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Seismicity analysis of the Eastern Hindu Kush Region using geospatial techniques

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Abstract

This study presents a geo-statistical approach to analyze the seismicity of the Eastern Hindu Kush region using earthquake records from the past 200 years obtained from the USGS open-source geo-database. The study also utilized SRTM, Digital elevation model to visualize the spatial range, magnitude, and depth of earthquakes in the region. The IDW and Weighted Overlay Analysis approaches were employed to interpolate seismic data in a GIS environment. For seismic assessment in the Eastern Hindu Kush region, a Seismic Hazard Zonation Map (SHZM) based on fault density, seismic depth, and magnitude was developed. The map highlights that the north-eastern side of region is located in a zone with a high level of seismic activity. Western Chitral, the western part of Upper Dir, and Lower Dir fall under a moderate seismicity zone, while Swat, south-eastern Chitral, and the northern section of Upper Dir lie in a zone with strong seismic activity. The study findings revealed that the Hindu Kush Region is vulnerable to moderate and high-magnitude earthquakes, posing a risk to the region's residents, particularly given their socioeconomic status and the highly susceptible nature of their houses. As a result, the findings of this study can give significant insights to disaster management authorities in decision-making and policy planning to improve community resilience and minimize the potential negative effects of future earthquakes.

1. Introduction

Globally, over the past few decades, catastrophic events have caused significant damage to various communities (Bommer 2022). Among these, earthquakes are one of the devastating geological hazards causing human deaths, physical damage, and social disruption (Khurram et al. 2021). Rima, Tibet, experienced an earthquake on August 15, 1950, which resulted in the deaths of over 3000 people and the displacement of about 5,000,000 people (Siddiqui 2022). An earthquake that struck on May 31, 1970, off the coast of Peru claimed the lives of almost 70,000 people (Jiménez et al. 2023). Off the coast of central Chile, there was an earthquake that killed 525 people and caused multiple structures to collapse in 2010 (Bouih et al. 2022).

The Himalayan, Hindukush, and Karakoram Mountain ranges are among the world's most seismically active areas, due to the convergence of the Eurasian and Indian plates (Joshi and Thakur 2016). The rugged Hindu Kush region, in particular, is a tectonically complex area and likely the world's most active zone for intermediate-depth earthquakes (Mitrofan et al. 2022). The presence of several reverse and oblique strike-slip faults in the Hindukush region is responsible for the frequent intermediate to severe earthquakes. Moreover, due to lithospheric subduction within the sharply falling Hindukush region, several mantle earthquakes impact the northeast-trending plane zone beneath the area, with an average of more than five earthquakes of 5 Mw per year occurring. This zone is approximately 700 km long and stretches to around 300 km depth. Understanding the seismicity of regions like the Hindukush is critical for predicting and mitigating the impact of earthquakes and other natural disasters (Khalid et al. 2021).

This study is an attempt to model earthquake susceptibility. Geostatistical modeling adds a scientific and data-driven dimension to earthquake risk assessment. This can improve the efficiency of mitigation strategies by more precisely focusing on high-risk zones of the Eastern Hindu Kush region (Du et al. 2023). This research is an important contribution to the field of seismic hazard mitigation because it will help to update policies and encourage inter-disciplinary collaboration. The mapping provides important information for land-

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use planning, infrastructure development, and emergency preparedness.

Pakistan is situated in a seismically active and earthquake-prone region of the world, where the Arabian, Indian, and Eurasian tectonic plates interact at different rates, resulting in a complex seismo-tectonic environment (Khurram et al. 2021). The Hindu Kush region, in particular, is notorious for large earthquakes that can cause fatalities and infrastructure damage. On October 26, 2015, the Hindu Kush earthquake occurred, causing significant damage in northern areas of Pakistan and Afghanistan (Yariyan et al. 2020; Lantada et al. 2018; Aslam et al. 2018). The earthquake, which had a magnitude of 7.5, was caused by reverse faulting that occurred at a depth of 210 kilometers beneath the Hindu Kush region of Afghanistan. The earthquake struck 45 kilometers southwest of Jarm village in Afghanistan's Badakhshan Province and 150 kilometers northwest of Pakistan's Chitral region (Aslam and Naseer 2020). Mountain ranges are created by massive geological pressures, while deformations within restricted borders or active fault zones commonly cause earthquakes (Rehman and Burton 2020; Chen and Shearer 2016).

