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Analysis of landslide susceptibility in the Middle Araz Basin (Nakhchivan) using GIS

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Abstract. In recent years, remote sensing methods and Geographic Information Systems (GIS), particularly their analytical tools, have been widely used to assess landslide susceptibility and evaluate landslide hazards and risks. These technologies provide significant advantages in collecting and analyzing data related to landslide susceptibility. This study analyzes the landslide susceptibility of the Middle Araz Basin (Nakhchivan, Republic of Azerbaijan) using GIS. Landslides are a serious natural hazard in our country, including in the Nakhchivan Autonomous Republic, where 76% of the territory is mountainous. Landslide events cause substantial damage to residential areas and pose significant threats to human life, impacting environmental structure and local ecosystems. Early detection and analysis of landslide-prone areas are essential to mitigate these impacts and to implement necessary preventive measures. Assessing landslide susceptibility in the Middle Araz Basin is a novel undertaking. In this study, the weighted overlay method (WOM) was employed to develop a landslide susceptibility map. Field studies and observations provided landslide inventory data specific to the region. Various conditioning factors affecting landslides – including slope, aspect, elevation, relief curvature, proximity to river networks, distance to roads, NDVI, distance to faults, and precipitation – were analyzed to identify high-risk areas. The resulting susceptibility map categorizes the Middle Araz Basin into five risk levels: very high (1.8%), high (14.5%), moderate (25.5%), low (34.6%), and very low (23.6%). This classification aids in understanding the risk levels across different areas, thereby supporting the implementation of appropriate protective measures.

Keywords: *weighted overlay method (WOM); remote sensing; landslide conditioning factors; gravitational force; slope; hazard mapping*

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INTRODUCTION

The mountainous regions of the Middle Araz Basin are considered high-risk zones due to both the recurrence of landslides and the emergence of new landslide sources. Over the years, landslides with varying levels of activity have occurred along the left slope of the Gomurchay Valley, in the upper reaches of the Zarnatukchay River, on the south-eastern slope of Dibakli Mountain, the southern slope of Buzgov Mountain, and in the upper reaches of the Lizbirtchay, Jahrichay, Pirchay, Shahbuzchay, and Tandirlichay rivers. Other affected areas include the areas between Kulus and Kechili villages, north of Bichanak village, and the surroundings of Akhura, Havush, Yukhari Yayji, Yukhari Buzgov, Garmachatag, Shada, Guney Gishlag, Kuku, Behrud, Bilav, Bist, and Tivi villages. These landslides continue to pose a significant threat to the region (Babayev *et al*. 2016; Kangarli 2017, Kangarli *et al.* 2020).

Over the past 20–25 years, numerous landslides causing significant damage have occurred in these areas, with the most devastating event taking place on 6 May 2011 in the village of Kechili, where a portion of the village was completely relocated to a new area. Additionally, relatively large new landslide sources continue to emerge within the study area. On 24 June 2024, a landslide triggered by a rockfall was observed at the summit of Gazangoldagh (3829 m). This landslide, which lasted three days and produced a strong rumbling sound, was clearly visible from surrounding villages, including Nasirvaz and Nurgut. During the event, debris – composed of rocky and clay-rich materials – flowed rapidly, filling the valley with large volumes of rocks (see Fig. 1). Recent observations indicate that the landslide is significantly expanding along the slope, both downward and upward, continuously impacting new areas.

In addition to past losses, factors such as relatively high population density in landslide-prone areas, ongoing human activities, an inadequate legislative framework, and low ecological awareness are further expanding the regions at risk of landslides. Meanwhile, changing climatic conditions are leading to increased extreme precipitation, with several days' worth of rainfall occurring in short periods (Huseynov 2022). This trend is expected to continue in the coming years, likely resulting in a rise in landslide occurrences. Therefore, identifying landslide distribution patterns, studying their activity, intensity, and dynamics, assessing landslide susceptibility, and developing strategic approaches to mitigate these processes are crucial.

Researchers have been working for years to minimize the damage caused by landslides, with a significant focus on developing landslide susceptibility maps. Landslide susceptibility refers to the spatial prediction of landslide occurrence. As such, creating landslide susceptibility zone maps is a vital tool for analyzing and managing landslide risk. These maps visually represent landslide-prone areas and safe zones (Hadji *et al*. 2018). The use of such maps not only helps reduce potential damage but also enhances overall safety and protection measures (Pourghasemi *et al*. 2012). The reliability of these maps depends largely on the quantity and quality of available data, the scale of the study, and the selection of appropriate methodologies (Guzzetti *et al*. 1999; Pourghasemi *et al*. 2012).

