0.332, -1.587, 1.3, 0.728 and weight for FR method are -0.33, 1.59, -1.3 and -0.73 respectively.

Distance from road: Area is distinguished into four regions 0-621, 621-1735, 1735-3683, 3683- 6702 measured from road in which most of the landslides (60%) are concentrated in the distance range of 0-621m. Positive weight of index (W_i^+) for these classes are -0.111, 0.072, 0.48, 0.374 and weight for FR method are 0.11, -0.07, -0.48 and -0.37 respectively.

Lithology: Study area lies in the Kuncha Formation, Fagfog Quartzite, Dandagaon Phyllite, Nourpul Formation, Purebesi Quartzite, Dhading Dolomite and Benighat Slate. Among them 85% of the landslides are concentrated in Kuncha Formation followed by Dandagaon Phyllite (5%). Positive weight of index (W_i^+) for these classes are -0.67, 2.67, 1.56, 1.4, 1.69, -0.37, -0.1and weight for FR method are 0.67, 2.68, 1.46, 1.3, 1.5, -0.23, -0.11 respectively.

Elevation: Study area was separated into four different elevation range (262-494), (494- 727), (727-959), (959-1192). Among them most of the landslide was concentrated in the range of 494-727 m (Figure 23). Positive weight of index (W_i^+) for these classes are 0.372, -0.238, 0.057, -1.59 and weight for FR method are 0.37, 0.19, 0.045, 1.39 respectively.

Sediment Transport Index (STI): STI values are categorized into four classes (0- 462), (462-924), (924-1386) and (1386-1848). Among the categorized classes most of the landslide (49.68 %) are observed in the value range of 0-462 and minimum of landslide (1.22) are observed in the range of 1386-1848. Wi+ for these classes are -0.068, 0.043, 0.12, 2.27 and weight for FR method are 0.07, 0.04, -0.12, -2.2.

Terrain Ruggedness Index (TRI): In the observation area TRI values are categorized into four regions (0.0099-0.254), (0.254- 0.4999), (0.4999-0.744), (0.744-0.989). Among them most of the landslide (52.83%) in the region of (0.54-0.499) and minimum of landslide (0.059%) in the region of 0.744-0.989. Positive weight of index (W_i^+) for these classes are -1.496, 0.059, -0.008, and -2.73 and weight for FR method are 1.5, -0.06, 2.74 and 2.74 respectively.

Distribution of Landslides in different classes of Conditioning factors.

The percentage distribution of landslides within each conditioning factor class is presented in Figure 3 and 4. The slope class of 22–44° shows the highest concentration of landslides, accounting for approximately 62% of the total landslides in the study area. Landslide occurrence decreases in the classes 0–22°, 44–66°, and 66–88°, respectively, with the 66–88° class exhibiting a negligible number of landslides. For annual rainfall, the 1719–2190 mm class has the highest landslide distribution, whereas the <1600 mm class has the lowest (Figure 4). In the SPI classes, landslide occurrence is strongly influenced by river erosion, with the percentage decreasing from highly erosive to less erosive zones (Figure 3). Regarding slope shape, convex slopes exhibit a higher landslide frequency than concave and flat slopes (Figure 4). The NDVI analysis indicates that most landslides are concentrated in areas with sparse vegetation. Similarly, the majority of landslides occur on northeast-facing slopes.

Conditional independence test of landslide related factor

The Chi-Square Test can be used in the Weight of Evidence (WoE) for assessing landslide susceptibility to determine if landslide-related variables are conditionally independent

Figure 3 : Bar graph showing a) Slope vs Area coverage, b) Slope aspect vs Area coverage, c) SPI vs Area coverage, e) Distance from stream (m) vs Area coverage, f) NDVI vs Area coverage, g) Land use landcover vs Area coverage and h) Distance from shear zone (m) vs area coverage.

