Remote Sensing Insights into Neotectonics and Climate-Driven Hazards in the Hindu Kush-Himalayan Region

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The Hindu Kush–Himalayan (HKH) region is a highly active tectonic belt where continuous uplift and erosion strongly influence river systems. This study investigates the neo-tectonic control and climate-driven hydrological response of the Luthkhow River basin in the Chitral Valley, northern Pakistan, using remote sensing and GIS-based morphometric analysis. Digital Elevation Models and satellite imagery were used to extract drainage networks, watershed boundaries, and lineaments, and key parameters, including stream density, drainage density, flow direction, and basin segmentation, were analyzed. The basin was divided into seven reaches to assess spatial variability, and a total of 2,663 stream segments were identified, with high drainage density concentrated near glacier-fed tributaries, indicating a strong influence of snow and glacier melt. Rose diagram analysis reveals a dominant north–south river flow, while drainage and lineament orientations mainly follow NE–SW to E–W trends. The close correspondence between drainage patterns and lineament directions demonstrates strong structural control and active neotectonic deformation. The results confirm that basin evolution is primarily tectonically governed, with cryosphere forcing enhancing erosion and geomorphic response. This study highlights the effectiveness of remote sensing-based morphometric analysis for understanding neotectonic processes in high-mountain environments of the HKH region.

Keywords: Watershed, Tectonics, Lineaments, Drainage Density, Stream Density, Rose Plots

Introduction:

Tectonic geomorphology examines how surface processes and tectonic forces interact to shape landscapes in areas of active deformation. In these regions, crustal uplift, fault movements, erosion, and river incision work in concert over extended timescales, leaving distinct signatures on the terrain. With the development of modern geochronological, geomorphological, and geodetic techniques, these processes can now be quantified using parameters such as drainage geometry, incision patterns, slope characteristics, and structural alignment. Consequently, tectonic geomorphology has become a key discipline for understanding neotectonic activity and assessing natural hazards in tectonically active regions [1][2]. The Hindu Kush-Himalaya (HKH) region represents one of the most tectonically active mountain systems on Earth, formed by the ongoing collision between the Indian and Eurasian plates. This continental collision has generated dramatic topographic relief, accelerated uplift, intricate fault networks, and intense seismic activity, especially in the Hindu Kush and Karakoram ranges. Major fault systems such as the Chaman fault and associated transpressional structures accommodate ongoing crustal deformation and exert strong control on river orientation, valley development, and slope instability [3][4]. Rivers draining this region respond sensitively to tectonic forcing through variations in channel direction, incision rates, drainage density, and basin asymmetry, making drainage networks reliable indicators of active deformation and strain distribution [5][6]. Beyond tectonic forces, climate-driven factors play a major role in shaping hydrological dynamics in the HKH region. Many river systems are fed primarily by snow and glacier melt, leading to pronounced seasonal variations in discharge that intensify erosion, sediment transport, and channel instability. Recent glacier retreat and increased meltwater input, linked to climate variability, have further intensified flood hazards, slope failures, and debris-flow activity in high mountain basins [7][8]. Previous studies indicate that drainage density, stream alignment, and longitudinal river profiles often reflect the combined influence of tectonic structure and climatic forcing, particularly in glaciated mountain environments [9][10]. The Luthkhow River basin, located in the Chitral Valley of northern Pakistan, lies within this highly active tectonic and climatic setting. Draining the glaciated highlands of the Hindu Kush, the basin exhibits intricate drainage networks, steep gradients, and numerous tributaries. Although it is highly prone to floods, erosion, and seismic hazards, detailed tectonic geomorphological studies of the area are still limited. Therefore, this study applies remote sensing and GIS-based morphometric techniques to analyze drainage characteristics, lineament patterns, and their spatial relationships. The main objective is to evaluate the degree of neo-tectonic control on basin evolution and to understand how climate-induced hydrological processes interact with structural features to influence natural hazard potential.

Objectives:

To evaluate the role of neo-tectonic activity in controlling the drainage geometry, lineament patterns, and geomorphic evolution of the Luthkhow River basin in the Hindu Kush-Himalaya region using remote sensing and GIS-based morphometric analysis.

To assess how climate-driven processes, particularly snow and glacier melt, interact with tectonic structures to influence hydrological behaviour and natural hazard potential, including erosion, flooding, and slope instability, within the basin.