There are various methods in the literature for producing landslide susceptibility maps, each with its own strengths and limitations. Statistical methods, such as logistic regression and frequency ratio models, are commonly used to analyze the relationship between landslides and their influencing factors, providing a quantitative approach to risk assessment. Heuristic methods, which involve expert judgment and the application of predefined rules, have been widely applied in areas with limited data, offering a more flexible but subjective approach (Huang *et al*. 2020). More recently, machine learning techniques, including decision trees, support vector machines, and neural networks, have gained popularity due to their ability to process large datasets and model complex, non-linear relationships (Orhan *et al*. 2022). These methods have demonstrated high accuracy in predicting landslide susceptibility, making them valuable tools for landslide risk management. Despite the advancement of these techniques, challenges remain in integrating them effectively, especially in regions with complex topography and limited data. This study aims to contribute to the existing body of knowledge by using a combination of these methods, integrated with geographic information systems (GIS) and remote sensing, to provide a comprehensive landslide susceptibility assessment for the Middle Araz Basin.

In recent decades, various methods have been developed for assessing and mapping landslide susceptibility (Pardeshi *et al*. 2013; Mahalingam *et al*. 2016). The use of satellite imagery and remote sensing technologies, for instance, enables the collection of detailed information on various factors in the area, providing more accurate analysis and predictions of landslide risks. While remote sensing was initially used for basic interpretation or as a backdrop for maps in the 1970s and 1980s, recent research now focuses on processing and analyzing this data more extensively (Jafarzade 2014). When integrated with geographic information systems (GIS), these methodologies also help in visualizing data and optimizing decision-making processes. As a result, modern methodologies improve the effectiveness of strategic measures to mitigate the impacts of landslide events and enhance public safety. According to data from the Web of Science, such studies are most commonly conducted in Italy, followed by China. In our country, landslide susceptibility, hazard,

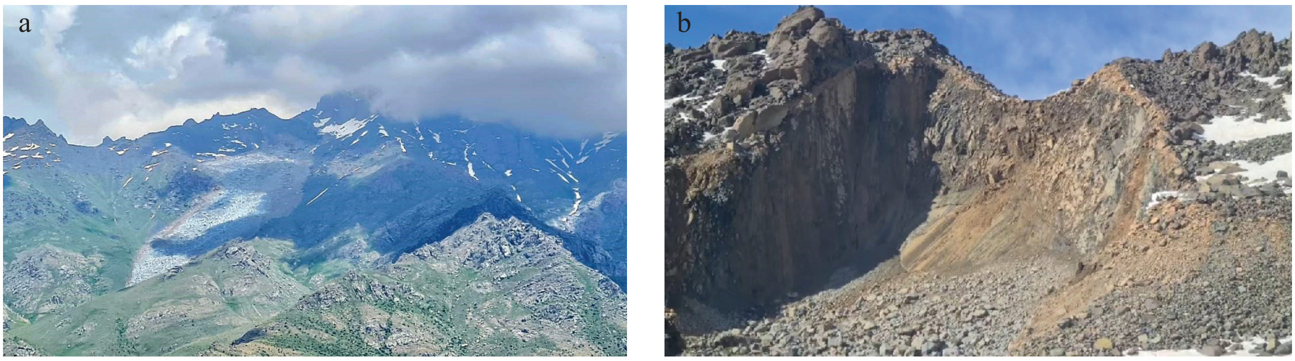

Fig. 1 Gazangoldagh Peak 3829 m (30 06 2024): the movement of sliding materials in the direction of gravitational force (a) and depression formed by a landslide (b)

and risk studies are primarily focused on the Greater Caucasus region (Tarikhazer *et al*. 2023; Mammadov, Tarikhazər 2023). Given the need to assess landslide susceptibility in the Middle Araz Basin, we have chosen this region as the focus of our study.

In this work, a semi-quantitative approach based on expert knowledge has been applied to map landslide susceptibility. This methodology bridges qualitative and quantitative methods by evaluating the significance of various conditioning factors.

The novelty of this study lies in its comprehensive approach to landslide susceptibility mapping in the Middle Araz Basin, an area that has not been extensively analyzed in previous research. The study investigates the intensity, activity, and distribution patterns of landslide processes using new methods, proposing innovative approaches for identifying landslide-prone zones. Its contribution to the literature is particularly aimed at filling existing gaps in the field of landslide risk assessment and mapping in the Nakhchivan region. This work also focuses on enhancing the effectiveness of modern methods in predicting landslide events and ensuring public safety by integrating geographic data and satellite technologies.

