**FOREST FIRE RISK MAPPING USING GEOGRAPHIC INFORMATION SYSTEM AND ANALYTIC HIERARCHY PROCESS IN RASUWA DISTRICT, NEPAL**

**Datasets Used**

Google Earth Engine (GEE) was used to analyze thematic layers such as NDVI, precipitation, and LST. Other thematic layers, including LULC, slope, aspect, elevation, TWI, distance from the settlement, and road were analyzed using ArcGIS 10.8. Each thematic layer was resampled to a resolution of 30 meters, and they were categorized using Table 6, taking weights for various classes that influence fire danger into account. A linear weighted combination was applied to combine all thematic layers by applying corresponding AHP weights to each to prepare for forest fire risk. 70% of the VIIRS hotspot data was used as a training point to establish the spatial relation between forest fire incidences and different classes of each factor, and the remaining 30% was used to validate the map through the ROC curve analysis. The remote sensing and GIS datasets used in this study are given in Table 1, and the methodological framework of this study is shown in Fig. 13.

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| --- | --- | --- | --- | --- |
| Table 1: Remote Sensing and GIS Datasets | | | | |
| **Factors** | **Sources** | **Data Format** | **Resolution** | **Data Period** |
| Land Cover | [ICIMOD - International Centre for Integrated Mountain Development](https://www.icimod.org/) | Raster | 30 m | 2010 |
| NDVI | [Landsat 8 OLI-TIRS (https://earthexplorer.usgs.gov/)](https://earthexplorer.usgs.gov/) | Raster | 30 m | 2023 |
| Slope | SRTM DEM (https://earthexplorer.usgs.gov/) | Raster | 30 m | 2014 |
| Elevation |
| Aspect |
| TWI |
| Distance from Settlement | UN OCHA (OCHA (unocha.org)) | Vector | 1:25000 | 2015 |
| Distance from Road |
| Precipitation | CHIRPS Pentad: Climate Hazards Group InfraRed Precipitation with Station Data | Raster | 4.8 km | 2004-2023 |
| LST | MODIS MOD11C3 V6.1(LP DAAC - Data (usgs.gov)) | Raster | 5.6 km | 2004-2023 |
| Wind Speed | [Global Wind Atlas (Global Wind Atlas)](https://globalwindatlas.info/en) | Raster | 250 m | 2020 |
| VIIRS hotspot | Fire Information for Resource Management System (NASA | LANCE | FIRMS) | Vector | 375 m | 2014-2023 |

**VIIRS Hotspot**

VIIRS data recorded on the LULC layer (i.e., vegetated area) were selectively considered in this study. To enhance the reliability and robustness of the data, we select data with nominal and high confidence levels. To ascertain no overlap between training and validation data, the data were split into 70% and 30% using subset tools in ArcGIS. 70% of the data were employed as the training point to assess the spatial relationship between fire incidences and different classes of each factor. The remaining 30% was used to validate the forest fire risk map.

**Assignment of weightage to the parameters**

While assessing complex decision problems with numerous criteria, the AHP approach helps decision-makers prioritize their decisions while allowing them to make the most beneficial choices possible (Saaty, 1980). The advantage of the Analytic Hierarchy Process (AHP) over other multi-criteria techniques is its capacity to detect discrepancies while furnishing decision-makers with flexibility and intuitive understandings (Ramanathan, 2001). The assessment of thematic layers' weight is decisive in envisaging the forest fire zone since the output relies profoundly on the assortment of weights. To assign relative priority values to each criterion, the following considerations were employed: an understanding of the causative factors, historic fire prevalences across different causative factors, peculiarities of the study area, and a meticulous literature review. The AHP method's initial stage involved comparing all elements against one another in pairs using Table 2 according to how important they were regarding the probability of forest fires (Table 4).

|  |  |
| --- | --- |
| Table 2: Importance table (Saaty, 1980) | |
| Intensity of importance | Definition |
| 1 | Equivalent importance to the objective |
| 3 | Considerable importance of one over another |
| 5 | Significant importance |
| 7 | Paramount importance |
| 9 | Imperative importance |
| 4,6,8 | Mid-range values |
| Reciprocals | Utilize for inverse comparison |