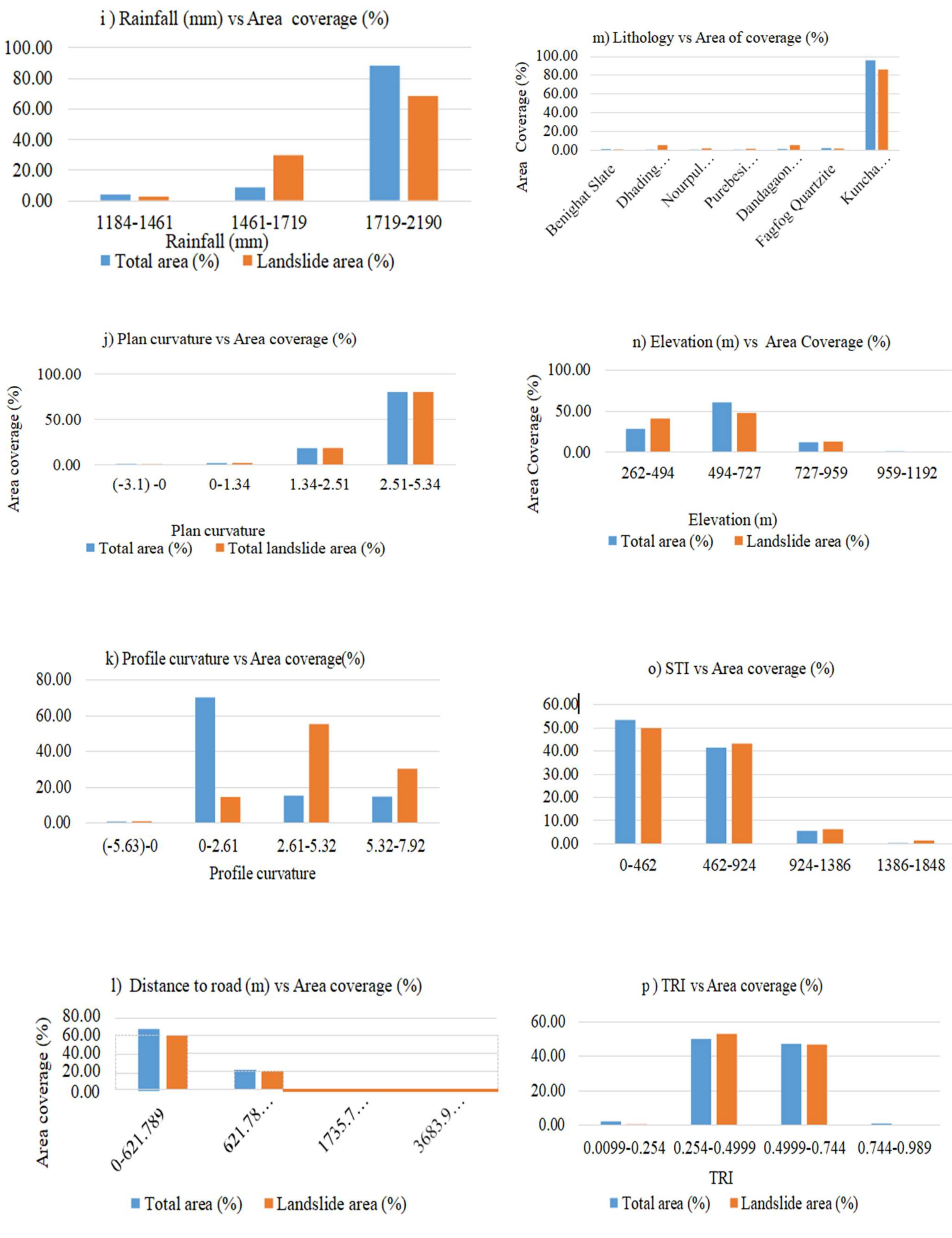

Figure 4: Bar graph showing i) Rainfall(mm) Vs Area coverage , j) Plan curvature vs Area coverage, k) Profile curvature vs Area coverage and l) Distance to road (m) vs Area coverage , m) Lithology vs Area coverage , n) Elevation(m) vs Area coverage , o) STI vs Area coverage.

