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Assessing Train - Elephant Collision Risk and Identifying Optimal Mitigation Areas Using GIS Approach

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Abstract
Train-elephant collisions have become to be a major threat to both wildlife conservation and railway safety in Sri Lanka specially in major railway lines that are located around the elephant habitats. This study aims to map and analyze the risk areas of train-elephant collisions along the Maho-Trincomalee railway line using Geographic Information System techniques. Multiple spatial factors including land use/land cover, elevation, rainfall, proximity to water bodies, proximity to identified elephant habitats and train speed were integrated into the analysis. Analytical Hierarchy Process (AHP) based weighted overlay and fuzzy overlay methods were used to generate elephant prone area maps. These maps were overlaid with the train speed data to produce final collision risk zone maps. The results of both approaches were spatially similar with most high-risk zones found in the locations which are favorable habitat conditions areas that overlap with high train speed. Assessment of accuracy based on historical collision records as well as the ROC analysis showed that the fuzzy overlay method was slightly better than the AHP method in recognizing high risk zones. The results indicate key hotspots areas where mitigation strategies such as speed limit, early warning devices and implementation of safe crossing corridors can be given priority to minimize the occurrence of collisions. This study proves that a multi criteria GIS analysis integrated with habitat and railway data can be used to aid in evidence-based decision making in elephant conservation and railway management in Sri Lanka.

Keywords: Train-Elephant Collision, Weighted Overlay, Fuzzy Overlay, GIS

Introduction

Wild elephants are distributed in 50 countries around the world and among them, 13 are Asian countries and the rest is African countries (Gunawansa *et al*., 2024) [3]. Wild Asia elephant population is differed from 35,000 to 50,000 around the world while 16,000 are in captivity (Nazareth & Nagarathinam, 2007). They are distributed in the countries and islands such as Bangladesh, Bhutan, Borneo, Cambodia, China, India, Indonesia, Malaysia, Myanmar, Nepal, Sri Lanka, Thailand and Vietnam (Perera, *et al*., 2007) [9].

The distribution of the elephants in Sri Lanka is widespread as some of them are in the wet zone while some are living in the dry zone. However, during the colonial period from 1505 to 1948, the wet zone was rapidly humanized while the dry zone is abounded (Fernando *et al*., 2010) [1]. As a result, the elephants have changed their habitats from wet zones to dry zones while many elephants in the wet zones were either killed or captured and exported. With the rapid growth of the human population, dry zones were also converted into human settlements, as a result, elephants lost their habitats in the dry zone also. With the infrastructure developments of the country (specially railway lines to the cities such as Jaffna, Trincomalee, Batticaloa, Talai Mannar and Puttlam), incidents of train-elephant collisions were started to record (Roy & Sukumar, 2017) [11].

Although the elephants in Sri Lanka are listed as an endangered species, they play a vital role for the economy of the country. Around 200 elephants have been killed annually from the human-elephant Conflict and approximately 80 human casualties have been recorded annually (Kopke *et al*., 2021) [5]. Department of Wild Life of Sri Lanka reported, 149 elephants were killed by train-elephant collisions over past 9 years and the year 2023 was recorded as the highest number of deaths per year (Jeyaram, *et al*., 2022) [4].

Traditional methods of elephant behavior and collision mapping are having a greater tendency which are based on field observation, traditional knowledge of local communities and analyzing existing details from journals, research papers and the publications of wildlife related NGO's and departments. Some field observations have been done along the railway track by counting the foot prints of the elephants to map their distribution (Roy & Sukumar, 2017) [11]. GIS based techniques integrated with Fuzzy Logic and Analytical Hierarchy Process (AHP) handle uncertainties related to parameter relationships and weight assignments. Fuzzy logic method, formally developed by Zadeh (1965) [15], in order to handle imprecise data and it was widely applied to represent uncertainties in the environmental mapping. On the other hand, AHP method, formally developed by Saaty (1987) [12] provides a conceptual framework to formalize the opinions of experts in weight assignments.