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table 3: Random Inconsistency values (Saaty, 1980) | | | | | | | | | | | |
| Number of criteria | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Random Inconsistency | 0.00 | 0.00 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.51 |

Divide each element by the sum of its columns to normalize the pairwise comparison matrix. To determine the criterion weights, estimate the row sums of the normalized matrix and divide by the number of factors. To generate the weighted sum matrix, multiply each element of the original matrix by the corresponding weight of the criteria. The weighted sum values of this matrix are obtained by adding the rows. To develop the consistency vector, divide each weighted sum value by the weight of its criterion. The primary eigenvalue (λmax) is estimated by calculating the average of the values of the consistency vector.

The consistency index (CI) was calculated using Eq.1 as follows:

CI = (λmax-n)/(n-1) ………………………… (1) where n is the number of factors used.

The consistency ratio (CR) was calculated using Eq.2 as follows:

CR = CI/RI ………………………… (2) where RI is the random index (Table 3).

The normalized pairwise comparison matrix, weightage of criteria, λmax, CI, and CR are illustrated in Table 5.

**Preparation of forest fire risk map**

Forest fire risk zones were established by applying the weighted linear combination approach, which involved multiplying the weights of various thematic layers by the weights of components and adding up all of the outcomes of all characteristics to generate the FFRI, as shown in Eq. 3.

FFRI = 0.18 \* LULC + 0.08 \* NDVI + 0.11 \* S + 0.04 \* A + 0.15 \* E + 0.03 \* TWI + 0.11 \* DS + 0.07 \* DR + 0.05 \* P + 0.16 \* LST + 0.02 \* WS………………………… (3)

Where FFRI = Forest Fire Risk Index, LULC = Land Use Land Cover, NDVI = Normalized Difference Vegetation Index, S = Slope, A = Aspect, E = Elevation, TWI = Topographic Wetness Index, DS = Distance from Settlement, DR = Distance from Road, P = Precipitation, LST = Land Surface Temperature, and WS = Wind Speed

**Validation of the map**

To determine the prediction efficacy of these selected approaches, validation is imperative in assessing forest fire vulnerability (Jaafari et al., 2017; Jaafari et al., 2019; Pham et al., 2020). The most frequently prevalent method for assessing modeling effectiveness, the ROC-AUC curve, was utilized to evaluate the generated forest fire risk map (Adab et al., 2013b; Ghorbanzadeh & Blaschke, 2018). According to Hosmer & Lemeshow (2000) , the AUC result was remarkable for values above 0.9, admirable for values between 0.8 and 0.9, and satisfactory for values between 0.7 and 0.8. For validation (as discussed in the section on the VIIRS hotspot), 30% of the entire VIIRS hotspot data was used.

Table 4: Pairwise Comparison

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Factors** | **LULC** | **NDVI** | **Sl** | **As** | **El** | **TWI** | **DS** | **DR** | **Ppt** | **LST** | **WS** |
| **LULC** | 1 | 3 | 2 | 3 | 2 | 4 | 2 | 3 | 3 | 2 | 5 |
| **NDVI** | 1/3 | 1 | 1/2 | 3 | 1/3 | 4 | 1/2 | 2 | 2 | 1/3 | 4 |
| **Sl** | 1/2 | 2 | 1 | 3 | 1/3 | 4 | 2 | 2 | 3 | 1/2 | 5 |
| **As** | 1/3 | 1/3 | 1/3 | 1 | 1/4 | 2 | 1/4 | 1/2 | 1/2 | 1/4 | 3 |
| **El** | 0.5 | 3 | 3 | 4 | 1 | 5 | 2 | 2 | 3 | 1/2 | 5 |
| **TWI** | 1/4 | 0.25 | 0.25 | 1/2 | 1/5 | 1 | 1/4 | 1/3 | 1/3 | 1/4 | 2 |
| **DS** | 1/2 | 2 | 1/2 | 4 | 1/2 | 4 | 1 | 3 | 3 | 1/2 | 4 |
| **DR** | 1/3 | 1/2 | 1/2 | 2 | 1/2 | 3 | 1/3 | 1 | 2 | 1/2 | 4 |
| **Ppt** | 1/3 | 1/2 | 1/3 | 2 | 1/3 | 3 | 1/3 | 1/2 | 1 | 1/3 | 4 |
| **LST** | 1/2 | 3 | 2 | 4 | 2 | 4 | 2 | 2 | 3 | 1 | 6 |
| **WS** | 1/5 | 1/4 | 1/5 | 1/3 | 1/5 | 1/2 | 1/4 | 1/4 | 1/4 | 1/6 | 1 |