(Table 3). An important assumption in WoE is conditional independence, which ensures that each factor's impact on landslides is statistically independent of the others.

Steps for the Chi-Square Test in WOE

Classification of landslide related factors: Sixteen landslide factors were divided into discrete value which includes slope, aspect, SPI, TWI, distance from stream, NDVI, land use land cover, distance from shear zone, rainfall, plan curvature, profile curvature, distance to road, lithology, elevation, STI and TRI.

Preparation of Contingency Table: Contingency table was prepared for each associated pair of factors (e.g., NDVI and LULC, SPI and STI, plan curvature and profile curvature) showing the frequency of landslide occurrences and non-occurrences.

Calculation of expected frequencies*:* Expected frequency was calculated for each cell in the contingency table assuming independence by using following formula.

Expected value = (Row total ×Column total)/Overall total

Chi-Square formula and degree of freedom: Chi square statistic was calculated by using the formula of

χ^2 = (Observed value - Expected value)^2/Expected value

Degree of freedom (df) was calculated by using the formula of df = (number of row-1) × (number of column -1) Calculated χ^2 value was compared with the critical value for the Chi-Square distribution table for 5 % significance level i.e α=0.05

Null Hypothesis

Two different factors are conditionally independent to each other.

Alternative Hypothesis

Two different factors are not conditionally independent to each other. If the value of P is greater than 0.05 (5 % level of significance) accept null hypothesis.

Frequency Ratio (FR) and Weight of Evidence (WoE) methods for the landslide susceptibility mapping

Both methods are useful for identifying landslide-prone zones, and the choice depends on data availability, study objectives, and the required level of detail.

Table 3: Contingency table prepared for conditional independence test by using chi square method .

Parameter	Observed (O)		Total	Expected (E)		(O-E)^2/E	
	NDVI $+ (W_i)$	LULC $+ (W_i)$		NDVI $+ (W_i)$	LULC $+ (W_i)$	NDVI (W_i^+)	LULC $+ (W_i)$
River	0	0	0	0	0	0	0
Settlemenmt	-2.228	-1.8	-4.02	-2.6	-1.424	-0.054	-0.099
Cultivation land	-0.246	0.34	0.18	0.06	0.03	1.493	2.729
vegetation cover	-0.022	-0.35	-0.37	-0.24	-0.134	-0.202	-0.370
Sparse forest	0.131	0.22	0.356	0.23	0.126	0.043	0.079
mixed forest	-0.132	0.21	0.086	0.05	0.030	0.633	1.157
Total	-2.497	-1.36	-3.86			1.912	3.496
	χ^2	= 5.4	df	= 5	p	= 0.36	
Remarks: P is greater than 0.05 so null hypothesis is accepted							
STI / SPI	STI $+ (W_i)$	SPI $+ (W_i)$	Total	STI $+ (W_i)$	SPI $+ (W_i)$	STI (W_i^+)	SPI $+ (W_i)$
0-462	-0.068	0.452	0.384	0.070	0.313	0.272	0.061
462-924	0.043	-0.562	-0.51	-0.095	-0.423	-0.201	-0.045
924-1386	0.12	0.532	0.652	0.119	0.532	0.00	0.000
Total	0.095	0.422	0.517			0.071	0.016
	χ^2	=0.087	df	=2	p	=0.957	
Remarks: P is greater than 0.05 so null hypothesis is accepted							
Plan/profile curvature	Plan $+ (W_i)$	Profile $+ (W_i)$	Total	Plan $+ (W_i)$	Profile $+ (W_i)$	Plan (W_i^+)	Profile $+ (W_i)$
-3.1-0	-0.673	0.332	-0.34	0.757	-1.098	2.701	-1.862
0-1.34	0.132	-1.587	-1.45	3.23	-4.686	2.972	-2.049
1.34-2.51	0.132	1.3	1.307	-2.90	4.209	-2.916	2.011
2.51-5.34	0.001	0.728	0.729	-1.61	2.347	-1.62	1.117
Total	-0.533	0.773	0.24			1.136	-0.783
	χ^2	=0.35	df = 3		P = 0.94		
Remarks: P is greater than 0.05 so null hypothesis is accepted							