With the easy accessibility to basic needs such as food, water and shelter compared to rugged highlands, elephants in the dry zone like to the lower elevated flat terrains in between 50m to 500m elevation (Palei *et al*., 2024) [8]. The railway network of Sri Lanka, except the line passing the Central province of the country, has been established in low flat terrains which leads to collisions. The availability of water plays a crucial role in spatial and temporal distribution of the elephants in Sri Lanka. It provides friendly environment to the growth of grass lands and shrubs. Also, elephants are highly depending on water for bathing and drinking, this relationship between the proximity to waterways and elephants become stronger and elephants are more often behaving within a distance of 1.5km around a water resource (Sood & Saaban, 2015) [13]. Therefore, rainfall also plays a critical role as it regulates the growth of grass and shrubs. As elephants have to move from wet zone to dry zone in colonial period, they are well settled up in the area. However, humans entered into the territories of elephants by clearing the forests for chena cultivations. As a result, human-elephant conflict has been started and both parties are engaged in order to protect their own boundaries.

Even though elephants usually exist in the forest and water areas, they come to cultivated areas in searching for food (Ortega & Eggert, 2004) [7]. Therefore, land use and land cover is a more critical factor in studying the behaviors of elephants and their movement patterns (Pittiglio *et al*., 2014) [10]. Further, it can be noticed that the behavioral pattern of elephants can be massively identified within a proximity of 5Km from the main habitats of elephants. In most of the train-elephant collision cases, speed of the train is a considerable factor and it can reduce the reaction time of both elephants and train's operator. Higher speeds, generally, takes a considerably long time to slow down the train and, as a result, it causes collisions, when elephants are cited in front of the train (Gunawansa, *et al*., 2023) [2].

Since the number of collisions and the impact is getting increasing day by day, it needs to introduce an achievable, innovative as well as sustainable solution to protect the elephants in Sri Lanka. Therefore, this study was developed with focusing on utilizing GIS technology to identify collision risk zones and to assess the effectiveness of fuzzy overlay and weighted overlay techniques in train elephant collision risk analysis.

Methodology

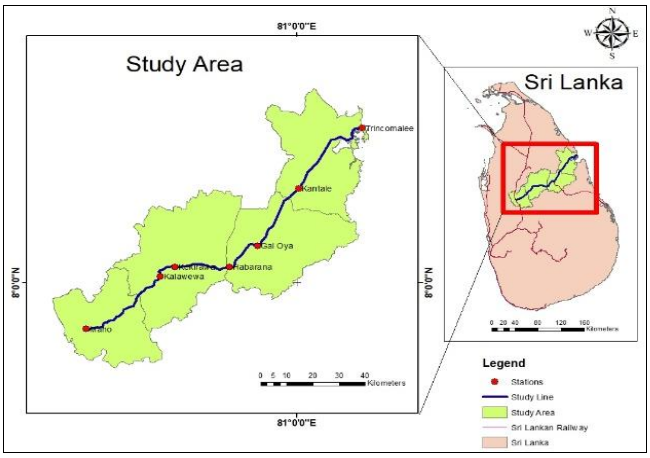


Fig 1: Study Area

The study was conducted along the railway line from Maho (7.8226° N, 80.2824° E) to Trincomalee (8.5711° N, 81.2337° E) covering the distance of 153km in the lower dry zone of Sri Lanka (Fig 1). Kalawewa, Kakirawa, Palugaswewa, Habarana, Galoya, Aluthoya, Agbopura, Kantale and Thambalagamuwa are the main railway stations that have to be passed through out a journey along this railway line. Kalawewa, Palugaswewa, Habarana and Galoya are very renowned areas for elephants in Sri Lanka since water tanks such as Kala, Minneria and Kaudulla are situated in this area.