Study Area:

Situated in northern Pakistan, the Chitral Valley lies within the Hindu Kush–Himalaya (HKH) region. This narrow mountainous corridor extends approximately 300 km from Kabul toward the plains of Kashmir, with a width of under 120 km. Administratively, Chitral is the largest district of Khyber Pakhtunkhwa Province, covering an area of about 14,800 km² and lying within the Malakand Division [11]. The valley is drained by the Chitral River (also known as the Kunar River), which flows southward and receives major contributions from glacier-and snow-fed tributaries. Chitral Valley lies at the western margin of the Indian-Eurasian collision zone and is characterized by active tectonics, high relief, and complex geology. The valley is surrounded by steep mountain ranges with elevations commonly ranging between 5,000 and 6,000 m, while Tirich Mir, the highest peak of the Hindu Kush, rises to 7,708 m above sea level. This tectonically active setting results in frequent seismic activity, rapid uplift, and strong structural control on valley morphology and river orientation [5][8]. Chitral experiences a predominantly continental climate with pronounced altitudinal variations. Summers are warm in the lower valleys but remain cold at higher elevations, whereas winters are harsh, especially in the upland regions. Most annual precipitation occurs as snowfall at high elevations, leading to extensive snowfields and glaciers that dominate the northern parts of the basin. Snow and glacier melt provide the primary source of river discharge, producing strong seasonal variability with peak flows during summer months and minimum discharge in winter [12].

Focusing on the Luthkhow River basin, this study examines a key tributary of the upper Chitral drainage. The river, originating from glaciated high-altitude catchments in the Hindu Kush, spans about 108 km. The river is nourished by several tributaries—Bashqar Gol, Raman Gol, Rizhun Gol, and Gasht Gol—before merging with the Mastuj River near Buni village, at an elevation of approximately 2,263 m. The combined flow ultimately contributes to the Chitral River system. The basin has an average catchment elevation of approximately 3,925 m and remains snow- and glacier-covered during winter months [13]Click or tap here to enter text.. Hydrologically, the Luthkhow basin exhibits high sediment loads due to intense glacial erosion and steep terrain. Seasonal meltwater generates high suspended sediment concentrations, enhancing channel erosion and downstream deposition. Historical discharge records indicate strong interannual and seasonal variability, with extreme flows linked to snowmelt and summer precipitation events. These characteristics make the basin highly sensitive to floods, erosion, and slope instability, particularly under ongoing climatic warming and active tectonic deformation [8].

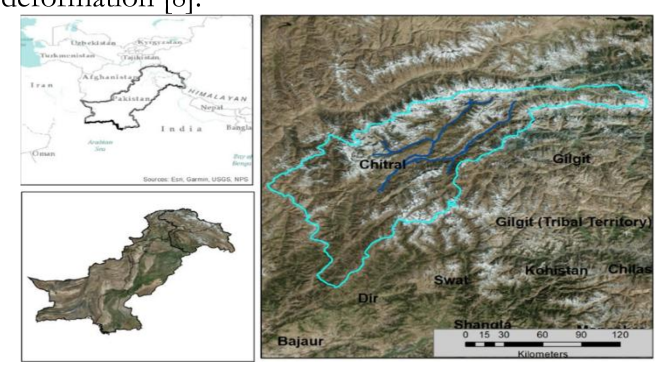


Figure 1. Location map of the Chitral Valley within the Hindu Kush–Himalaya region, northern Pakistan.

Figure 2. Detailed map of the study area showing the Luthkhow River basin, major tributaries, and surrounding topography.

Materials and Methods:

Data Acquisition and Sources:

This study employs remote sensing and elevation data to analyse the geomorphic and tectonic characteristics of the Luthkhow River basin. Two primary datasets were used: (i) multispectral Landsat-8 Operational Land Imager (OLI) imagery with 30 m spatial resolution, and (ii) Digital Elevation Models (DEMs) derived from the Shuttle Radar Topographic Mission (SRTM). These datasets provide synoptic coverage and adequate spatial resolution for drainage extraction, morphometric analysis, and lineament mapping in a high-relief mountain environment.

Data Processing and Analytical Framework:

The methodological framework integrates DEM-based hydrological modelling with satellite image interpretation to identify drainage networks, watershed characteristics, and tectonically controlled lineaments. Linear geomorphic features such as valleys, ridge lines, slope breaks, and lithological boundaries were interpreted as surface expressions of subsurface structural controls.

Landsat-8 OLI imagery was pre-processed through band stacking to generate false colour composite images. The resulting multi-band GeoTIFFs were geometrically corrected and projected to the UTM Zone 43N coordinate system using the WGS-84 datum. Standard image enhancement techniques, including contrast stretching, spatial filtering, and colour composites, were applied to improve the visual interpretation of geomorphic features. Supervised classification was carried out using the Maximum Likelihood Estimator (MLE), with spectral signatures derived from representative training samples to differentiate surface features and land-cover classes [14].

Drainage Network and Watershed Extraction:

Drainage networks and watershed boundaries were derived from the SRTM DEM using the D8 flow-direction algorithm. Initially, sinks and depressions in the DEM were identified and filled to ensure hydrological continuity. Flow direction was then computed based on the steepest descent, followed by flow accumulation to identify channel initiation points. Stream definition thresholds were applied to extract the drainage network, which was subsequently converted from raster to vector format. Catchment areas were delineated to define individual contributing basins, facilitating spatial analyses of drainage density and stream networks. This approach reliably captures surface hydrology and geomorphic responses in tectonically active regions [15].