MATERIALS AND METHODS

Study area

The Middle Araz Basin is located in the southernmost region of the South Caucasus, situated between 38°51'–39°47' north latitude and 44°46'–46°10' east longitude, in the south-western part of the Lesser Caucasus (see Fig. 2). The area spans approximately 1,300 km² of piedmont plains and 4,200 km² of mountainous terrain (Alizade *et al*. 2017a, b). Stretching 158 km from northwest to southeast, the basin's shape resembles an irregular rhombus. Despite its relatively small size, the terrain is highly diverse. The region's complex relief is shaped by high mountain massifs, deep intermontane depressions, river valleys, and the structural, lithological, and physical geographical conditions that create both vertical and horizontal zonality.

Landslide inventory information for the research area

To compile the landslide inventory for the study area, we used satellite images, large-scale topographic maps, field observations, and previously published scientific and methodological papers on the subject (Bababayli *et al*. 2020).

Conditioning factors used

The manifestation of landslide processes in various forms across the area necessitates their detailed study and classification based on different criteria. A review of articles published in high-impact journals between 2000 and 2024 reveals the use of 31 different conditioning factors, each playing a significant role in evaluating landslide susceptibility. The accuracy of the susceptibility map is enhanced by the correct

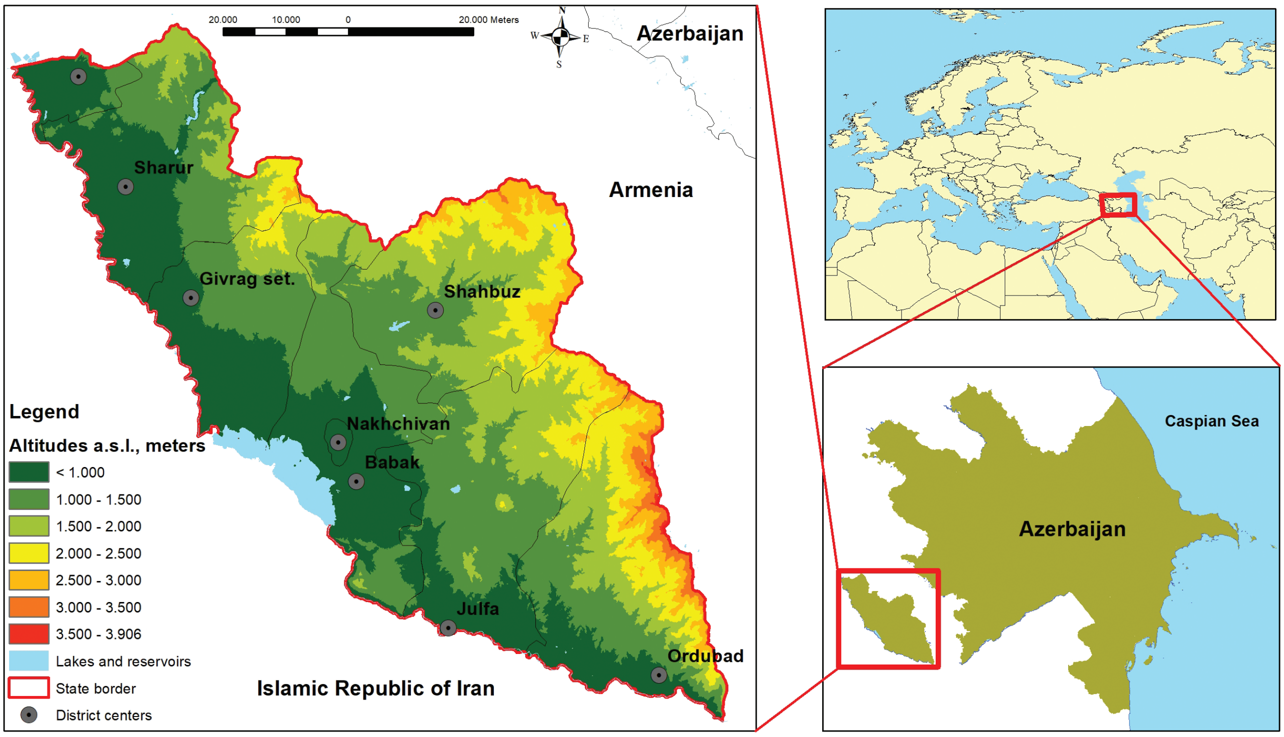

Fig. 2. Physical-geographic location of Middle Araz (Nakhchivan) province

Table 1 Data sources for factors used in landslide susceptibility analysis

Factor	Data source	Description of data	Resolution/Time period
Proximity to fault lines	National Atlas of Azerbaijan (Bababeyli 2020)	Fault lines digitized from the national geological map	1:500,000 scale
Proximity to river	Digitized river network shapefiles from OSM and hydrological maps	OpenStreetMap (OSM) and hydrological maps	1:50,000 scale
Proximity to roads	OpenStreetMap (OSM)	Roads data downloaded from OSM	1:50,000 scale
NDVI (Normalized Difference Vegetation Index)	Landsat 8 imagery	NDVI calculated from the red and near-infrared bands of Landsat satellite images	30 m resolution, 2022
Slope curvature	DEM data from ASTER (NASA)	Slope curvature derived from the Digital Elevation Model (DEM)	30 m resolution
Aspect	DEM data from ASTER (NASA)	Aspect calculated from the Digital Elevation Model (DEM)	30 m resolution
Precipitation	WorldClim (www.worldclim.org)	Precipitation data obtained from WorldClim datasets.	30 arc-seconds (1 km)
Slope	DEM data from ASTER (NASA)	Slope calculated from the Digital Elevation Model (DEM).	30 m resolution
Elevation	DEM data from ASTER (NASA)	Elevation derived from the Digital Elevation Model (DEM).	30 m resolution

analysis of these factors. However, conditioning factors affecting landslide susceptibility can vary from region to region due to differences in terrain, and thus no standardized set of factors exists.

In our research, we selected 9 conditioning factors: slope, aspect, elevation, curvature, proximity to river networks, proximity to roads, NDVI, faulting, and precipitation (Table 1). These factors were chosen after reviewing numerous literature sources and incorporating findings from personal field research. The first seven factors were derived from the 30 m spatial resolution SRTM DEM (Shuttle Radar Topography Mission Digital Elevation Model) and classified into 9 categories. Given that most landslides in the area occur in Upper Pleistocene and Holocene age rocks, the lithological factor was excluded from the analysis.