Table 5: Normalized pairwise comparison matrix and computation of weights

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Factors** | **LULC** | **NDVI** | **Sl** | **As** | **El** | **TWI** | **DS** | **DR** | **Ppt** | **LST** | **WS** | **Criteria Weights** |
| **LULC** | 0.21 | 0.19 | 0.19 | 0.11 | 0.26 | 0.12 | 0.18 | 0.18 | 0.14 | 0.32 | 0.12 | 0.18 |
| **NDVI** | 0.07 | 0.06 | 0.05 | 0.11 | 0.04 | 0.12 | 0.05 | 0.12 | 0.09 | 0.05 | 0.09 | 0.08 |
| **Sl** | 0.10 | 0.13 | 0.09 | 0.11 | 0.04 | 0.12 | 0.18 | 0.12 | 0.14 | 0.08 | 0.12 | 0.11 |
| **As** | 0.07 | 0.02 | 0.03 | 0.04 | 0.03 | 0.06 | 0.02 | 0.03 | 0.02 | 0.04 | 0.07 | 0.04 |
| **El** | 0.10 | 0.19 | 0.28 | 0.15 | 0.13 | 0.14 | 0.18 | 0.12 | 0.14 | 0.08 | 0.12 | 0.15 |
| **TWI** | 0.05 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 | 0.04 | 0.05 | 0.03 |
| **DS** | 0.10 | 0.13 | 0.05 | 0.15 | 0.07 | 0.12 | 0.09 | 0.18 | 0.14 | 0.08 | 0.09 | 0.11 |
| **DR** | 0.07 | 0.03 | 0.05 | 0.07 | 0.07 | 0.09 | 0.03 | 0.06 | 0.09 | 0.08 | 0.09 | 0.07 |
| **Ppt** | 0.07 | 0.03 | 0.03 | 0.07 | 0.04 | 0.09 | 0.03 | 0.03 | 0.05 | 0.05 | 0.09 | 0.05 |
| **LST** | 0.10 | 0.19 | 0.19 | 0.15 | 0.26 | 0.12 | 0.18 | 0.12 | 0.14 | 0.16 | 0.14 | 0.16 |
| **WS** | 0.04 | 0.02 | 0.02 | 0.01 | 0.03 | 0.01 | 0.02 | 0.02 | 0.01 | 0.03 | 0.02 | 0.02 |
| **Lmax = 11.67** | | | | | | | | | | | | |
| **n = 11** | | | | | | | | | | | | |
| **CI = 0.07** | | | | | | | | | | | | |
| **RI = 1.51** | | | | | | | | | | | | |
| **CR = 0.04** | | | | | | | | | | | | |

For both Tables 4 and 5: LULC=Land Use Land Cover, NDVI=Normalized Difference Vegetation Index, Sl=Slope, As=Aspect, El=Elevation, TWI=Topographic Wetness Index, DS=Distance from Settlement, DR=Distance from Road, Ppt=Precipitation, LST=Land Surface Temperature, WS=Windspeed

To avoid repetition and enhance the legitimacy of the discernment, Saaty (1980) suggests a CR value of less than 0.1. The calculated consistency ratio of 0.04 shows the reliability of the generated pairwise comparison matrix (i.e., Table 4) and the validity of the generated FFRI model.