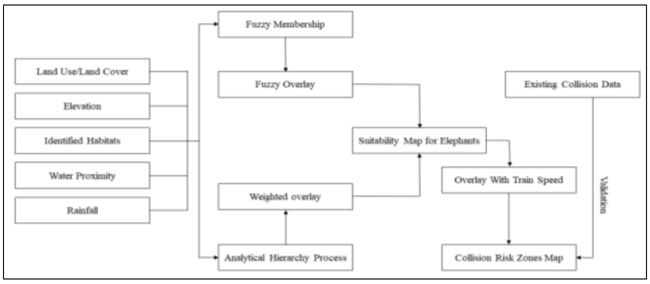


Fig 2: Methodology

Fig 2 shows the conceptual methodology of the study. All raster layers were projected into one projection system, Kandawala Sri Lanka Grid to ensure consistency in all the spatial analyses and they were further processed to a common resolution of 12.5 m to enhance the comparability and accuracy. Open Street Map (OSM) was used to download the railway line over the country and clip it to the study area. Speed limit data which were collected from Railway Department of Sri Lanka was put into excel sheet. Using linear referencing tool in ArcMap software package, Train Speed shape file was prepared. In order to develop the Land Use and Land Cover (LULC) raster, ESRI land cover 2024 dataset was used. The dataset was clipped to the study area and it was reclassified into five categories: forest cover, buildup Area, water bodies, bare lands and vegetation. An elevation raster with a 12.5m spatial resolution was generated using the ALOS PALSAR Digital Elevation Model (DEM). Water proximity raster was derived through Euclidean Distance analysis based on the waterway network data taken from OSM. Rainfall raster was developed using Inverse Distance Weighting (IDW) interpolation method with the help of average monthly rainfall data obtained through Meteorological Department of Sri Lanka. Habitat raster was derived through Euclidean Distance analysis based on the data which collected from the Department of Wild Life Conservation Sri Lanka.

In Analytical Hierarchy Process (AHP), the relative significance of the parameters was determined through the pairwise comparison technique. Each factor was systematically compared with all other factors and the degree of importance was quantified using the standardized scale. It assigns weights to the parameters according to their relative importance. A structured questionnaire was prepared through a Google form in order to get the opinions regarding the importances of the parameter from the experts in the field. Based on these responses, the pairwise comparison matrix and normalized matrix were prepared as Equation 1.

$$n_{ij} = \frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}} \quad (1)$$

Where (nij) is the normalized value, (aij) is the pairwise comparison value and (n) represents the number of parameters (Saaty, 1987) [12].

The comparisons were checked for consistency using Consistency Ratio (CR) (Equation 2).

$$CR = \frac{CI}{RI} \quad (2)$$

Where (CI) is the Consistency Index and (RI) is the Random Index.

The consistency index was calculated as Equation 3 below.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

Where λmax is the maximum eigenvalue of the pairwise comparison matrix. A CR < 0.1 indicates an acceptable consistency (Saaty, 1987) [12].

Fuzzy overlay method was used to map the areas prone for elephants by combining various spatial layers and considering uncertainty. The input variables were transformed into a continuous scale ranging from 0 to 1 using the Fuzzy Membership tool. In this, 0 stands for locations that obviously not a member of the given set and 1 signifies the places are completely within the set. Intermediate values reflect the degrees of membership. The entire range of possibilities between 0 and 1 indicates varying levels of membership with larger numbers representing a higher possibility of membership.

The fuzzy linear function was used where the membership value of parameters was increasing or decreasing linearly with input variables. This function was utilized for the train speed raster. The fuzzy small function was used for parameters where lower values indicating a higher influence such as water proximity and identified elephant habitat raster. The function was defined by a user specified midpoint (which is assigned a membership of 0.5) with a defined spread. The small function was modeled by using the following Equation 4. Fuzzy large function was used for the parameters where higher values indicating a higher contribution such as LULC and rainfall. The function was defined by a user specified midpoint with a spread. The large function is modeled by using the following Equation 5. The fuzzy Gaussian membership function defines the form of a normal distribution with a user defined midpoint where the membership value is equal to maximum level (1). Based on this midpoint value, rest is gradually blend in to zero in a given spread value. This function was used for the parameters with a smooth and gradual change in elephant prone area such as DEM. The gaussian function was modeled by using the following Equation 6.