Combining these methods with GIS tools enhances the accuracy and usability of susceptibility maps. Based on the area under curve generated from the evaluation outcomes, the FR and WoE approaches have an accuracy percentage of around 72% and 76%, respectively. In order to simulate, compare, and validate landslip susceptibility, this study used the FR and WoE methods (Figure 5 and 6). In contrast, the WoE technique is a traditional and popular approach for landslip susceptibility because it is more precise and succinct. The WoE method allocates a smaller area to low susceptibility (26.58%) compared to the FR method (29.71%), but a larger area to medium susceptibility (35.97% in WoE vs. 29.21% in FR). This suggests WoE tends to classify more areas into medium-risk zones. The FR method classifies a higher percentage of the area as high (34.54%) and very high (6.54%) compared to WoE, which classifies 32.61% as high and only 4.36% as very high.

This indicates that the FR method is slightly more conservative in assigning high-risk zones. Overall, while both methods show a similar general trend, the FR method highlights a larger portion of the area as being at higher risk (high and very high).

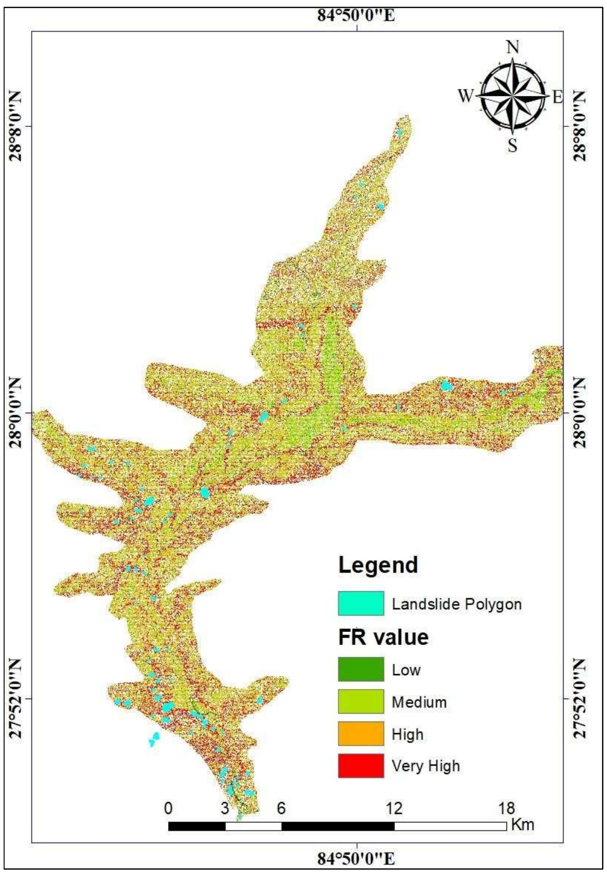

Figure 5: Landslide susceptibility mapping by using Frequency Ratio Method.

Comparison between results of WoE and FR methods:

The WoE method allocates a smaller area to low susceptibility (26.58%) compared to the FR method (29.71%), but a larger area to medium susceptibility (35.97% in WoE vs. 29.21% in FR). This suggests WoE tends to classify more areas into medium-risk zones (Table 2). The FR method classifies a higher percentage of the area as high (34.54%) and very high (6.54%) compared to WoE, which classifies 32.61% as high and only 4.36% as very high.