Lineament Extraction and Structural Analysis:

Lineaments were defined as linear or curvilinear features representing zones of structural weakness, including faults, fractures, and joints. In this study, lineaments were extracted using a combination of automatic and interpretative approaches. Valleys and ridgelines were first derived from the DEM-based drainage network, while additional linear features were identified through enhanced terrain visualization. Edge enhancement and hill-shading techniques were applied to emphasize linear discontinuities in the terrain. Aspect and slope models were used to validate the orientation and continuity of extracted lineaments [16]. Automated lineament extraction was performed in PCI Geomatica using standard parameters optimized for SRTM DEM data, including edge gradient thresholds, curve length, angular difference, and linking distance [17].

Orientation Analysis Using Rose Diagrams:

The directional relationship between drainage networks and lineaments was analyzed using rose diagrams. Circular histograms were constructed to represent the frequency and length distribution of drainage segments and lineaments based on their azimuths. Rose plots provide an effective visual tool to evaluate dominant structural trends and their correspondence with river orientation (Potter and Pettijohn, 1963; Potter and Pettijohn, 1977).

Drainage and lineament rose diagrams were compared to evaluate the tectonic influence on basin development. Shaded relief and classified aspect maps further aided in interpreting the spatial correlation between geomorphic and structural features.

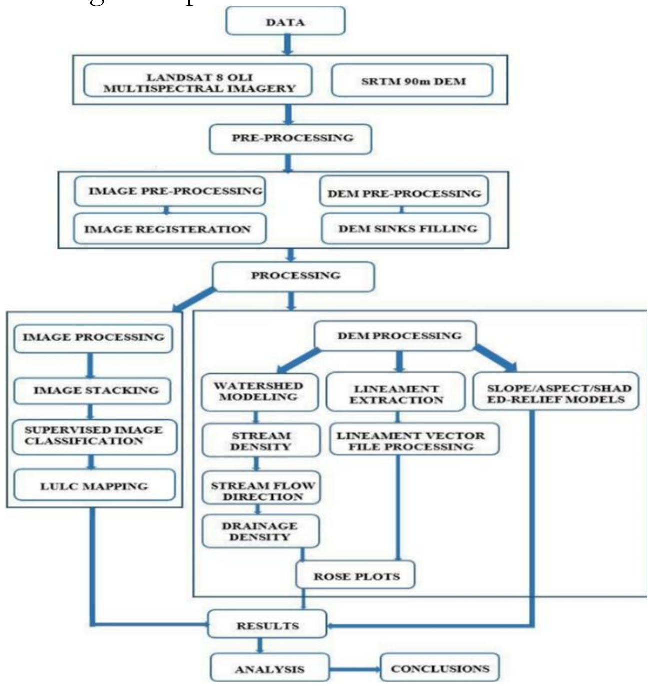


Figure 3. Flowchart illustrating the sequential methodology adopted for drainage extraction, lineament mapping, and morphometric analysis of the Luthkhow River basin.

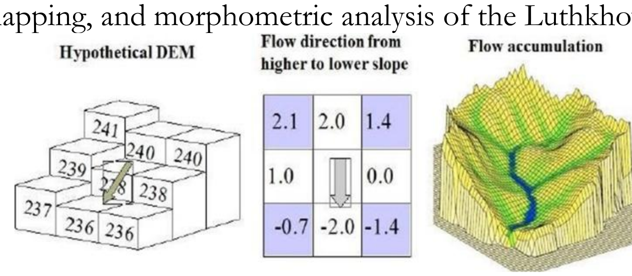


Figure 4. Workflow of DEM-based drainage and watershed modeling using the D8 algorithm.

Table 1. Parameters used for automated lineament extraction in PCI Geomatica.

Name	Description	Values
RADI	Radius of filter in pixels	40
GTHR	Threshold for edge gradient	50
LTHR	Threshold for curve length	30
FTHR	Threshold for line fitting error	3
ATHR	Threshold for angular difference	15
DTHR	Threshold for linking distance	0

Results and Discussion:

Land Cover and Basin Characteristics:

The land use–land cover (LULC) analysis shows that the Luthkhow River basin is dominated by glaciers, snow-covered terrain, barren land, and sparse vegetation, with dense vegetation concentrated along the river corridor and valley floors (**Figure 6**). The river originates in high-altitude glaciated terrain and is continuously fed by ablation of snow and glaciers, confirming a strong cryospheric control on basin hydrology. Vegetation density increases downstream, particularly near the confluence with the Mastuj River at Booni, where favorable moisture availability supports orchards and cultivated land. This spatial pattern highlights the direct influence of glacial meltwater on ecological productivity and sediment transport in the basin.

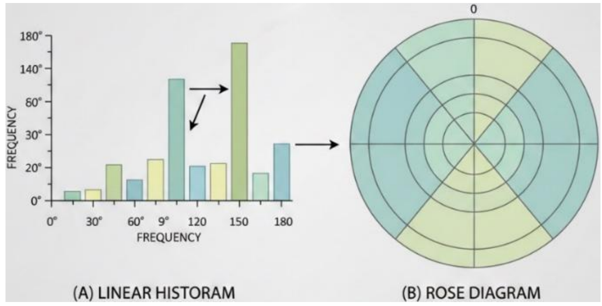


Figure 5. Conceptual representation of linear histogram (A) and corresponding rose diagram (B) used for orientation analysis.