$$\mu(x) = \frac{1}{1 + (\frac{x}{f_2})^{f_1}} \quad (4)$$

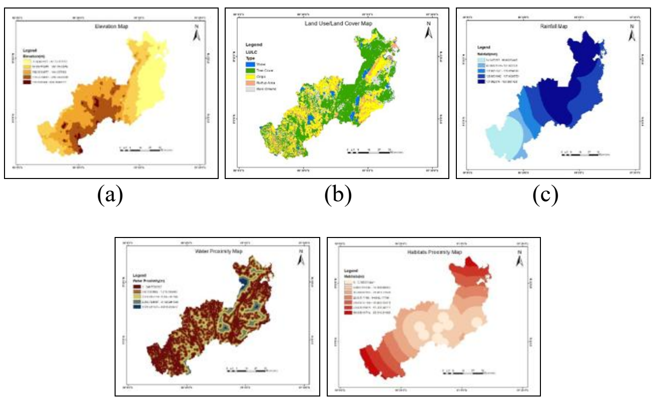
$$\mu(x) = \frac{1}{1 + (\frac{x}{f_2})^{-f_1}} \quad (5)$$

$$\mu(x) = (e)^{-f_1(x-f_2)^2} \quad (6)$$

Where $\mu(x)$ is the fuzzy membership value, x is the input raster value, f_1 is the spread and f_2 is the midpoint.

The fuzzy overlay operation was conducted using the Gamma operator which integrates the fuzzy membership layers into a comprehensive Elephant Prone Area map. The gamma operator combines the results of the fuzzy product and fuzzy sum to account for the interaction between layers. Both the fuzzy overlay and weighted overlay methods were validated using ROC analysis. The AUC values were calculated to evaluate the predictive accuracy of each risk map. Historical collision data were used as reference points for the model validation process.

Results and Discussion



(a) (b) (c) (d) (e)

Fig 3: (a) Elevation Map, (b) LULC Map, (c) Rainfall Map, (d) Water Proximity Map and (e) Habitats Map

The elevation map of the study area, as shown in Figure 3(a), was reclassified into five categories. In the dry zones of Sri Lanka, elephants are more likely to be available in the elevations, ranging from 100m to 400m as these elevations provides ideal conditions for the growth of the grasses. The LULC map of the area, Figure 3(b), displays various land cover types. Tree cover, water and crop lands were considered as the most suitable areas for elephants while bare lands were considered as moderately suitable areas. Buildup areas with dense human settlements were taken as the least suitable area for elephants. The monthly average rainfall in terms of spatial variation is shown in figure 3(c). Areas with higher rainfall are facilitating better conditions to the elephant movement and habitat as the conditions are favorable for the distribution of vegetation and water resources. The spatial difference in distance to the large water sources such as rivers, canals, tanks and streams is explained by the waterway proximity map of the region in Figure 3(d). Region within 1.5km from a waterbody is ideal for elephants and their behaviors. The habitat proximity map of the area, Figure 3(e) displays the spatial distribution of the region based on their distance from identified elephant habitats. Areas located within 5,000 meters which are shown in lighter shades representing zones with higher likelihood of elephant presence.

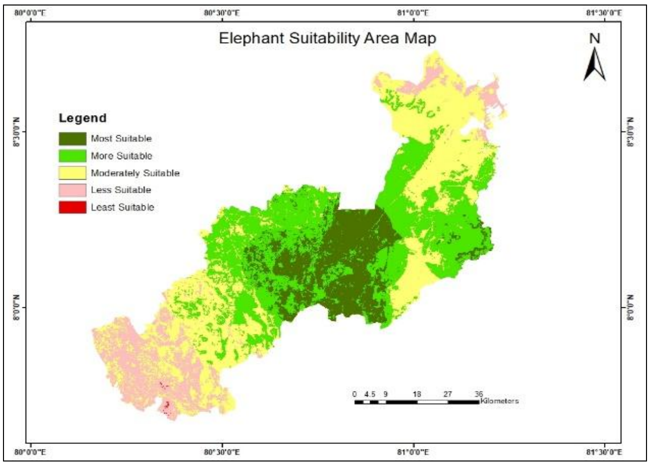


Fig 3: Suitability Area Map (Weighted Overlay)

Fig 4 shows the suitability area map which was developed through the weighted overlay method. This map was divided into five categories such as least suitable, less suitable, moderately suitable, more suitable and most suitable.