Given the high seismicity of the Hindu Kush region and its potential for devastating earthquakes, research in this area is critical for understanding the seismo-tectonic environment and seismic risk (Aslam et al. 2021). There is a need for comprehensive studies to identify the active faults, their characteristics, and the magnitude and frequency of earthquakes in the region (Hildebrandt et al. 2021). This research can help develop earthquake hazard maps, assess the potential impacts of earthquakes on the built environment and infrastructure, and develop effective strategies for disaster risk reduction and mitigation. Furthermore, research can help improve the understanding of earthquake ground motion characteristics and the response of structures to seismic loads in the region. This knowledge can inform the development of building codes and guidelines to improve the earthquake resistance of structures and reduce the potential for damage and loss of life in the event of an earthquake.

2. Method

The present study utilized geospatial approaches to analyze seismicity events primarily based on secondary data obtained from various sources. Spatial interpolation was applied to geo-visualize the spatial pattern of earthquake magnitude and depth. All spatial input layers were combined using weighted overlay analysis in GIS environment. The study employed earthquake data with magnitude 4 and above for the last 200 years from the United States Geological Survey (USGS) earthquake catalog. The data include location (latitude and longitude), depth, and magnitude. The Shuttle Radar Topographic Mission (SRTM), Digital Elevation Model (DEM) with a spatial resolution of 30 meters was also obtained from the USGS open-source geo-database. The geological map including geological formations and geological structures of the study region was acquired from the Geological Survey of Pakistan (GSP). Political map of Pakistan containing international and district boundaries was acquired from the Survey of Pakistan (SoP). The acquired data were processed and then Geo-database was created to store it. The earthquake location was geo-visualized in the form of point data in GIS environment. The earthquake depth and magnitude were linked to the location data in Geo-database. Then geological and political maps were digitized and .shp files of geological formations, geological structures particularly fault lines and pollical boundaries were created.

The spatial pattern of earthquake depth and magnitude was revisualized by utilizing Inverse Distance Weighted (IDW) technique of spatial interpolation. IDW technique was used for the set of points to identify the amount of surface variation required for analysis (Watson and Philip 1985). The study employed Weighted Overlay Analysis to create thematic maps for visualizing seismicity geographically. For Weighted Overlay Analysis, an important step was to reclassify layers of variables like seismic magnitude, seismic depth, and fault density. Depending on each input layer's relative significance to the analysis, each layer was assigned a weight. The Delphi technique was used to assign weights to the classes of each input layer. The study analyzed the geospatial patterns of earthquake hazards and identified areas of high and low seismic activity.

2.1. Study Area

The Hindu Kush extends southwestward from the Pamir Knot to Afghanistan and serves as a natural barrier separating South and Central Asia (Khan et al. 2021). Tirich Mir is the highest peak in the Hindu Kush Mountains with an elevation of 7,708 meters above mean sea level. In Pakistan, the districts of Chitral, Swat, Upper, and Lower Dir cover the Eastern Hindu Kush. The 700 km-long Hindu Kush Mountain range is located in northeast and central Afghanistan and northwest of Pakistan (Rusk et al. 2022). The Hindu Kush system has a median north-south dimension of around 240 km and a cross-sectional area of about 966 km (Joya et al. 2021).

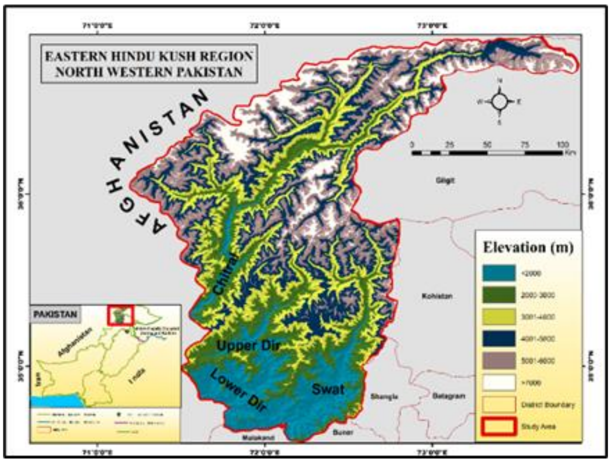

Figure 1. Location map of study area

The Eastern, middle, and Western are the three sections of the Hindu Kush (You et al. 2017). Administratively, the eastern Hindu Kush covers districts of Chitral, Dir Upper, Dir Lower, and Swat (Figure 1). Geographically, it extends from 34º34'11" to 36º54'30"N latitude and 71º11'56" to 73º52'5"E longitude (Mahmood and Atiq 2022). In this area, the Indian plate gradually rotates counterclockwise to encroach into the Eurasian plate. The region is seismically active. The focal depth of earthquakes ranges from 50 to 300 km (Mitrofan et al. 2022).