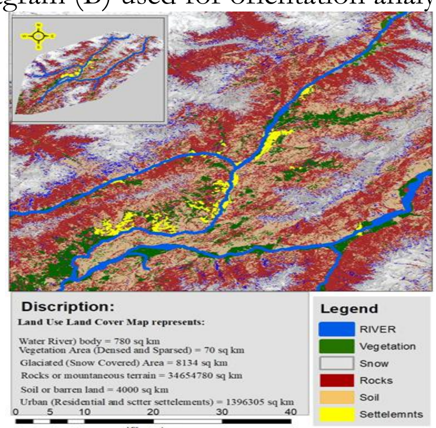


Figure 6. Land use–land cover map of the Luthkhow River basin showing dominant glacial, barren, and vegetated zones

Drainage Network and Morphometric Response:

Digitization of the river course indicates that the Luthkhow River extends for approximately 100 km and was subdivided into seven reaches (approximately 14-15 km each) to capture longitudinal variations in geomorphic behaviour (Figure 7). DEM-based hydrological analysis extracted a total of 2,663 stream segments, indicating a highly dissected terrain and active surface processes. Analyses of stream flow direction and drainage patterns indicate predominantly braided, structurally guided channels, reflecting uniform lithologic resistance and significant tectonic influence. Stream density is greatest near glacier-fed headwaters, highlighting the dominant role of meltwater in channel initiation and runoff generation (Figure 8). Slope analysis further shows that most streams originate on steep slopes, promoting rapid erosion, high sediment yield, and downstream deposition.

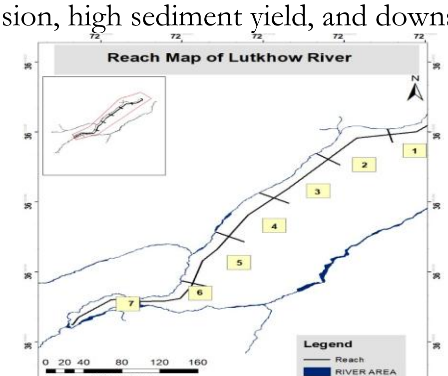


Figure 7. A reach or segmented map. The figure represents the river area with its seven segmented reaches, approximately 14 km long.

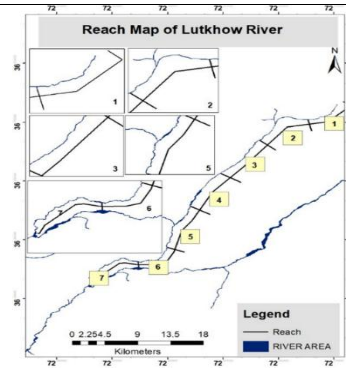


Figure 8. Stream density and slope relationship highlighting glacier-fed headwaters and steep terrain.

Drainage Orientation and Tectonic Control:

Shaded relief and aspect analyses reveal that the overall drainage network follows a dominant north-south river flow, while tributary alignment shows preferred orientations in the NE-SW to E-W directions. The Rose diagram analysis indicates that the drainage system consistently trends toward the western sector, suggesting that its development is structurally controlled rather than driven by random surface runoff (Figure 9). Such systematic orientation is typical of drainage development influenced by tectonic tilting and fracture-guided erosion in active mountain belts.

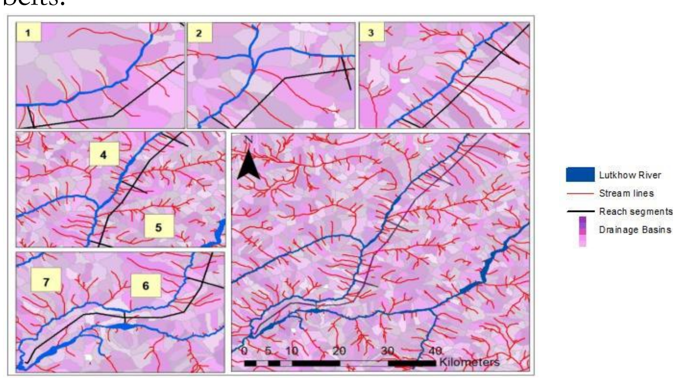


Figure 9. A Watershed map. Drainage basins generated through SRTM 90 DEM along the segmented reach. Red bold lines show the stream network, and purple-colored polygons show the drainage basins or catchments associated with the Luthkhow River.