Figure 5(a) illustrates the elevation layer that was generated with the use of a fuzzy Gaussian membership function for habitat suitability. The midpoint was set at 200 m which is a good height since it falls within the range of movement of an elephant. Figure 6(a) shows the associated Gaussian membership curve with the most appropriate suitability values at the 200 m mark gradually declining as the elevation shifts away from this optimal range. Figure 5(b) presents the land use/land cover map and it processed using a fuzzy large membership function. Areas like tree cover and water were assigned higher fuzzy membership values indicating more suitability for elephant's presence. The corresponding graph in Figure 6(b) demonstrates the fuzzy large membership function, how membership values varied with the different land cover types. The suitability of the elephants was modeled using fuzzy large membership function in order to incorporate rainfall for the analysis. Figure 5(c) indicated that areas with higher rainfall were found to be more desirable to the activities of the elephant. In Figure 6(c), it shows where the membership curve increases with higher values of rainfall as wet areas will be more suitable than drier ones. Proximity to waterways was modeled in the analysis by the use of fuzzy small membership function. As shown in Figure 5(d), areas which are close to water bodies have the largest values of suitability which highlight the significance of water availability for elephant habitats. The same relation is also illustrated in Figure 6(d) where membership functional curve demonstrates a clear decline in fuzzy values as distance from water bodies increases. Figure 5(e) shows the habitats proximity map, processed using fuzzy small membership function. Areas closer to habitats were assigned higher fuzzy membership values indicating a more suitability for elephants while the distance is increasing from the habitats, the likelihood reducing. The same relation is also illustrated in Figure 6(e) where membership functional curve demonstrates a clear decline in fuzzy values as distance from identified habitats increases.

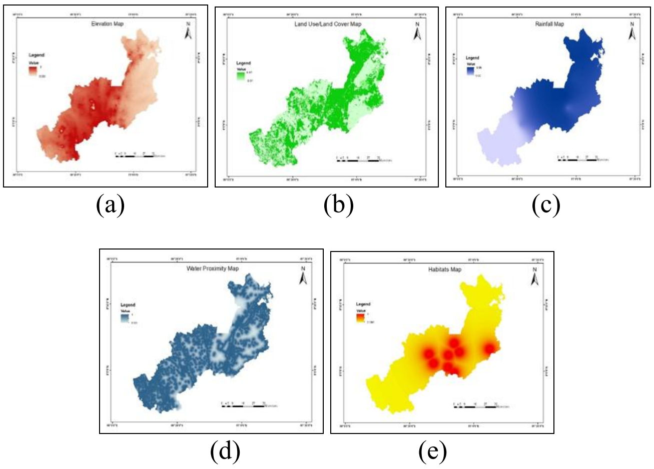


Fig 4: Fuzzyfied (a) Elevation Map, (b) LULC Map, (c) Rainfall Map, (d) Water Proximity Map and (e) Habitats Map

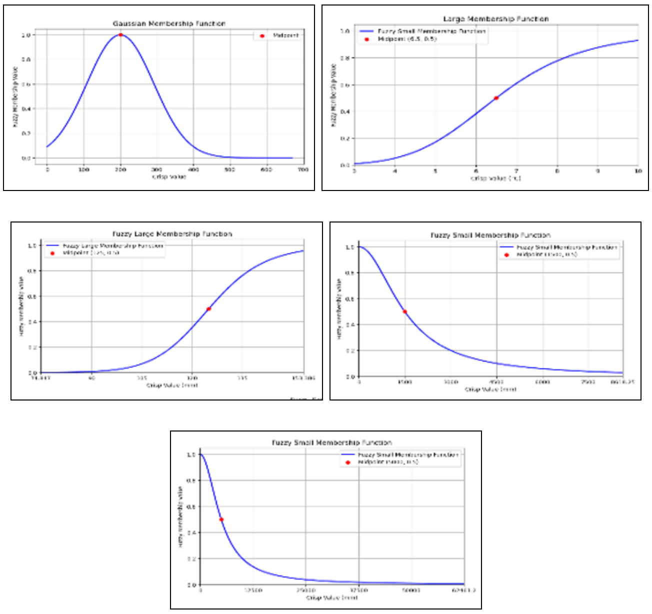


Fig 5: Fuzzified (a) Elevation Map, (b) LULC Map, (c) Rainfall Map, (d) Water Proximity Map and (e) Habitats Map