**Methodological Framework**

Wind Speed

Topographic Wetness Index (TWI)

Aspect

**RESULT**

**DATA PROCESSING**

Land Surface Temperature (LST)

Precipitation

Slope

Fig. 13: Methodological framework of the study

Weighted Linear Combination

Forest Fire Risk Index

Testing (ROC, AUC)

Validation

Forest Fire Risk Map

Anthropogenic factors

**INPUT**

VIIRS 375 m

Prioritization and calculation of final weights using AHP method

Pairwise Comparison

Buffering/ Resampling

Database

Topographic factors

Consistency Check

Climatic factors

Distance from Settlement

Biophysical factors

Distance from Road

Elevation

Land Use Land Cover (LULC)

Normalized Difference Vegetation Index (NDVI)

**RESULT**

The computed weights for each factor using the AHP method and the potentiality of forest fire risk in different classes of each factor are presented in Table 6.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Table 6: Weights and ratings assigned to factors and classes for forest fire risk modeling | | | | | |
| **S. No** | **Factors** | **Class** | **Potentiality for FFRM** | **Rating** | **AHP Weight** |
|  |
| 1 | Land use/ land cover | Needle-leaved Closed Forest | Very High | 5 | 0.18 |  |
| Needle-leaved Open Forest | High | 4 |  |
| Broad-leaved Closed Forest | Very High | 5 |  |
| Broad-leaved Open Forest | High | 4 |  |
| Shrubland | Low | 2 |  |
| Grassland | Moderate | 3 |  |
| 2 | NDVI | >0.6 | Very High | 5 | 0.08 |  |
| 0.4-0.6 | High | 4 |  |
| 0.2-0.4 | Moderate | 3 |  |
| 0-0.2 | Low | 2 |  |
| <0 | Very Low | 1 |  |
| 3 | Slope (degree) | >60 | Low | 2 | 0.11 |  |
| 45-60 | Moderate | 3 |  |
| 30-45 | Very High | 5 |  |
| 15-30 | High | 4 |  |
| <15 | Very Low | 1 |  |
| 4 | Aspect | South/South West | Very High | 5 | 0.04 |  |
| South East | High | 4 |  |
| East/West | Moderate | 3 |  |
| North East/North West | Low | 2 |  |
| Flat/North | Very Low | 1 |  |
| 5 | Elevation (m) | <2000 | Very High | 5 | 0.15 |  |
| 2000-3000 | High | 4 |  |
| 3000-4000 | Moderate | 3 |  |
| 4000-5000 | Low | 2 |  |
| >5000 | Very Low | 1 |  |
| 6 | TWI | <4 | Very High | 5 | 0.03 |  |
| 4-6 | High | 4 |  |
| 6-8 | Moderate | 3 |  |
| 8-10 | Low | 2 |  |
| >10 | Very Low | 1 |  |
| 7 | Distance from  Settlement (m) | <1000 | Very High | 5 | 0.11 |  |
| 1000-2000 | High | 4 |  |
| 2000-3000 | Moderate | 3 |  |
| 3000-4000 | Low | 2 |  |
| >4000 | Very Low | 1 |  |
| 8 | Distance from Road (m) | <1000 | Very High | 5 | 0.07 |  |
| 1000-2000 | High | 4 |  |
| 2000-3000 | Moderate | 3 |  |
| 3000-4000 | Low | 2 |  |
| >4000 | Very Low | 1 |  |
| 9 | Precipitation (mm) | <950 | Very low | 1 | 0.05 |  |
| 950-1150 | Low | 2 |  |
| 1150-1350 | Moderate | 3 |  |
| 1350-1550 | High | 4 |  |
| >1550 | Very high | 5 |  |
| 10 | LST (°c) | 20-25.06 | Very High | 5 | 0.16 |  |
| 15-20 | High | 4 |  |
| 10-15 | Moderate | 3 |  |
| 5-10 | Low | 2 |  |
| <5 | Very Low | 1 |  |
| 11 | Wind Speed (m/s) | <2 | Very High | 5 | 0.02 |  |
| 2-4 | High | 4 |  |
| 4-6 | Moderate | 3 |  |
| 6-8 | Low | 2 |  |
| 8-23.13 | Very Low | 1 |  |