Lineament Distribution, Drainage Coupling, and Neo-tectonic Implications:

Automated lineament extraction from the SRTM DEM reveals a dense network of linear features representing faults, fractures, ridges, and slope breaks. The dominant lineament trends are NW-SE, N-S, and NE-SW, consistent across shaded relief, slope, and aspect models (**Figure 10**). High lineament density is observed along steep slopes and near major tributary junctions, particularly around Booni and adjacent valleys, indicating zones of enhanced structural weakness. Frequency and length rose diagrams show a pronounced NE-SW structural trend, with secondary trends in NNE-SSW and NW-SE directions. These orientations correspond closely with regional tectonic structures of the Hindu Kush and suggest ongoing neo-tectonic deformation rather than lithology-controlled patterns alone. Comparison of drainage density and lineament density reveals a strong spatial correspondence, where areas of high stream density coincide with zones of dense fracturing (Figure 11). This relationship suggests that structural weaknesses promote channel formation and enhance erosion. Comparisons of Rose diagrams further reveal that the primary orientations of drainage channels align closely with those of lineaments, confirming the tectonic influence on basin development. The alignment between drainage networks and fracture systems demonstrates that the Luthkhow River basin is governed by active neo-tectonic processes, with climate-driven glacial melt acting as an amplifying factor. Enhanced runoff along structurally weakened zones accelerates incision, sediment transport, and slope instability, increasing susceptibility to floods and geomorphic hazards.

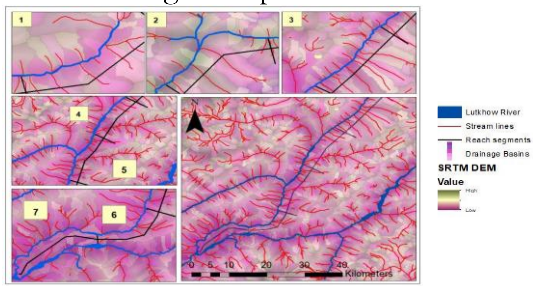


Figure 10. A watershed map. The watershed model is fused with the SRTM 90 DEM. Red bold lines shows stream network, and purple-colored polygons shows drainage basins or catchments associated with the Luthkhow River.

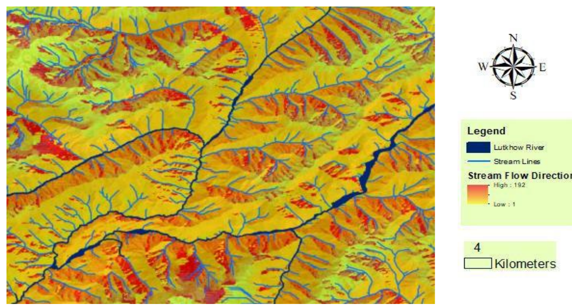


Figure 11. A Stream flow direction map. Yellow colored areas represent the flat terrain or low steepness value; orange color represents the steep elevation, i.e., the origination of streams, and red colors represent the peaks of mountains, the most elevated features.

Stream Density and Drainage Density Patterns:

Stream density represents the concentration of channels per unit area and is a key indicator of runoff generation and erosion intensity. In the Luthkhow basin, stream density is highest near glacier-fed zones, confirming that snow and glacier melt strongly control channel initiation. Drainage density decreases downstream as slopes flatten and meltwater contribution diminishes. The analysis also highlights a highly dense watershed network, characteristic of tectonically uplifted areas with steep gradients and active incision. These patterns indicate enhanced erosional efficiency and sediment transport across the basin.

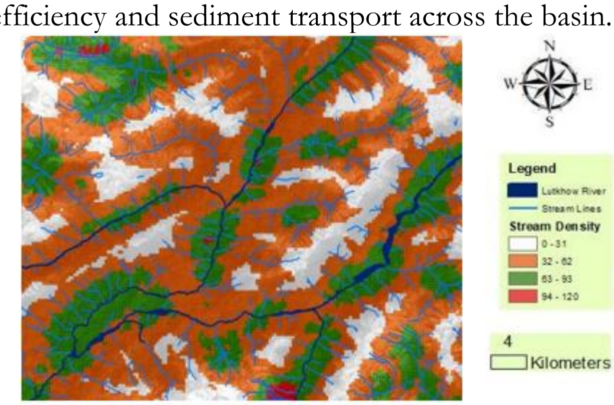


Figure 12. A stream Density Map. Stream Density model generated through the stream network.

Slope and Aspect Controls on Drainage:

Slope analysis was conducted to evaluate terrain steepness and its influence on erosion and channel development. The results show that most streams originate from steep slopes, promoting rapid incision and downstream sediment delivery. Flat terrain is limited to valley floors and floodplain zones. Shaded relief maps generated using different illumination angles (0° and 90° azimuths) enhance visualization of drainage orientation and structural trends. These maps revealed a dominant north-south river flow, with tributaries showing systematic NE-SW and E-W alignments. Aspect analysis indicates a uniform westward tilt of the basin, suggesting tectonic deformation rather than random surface processes.