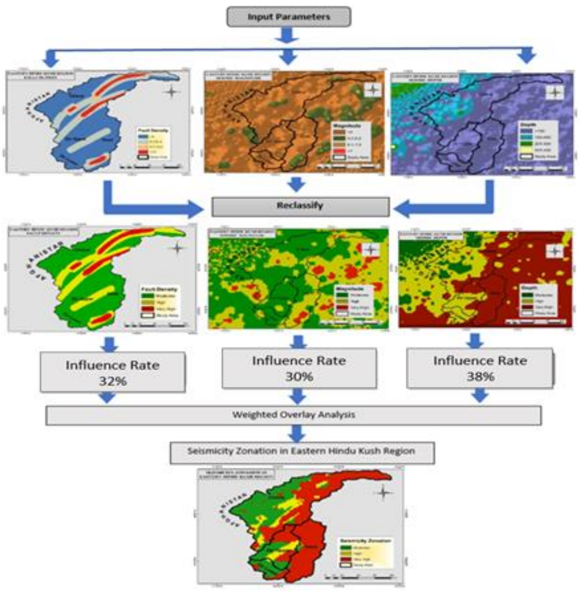

Figure 2. Seismic Magnitude in Eastern Hindu Kush

3. Results

3.1. Seismicity in Eastern Hindu Kush during 200 years span

The Hindu Kush region is characterized by a high degree of seismic activity, as demonstrated in Figure 3, which displays earthquakes with magnitudes of 4 and above over the past 200 years in the Eastern Hindu Kush.

3.2. Causes of Earthquake in Eastern Hindu Kush

Pakistan, located in South Asia, is situated in a highly seismically active region and holds significant importance within the Indian-Eurasian collision zone. The convergence of the Indian and Eurasian plates in the western Himalayas and the subduction of the Arabian plate beneath the Eurasian plate near Makran are two key factors responsible for the elevated seismicity of the region (Rehman et al. 2016). The country's seismic environment has a notable impact on the seismicity of Asia.

3.3. Seismic Magnitude

The area has been divided into different groups according to the seismic magnitude. The values of seismic magnitude vary from region to region. The brown color in the map shows the area where there is low seismic magnitude whereas the light brown color shows the areas with higher seismic magnitude. According to a study, earthquakes of magnitude 5.0 and above are frequent in the Hindu Kush region.

3.4. Seismicity Zonation

The approach of seismicity zoning of the Eastern Hindu Kush region has been depicted in Figure 9. The region is delineated into three zones based on fault density, seismic depth, and magnitude. The resulting seismic hazard map highlights that the north-eastern side of the region is located in a zone with a high level of seismic activity. On the other hand, the western Chitral, the western part of Upper Dir, and Lower Dir fall under a moderate seismicity zone, while Swat, south-eastern Chitral, and the northern section of Upper Dir lie in a zone with strong seismic activity (Figure 9). This area is highly vulnerable to earthquakes due to weak building codes and the susceptibility of existing structures. As a result, the region is at a high risk of being severely impacted by seismic events.

4. Discussion

The analysis revealed that the earthquakes in the Eastern Hindu Kush are caused by the collision of Indian and Eurasian tectonic plates (CUI et al. 2019). The findings indicate that the northeastern side of this region has quite active seismic activity. Swat, south-eastern Chitral, and the northern part of Upper Dir have strong seismic activity, compared to western Chitral, the western half of Upper Dir, and Lower Dir, which have moderate seismicity. The region's seismic hazard is undeniable, as shown by historical occurrences like the 2005 Kashmir Earthquake, which had an epicenter nearby the earthquake that occurred on October 26 and produced multiple aftershocks, and a much more recent earthquake of 5.2 magnitudes that occurred on November 22 (Basharat et al. 2021).

The analysis also revealed the cascading nature of disasters in the Hindu Kush region. It is essential to recognize that earthquakes can trigger secondary and tertiary hazards, such as landslides, landslide dams, and glacial lake outburst floods. As observed by Shafique (2020), landslides that were both widespread and disastrous were caused by the 2005 earthquake.

The study emphasizes that disaster resilience in the mountainous area requires making decisions based on the best Disaster Risk Reduction (DRR) and climate change adaptation studies available. A comprehensive framework is necessary for evaluating hazards' risks and recommending actions to make communities in the Eastern Hindu Kush region more resilient.

5. Conclusion

In conclusion, the study sheds light on the high seismicity and potential dangers posed by earthquakes in the Eastern Hindu Kush region. With the region being prone to secondary and tertiary hazards triggered by earthquakes, such as landslides and glacial lake outburst floods, it is crucial to adopt a multi-hazard approach to disaster risk reduction. By prioritizing initiatives that increase the population's resilience to catastrophic disasters, constructing earthquake-resilient buildings, avoiding construction on slopes, and addressing vulnerabilities found in socio-economic and political situations and processes, policymakers can significantly reduce disaster risk and protect the region's population.

Overall, the study highlights the importance of understanding the nature of disasters and adopting appropriate measures to ensure the safety and well-being of communities in the Eastern Hindu Kush region.

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