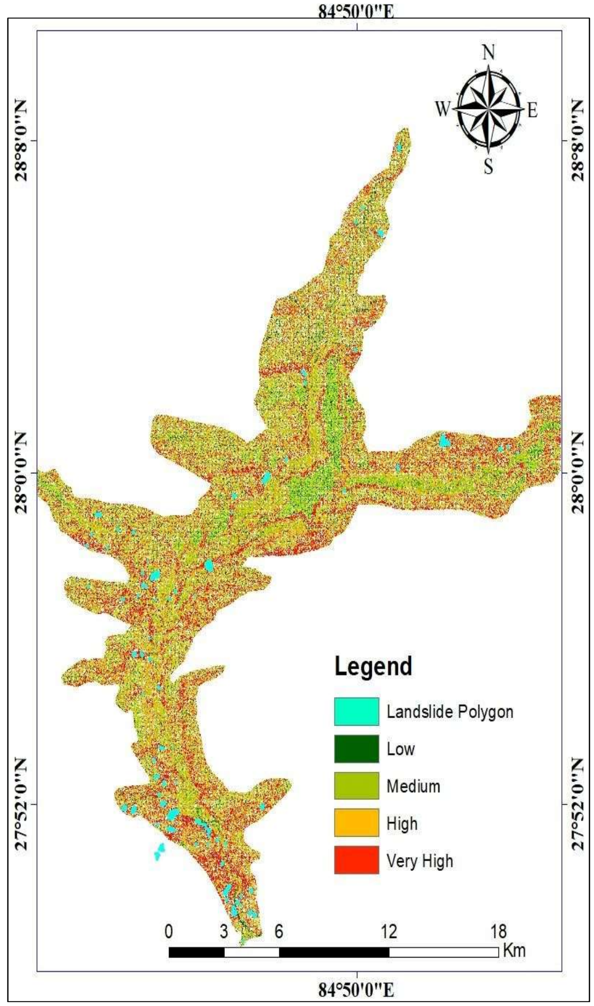

Figure 6: Landslide susceptibility mapping by using Weight of Evidence Method.

The pie chart (Figure 7) illustrates the distribution of landslide susceptibility categories based on the Weight of Evidence (WoE) method, divided into four levels: Low, Medium, High, and Very High. The largest proportion is represented by the medium susceptibility category, which accounts for 35.97% of the total area.

Figure 8 compares the percentage of area coverage in four landslide susceptibility classes (Low, Medium, High, and Very High) using the WoE and FR methods. The FR method assigns a slightly larger area to the Low suscepti-

Table 2: Comparison of landslide susceptibility class with WoE and FR method of landslide study.

Method of study	Susceptible Class			
	Low	Medium	High	Very High
WoE	4.36	35.97	32.61	26.58
FR	6.54	29.21	34.54	29.71

-bility class, indicating more areas with minimal landslide risk. In contrast, the WoE method shows greater coverage in the Medium susceptibility class. For the High and Very High susceptibility classes, the FR method allocates a larger area than the WoE method, particularly in the Very High

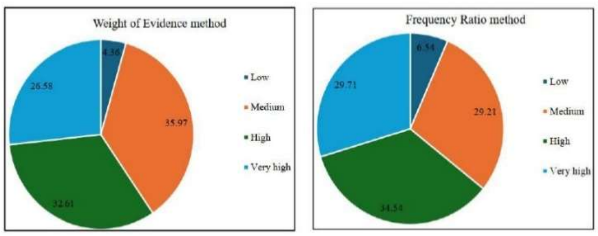

Figure 7: Pie chart showing comparison between total landslide coverage area coverage of each susceptible class using WoE and FR methods.

class, suggesting that the FR model places stronger emphasis on identifying zones with the greatest landslide susceptibility.

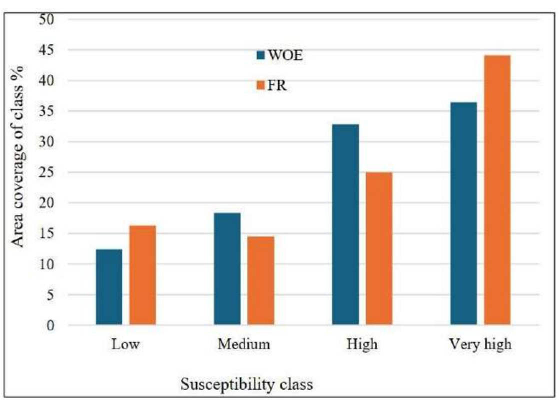

Figure 8: Comparison total area coverage of susceptible classes in susceptibility maps using WoE and FR methods.