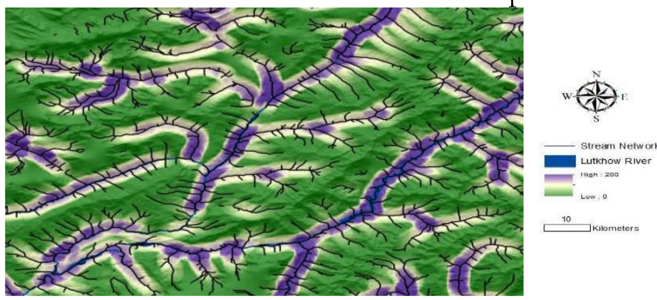


Figure 13. A drainage Density map. Thin black lines represent the stream network, and purple color shows the density of running streams.

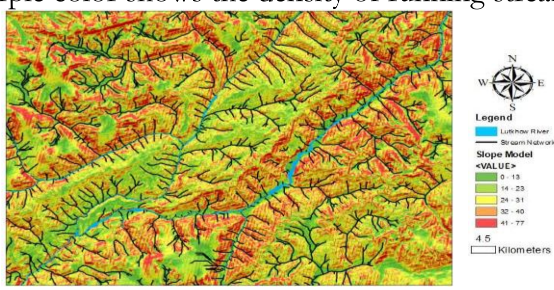
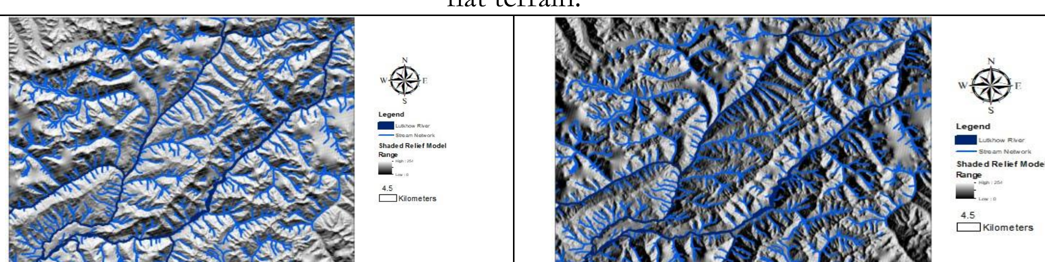


Figure 14. Slope Model. Black bold lines represent the stream network generated from the SRTM 90m DEM. The steeper the slope is shown in red color, and green color shows the flat terrain.



(a) (b)

Figure 15. Gray-scale shaded relief maps derived from SRTM 90 m DEM showing drainage orientation under different illumination conditions: (a) left sun azimuth 0° with a solar elevation of 30°, and (b) right sun azimuth 90° with a solar elevation of 30°. Bold blue lines represent the extracted stream network.

Lineament Distribution and Structural Trends:

Lineament analysis was conducted to identify surface expressions of faults, fractures, ridgelines, and slope breaks. Automated extraction from the SRTM DEM revealed a dense network of linear features throughout the basin. Dominant lineament orientations are NW-SE, N-S, and NE-SW, consistent across shaded relief, slope, and aspect models. High lineament density is observed near steep slopes and major tributary junctions, particularly around Booni and adjacent valleys. These zones represent structurally weakened areas that facilitate erosion and channel incision.

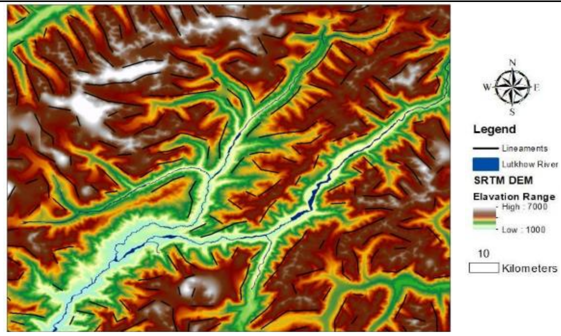


Figure 16. Automatically extracted lineaments through SRTM 90m DEM along the Luthkhow River. Black lines represent the extracted lineaments on the SRTM DEM superimposed on the satellite imagery.

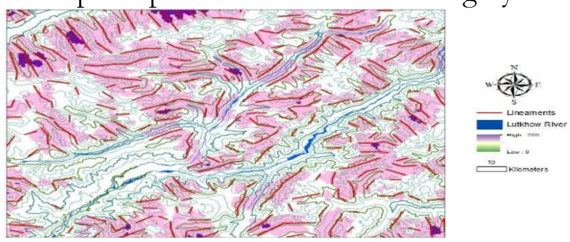
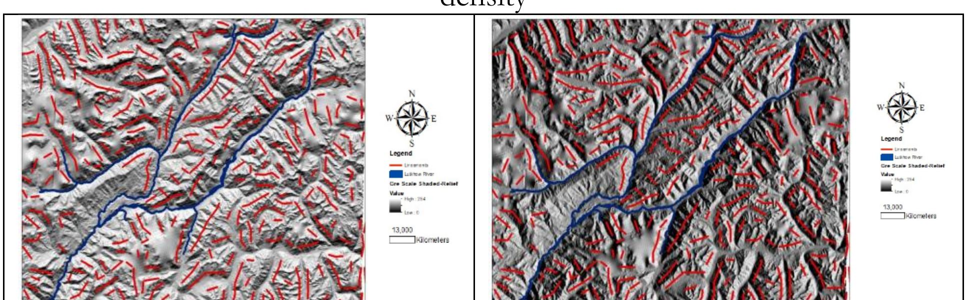


Figure 17. A lineament density map. Red bold lines represent the automatically extracted lineaments. Topographic contours are shown in green color. Purple color shows a higher density



(a) (b)

Figure 18. Gray-scale shaded relief maps derived from SRTM 90 m DEM showing lineament patterns under different illumination conditions: (a) left sun azimuth 0° with a solar elevation of 30°, and (b) right sun azimuth 90° with a solar elevation of 30°. Bold red lines represent the automatically extracted lineaments.