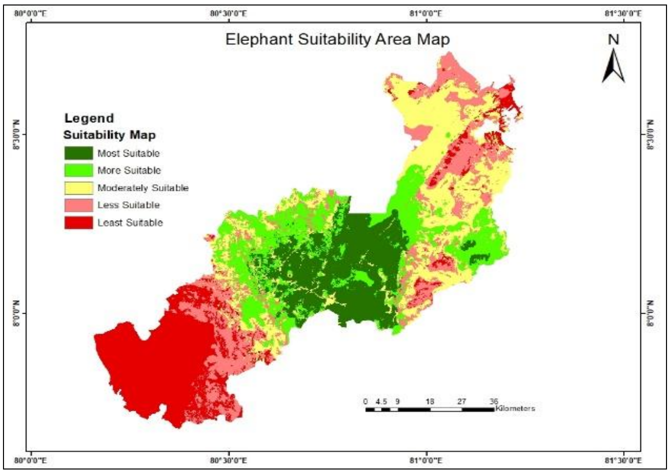


Fig 6: Suitability Area Map (Fuzzy Overlay)

This map was divided the region into five distinct risk categories such as least suitable, less suitable, moderately suitable, more suitable and most suitable (Fig 7).

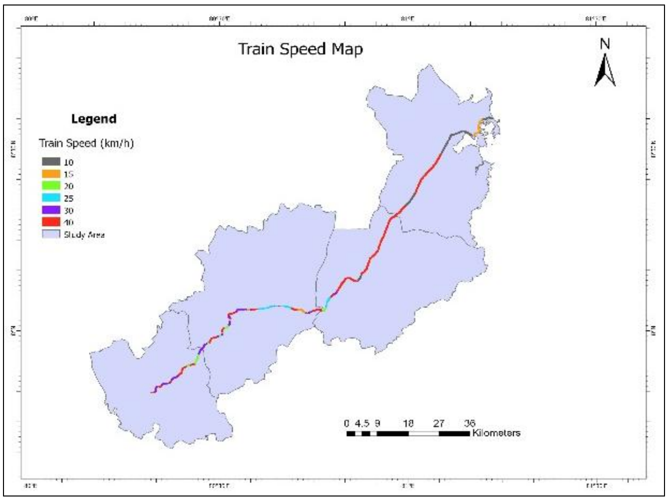


Fig 7: Train Speed Map from Maho to Trincomalee

The train speed map of the study area, Fig 8, illustrates the variation of operating speeds along the railway line. The higher speed operating sections are associated with an increased risk of elephant train collisions as it reduces the reaction time available for both train operators and elephants. Train speed is a critical factor in order to identifying potential high-risk zones for elephant train collisions.

The elephant prone area maps which prepared using both the AHP and fuzzy overlay methods were integrated with the train speed factor in the last phase of the analysis to determine areas of potential collision risks. This was achieved by performing a raster overlay between the respective elephant distribution suitability layers and the train speed map. The resulting collision risk zone maps were produced separately for both the AHP (Fig 9) and fuzzy methods (Fig 10).

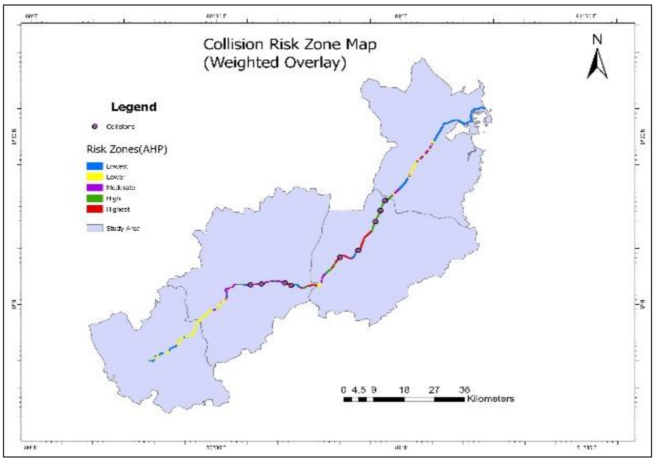


Fig 8: Collision Risk Zone Map (Weighted Overlay)