Discussion

Slope angle and geological conditions are the main factors controlling land stability in the study area. Landslides are primarily triggered by heavy rainfall, earthquakes, human activities (such as land clearing and road construction), and river undercutting due to tectonic processes. Most landslides occur on slopes steeper than 40° and are associated with weak, fractured, and highly weathered rocks, including slate, phyllite, and schist. The interbedding of weak phyllite and slate with resistant quartzite further increases slope instability and mass movement.

Both FR and WoE methods effectively identify landslide-prone areas, especially when integrated with GIS. The FR method achieved a higher prediction accuracy (72%) than the WoE method (76%). Compared to WoE, the FR model classified larger areas as high (34.54%) and very high (6.54%) susceptibility, whereas WoE assigned more area to the medium susceptibility class, indicating a more moderate risk distribution.

Conclusion

Landslide susceptibility mapping of the proposed Budhi Gandaki Reservoir area identified zones prone to slope instability, which is essential for the safe and sustainable development of the hydropower project. The study area is underlain by metamorphic rocks of the Nawakot Complex, including the Kuncha Formation, Fagfog Quartzite, Dandagaon Phyllite, Nourpul Formation, Purebesi Quartzite, Dhading Dolomite, and Benighat Slate. A weathered zone observed between the Dhading Dolomite and Benighat Slate suggests an erosional unconformity.

Landslide susceptibility was assessed using Frequency Ratio (FR) and Weight of Evidence (WoE) models based on sixteen conditioning factors, including topographic, hydrological, geological, and land-use parameters. Validation using the AUC method showed that the FR model (72%) performed slightly better than the WoE model (76%). Landslides are predominantly associated with steep slopes, highly weathered and fractured phyllite and slate, deep-seated gravitational slope deformation, and shallow failures. Infiltration through loose Quaternary colluvial and alluvial deposits increases pore-water pressure in clay-rich residual soils, further promoting slope failure, particularly along terrace margins, debris-flow deposits, and steep tributary valleys.

Recommendation

The GIS-based landslide susceptibility assessment methods employed in this study can be applied to other areas with similar geological and geomorphological conditions within the Lower Budhi Gandaki catchment. Further work should focus on detailed engineering geological mapping, lithostratigraphic and petrographic investigations, and structural characterization of major formation contacts. In particular, comprehensive geotechnical studies along the Dhading Dolomite–Benighat Slate boundary are necessary to clarify its geological nature and improve understanding of regional stratigraphic and structural controls on slope instability.

The susceptibility analysis identified the Phujel Khola catchment, the Bharmale–Dandagaon sector along Ankhu Khola, and the Budhi Gandaki valley upstream of Arkhet Bazaar as major landslide-prone areas. While slopes within the proposed reservoir area are relatively stable, the upstream reaches of the Budhi Gandaki and Ankhu Khola valleys are highly susceptible to shallow landslides and mass movements. Enhanced engineering geological and geotechnical investigations are particularly recommended in the tectonically disturbed contacts between the Nourpul Formation and Dandagaon Phyllite, and between the Dhading Dolomite and Benighat Slate, where intense shearing and fracturing have significantly reduced rock mass stability.

Data Availability Statement

The Topographic maps used in this study including Malekhu (2784 04C), Gorkha (2784 03B), Jogimara (2784 03D), Salbas Chainpur (2784 04A), and Arughat (2884 16) at a scale of 1:25,000 are available at Survey Department of Nepal. The regional geological map of the study area and Rainfall data are available in the Department of Mines and Geology, Nepal and the Department of Hydrology and Meteorology, Nepal respectively.

A preliminary landslide inventory map was developed using historical landslide information derived from the 1:25,000 scale topographic maps and interpretation of high-resolution imagery from Google Earth Pro. These images are publically available online. In addition, field investigations were conducted to generate the primary datasets utilized in this study. The datasets collected from field inverstigations are available from the co- author upon reasonable request.

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