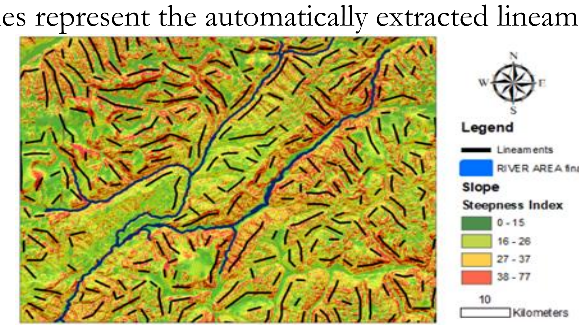


Figure 19. A slope map. Black bold lines show the automatically generated lineaments along the Luthkhow River basin. Red color shows the steepest slope, and green represents the flat terrain.

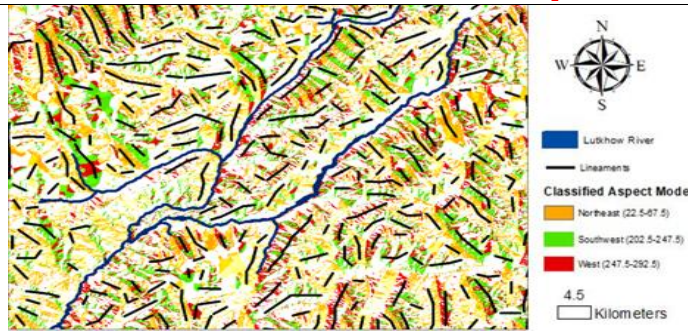


Figure 20. A classified aspect model. Classified aspect model for the angles between 2800 and 3500.

Drainage-Lineament Relationship and Neo-tectonic Implications:

The spatial relationship between drainage networks and lineament patterns underscores the influence of neo-tectonic forces. Analysis of drainage and lineament density maps reveals a clear correspondence, indicating that channels are more likely to develop along zones of structural weakness. Frequency and length rose diagrams of drainage and lineaments show overlapping dominant trends, particularly in the NE-SW and NW-SE directions. This alignment confirms that drainage development is structurally controlled and reflects active neotectonic deformation. Additionally, climate-driven snow and glacier melt enhance this process by increasing runoff and erosive intensity along fracture-guided channels.

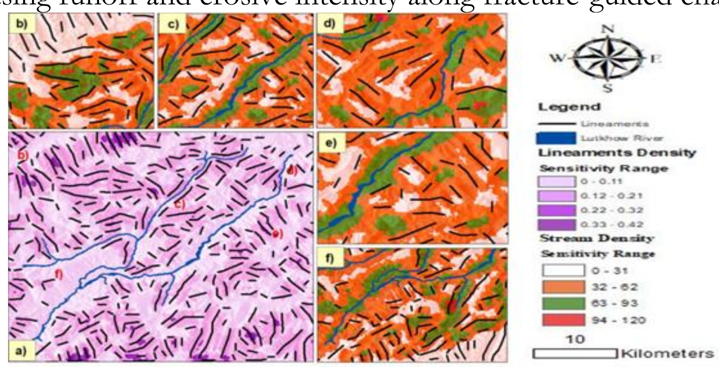


Figure 21. A density comparison map. Black bold lines show the automatically generated lineaments along the Luthkhow River basin. a) shows lineament density where dark areas show higher density. b), c), d), e), and f) show areas of high stream density in relationship with lineament density.

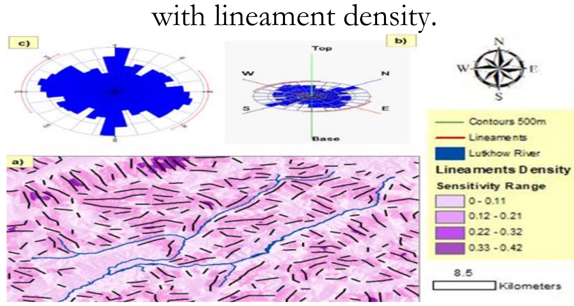


Figure 22. A lineament density map. a) Shows a lineament density map where bold red lines represent the automatically generated faults. Purple color shows the highly dense lineaments in the basins. Topographic contours are also shown in green colors. b) shows frequency distribution rose plots of lineament density, and c) shows the 3D model of the lineament's distribution rose plots of the drainage density