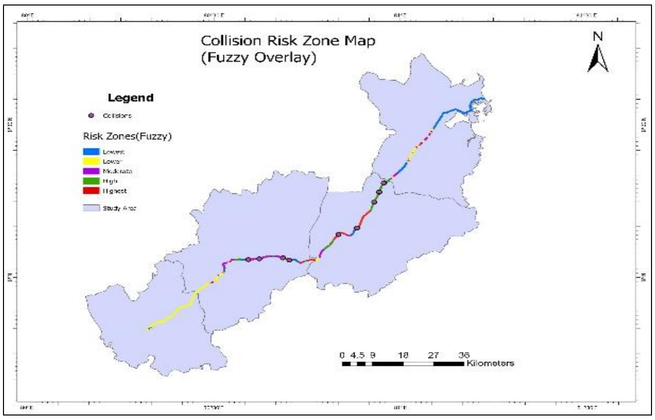


Fig 9: Collision Risk Zone Map (Fuzzy overlay)

Both outputs consistently showed highest and very higher risk areas along the same sections of the railway. Therefore, strong agreement between these two methods of analysis can be observe.

Table 1 presents the distribution of the recorded locations of elephant-train collisions in various risk classes. In the fuzzy overlay approach, 11 incidents were studied and 3 of them were in moderate risk, 5 of them in higher risk and 3 in highest risk zones. The higher and the highest risk zones collectively constituted 8 incidences, which were 72.7% of the total occurrences of collisions. The pattern of weighted overlay done using AHP had a small variation. There was no change in the number of incidents in the highest risk zone but the moderate risk area had 2 incidents and the higher risk area increased for 6 incidents.

Table 1: Distribution of existing collision data

Risk Class	Number of Incidents	
	Fuzzy Overlay	Weighted Overlay
Lowest	0	0
Lower	0	0
Moderate	3	2
Higher	5	6
Highest	3	2

ROC analysis was conducted to evaluate the effectiveness of the two approaches to identify the difference between collision prone and non-prone areas (Fig 11). Both ROC curves were generated using a Python code.

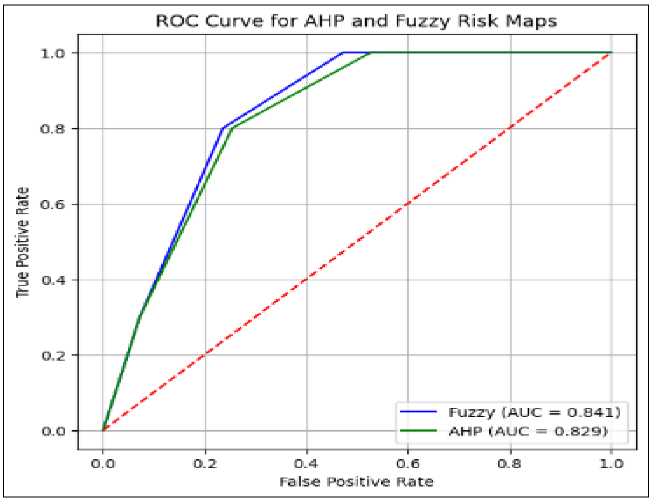


Fig 10: ROC Curves for AHP and Fuzzy Methods

The fuzzy overlay method achieved a higher AUC value of 0.841 which implies the ability to correctly identify elephant collision prone zones while the AHP method recorded a slightly lower AUC value of 0.829 which is weaker compared to fuzzy model.

Conclusion

This study focused on mapping and analyzing elephant train collision risks along the Maho to Trincomalee railway line in Sri Lanka using GIS based techniques. By applying both weighted overlay (AHP) and fuzzy overlay methods, the research identified elephant prone areas and they are integrated with train speed data to generate final collision risk maps. The results indicate that regions characterized by low elevations, closer proximity to water sources and habitats, favorable land cover types and areas intersecting with high-speed railway segments are more vulnerable to elephant train collisions. A comparison between the two methods showed that both produced more similar results. But the fuzzy overlay method offering slightly smoother risk transitions. These findings highlight the effectiveness of combining environmental and infrastructural parameters within GIS based environment to identify high risk collision zones to providing valuable insights for targeted mitigation strategies and improved wildlife management.

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