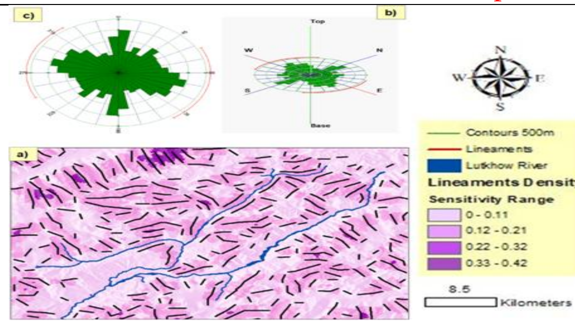


Figure 23. A lineament density map. a) shows a lineament density map where bold red lines represent the automatically generated lineaments. Purple color shows the lineaments of high density in the basins. Topographic contours are also shown in green colors. b) shows length rose plots of lineament density, and c) shows the 3D model of the length rose plots of the lineament density

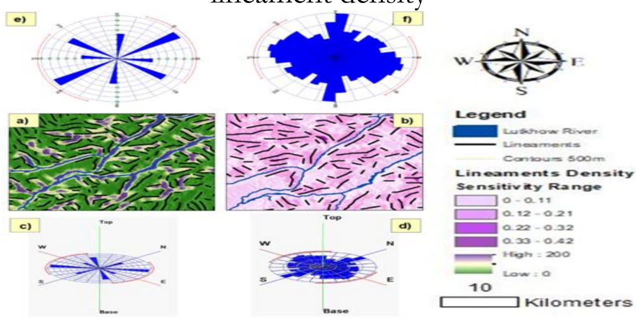


Figure 24. A density comparison map. a) shows lineament density, b) shows drainage density. Topographic contours are also shown. Automatically generated lineaments are shown in bold black lines, c) & d) show 2D model frequency distributed rose plots for drainage density and lineament density respectively, and e) & f) show 3D model of frequency distributed rose plots for drainage density and lineament density respectively

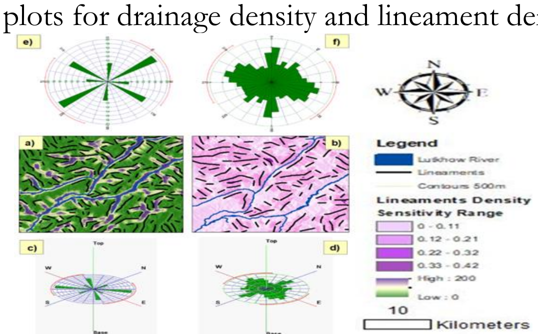


Figure 25. Density comparison map. a) shows lineament density, b) shows drainage density. Topographic contours are also shown. Automatically generated lineaments are shown in bold black lines, c) & d) show 2D model length distributed rose plots for drainage density and lineament density respectively, and e) & f) show 3D model of length distributed rose plots for drainage density and lineament density respectively

Discussion:

Conclusion:

This study demonstrates that DEM-based drainage extraction is an effective and reliable approach for analysing geomorphic deformation and neo-tectonic influence in high-mountain environments. The digitally extracted drainage network of the Luthkhow River basin closely represents the actual valley geometry and spatial organization of streams, providing a robust basis for evaluating terrain deformation, drainage density, and structural control. Compared with conventional linear feature mapping, DEM-derived drainage networks offer a direct link to surface morphology and physical landscape properties.

The analysis identified a dense and well-organized drainage system, with the highest stream and drainage density concentrated in glacier-fed headwaters and structurally weakened zones. A total of 2,663 stream segments were extracted, reflecting strong basin dissection and active surface processes. Drainage density patterns indicate that areas with higher channel concentration are more efficiently supplied by runoff and meltwater, confirming the dominant role of snow and glacier melt in sustaining year-round flow in the Luthkhow River. Directional analysis shows that the main river follows a north–south trend, while tributary orientations and drainage density rose plots reveal systematic alignment consistent with regional structural trends. Similar directional patterns observed in lineament analysis confirm that drainage development is strongly controlled by tectonic structures rather than random surface processes. The close spatial correspondence between high drainage density and high lineament density zones indicates that streams preferentially exploit fracture and fault-controlled pathways, reflecting ongoing neotectonic deformation in the basin. Continuous glacial and rainfall-fed discharge enhances erosional efficiency, particularly in areas of steep slopes and dense fracture networks. These conditions increase susceptibility to erosion, sediment transport, and seismic-related geomorphic responses. The confluence zone near Booni, where the Luthkhow and Mastuj rivers merge, emerges as a geomorphically active area with sustained discharge and sediment supply, suggesting potential suitability for small-scale hydropower development under appropriate environmental and hazard assessments.

Overall, the results confirm that the evolution of the Luthkhow River basin is primarily governed by neo-tectonic processes, with climatic forcing acting as an amplifying factor. The integration of remote sensing, DEM-based morphometric analysis, and drainage-lineament relationships provides a valuable framework for understanding landscape evolution and associated hazard potential in the Hindu Kush-Himalaya region.

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