Slope

Slope is a key indicator that directly influences landslide processes. As a result, it is used by nearly all researchers as one of the most important conditioning factors in the preparation of landslide susceptibility maps (Arca *et al*. 2019; Bahrami *et al*. 2020). The general trend regarding this factor is that as its quantitative values increase, susceptibility to landslides also rises (Lee, Min 2001; Kayastha *et al*. 2013). However, some argue that slope has little effect on landslide processes (Gokcheoghlu *et al*. 2001). It is important to note, though, that this view primarily applies to areas with extremely steep slopes, where the slope approaches a vertical direction.

As Meusburger and Alewell (2008) pointed out, on very steep slopes, the soil cover is continually exposed to surface erosion and becomes thinner. Thinner soil profiles are less susceptible to landslides due to the reduced gravitational force acting on them. Additionally, the development of erosion on slopes can vary depending on the types of soil in the area. For example, in the mountainous zone of the Middle Araz Basin, grassy mountain-meadow soils predominantly develop on slopes with gradients greater than 20°, while degraded mountain-meadow soils develop on slopes with gradients between 10–20° (Alirzayev 2005). In the first case, despite the steep slopes, the soils are less prone to erosion due to the higher resistance of grassy mountain-meadow soils compared to degraded semi-steppe soils. Long-term studies indicate that for landslides to occur, the thickness of soft fragmental rocks must be at least 1–2 meters (Berber 2023).

In the mountainous region of the Middle Aras Basin, surface slope is significantly higher compared to the general area. This parameter varies across different parts of the mountainous zone. The southern slopes of the Zangezur Range, located within the Ordubad and Julfa districts, are characterized by steep slope angles. As the slope angles decrease towards the centre and northwest, there is less intense transport of debris materials, leading to more active accumulation of soil-forming deposits (Gurbanov *et al*. 2024). Consequently, landslides are primarily observed in the eastern and, to some extent, western parts of the Daraleyez and the north-western parts of the Zangezur Range (Kangarli *et al*. 2020).

GIS analyses show that in the mountainous part of the Middle Araz Basin, slope angles generally range between 10° and 30°. Slopes within this range (10°–30°) are considered favourable for the occurrence and development of landslide processes. No landslide traces are observed in areas with slopes up to 10°, where the low gradient suggests that the risk of soil displacement is virtually nonexistent. However, in exceptional cases, this risk could materialize during heavy rainfall events. Slopes exceeding 30° are highly prone to erosion and are considered particularly hazardous areas, though in most cases landslide processes have not yet developed. Slope angles in the area can reach up to 83°, prompting the creation of a classification system divided into 9 sub-classes.

Aspect

Although there is no direct relationship between aspect and landslide formation potential, it does have an indirect effect. This is because slope aspect plays a significant role in local climate conditions, rock weathering, and vegetation cover (Hoşgören 2014). In this context, aspect can influence both landslide preparation and triggering factors. However, there is no consensus among researchers on this issue, and different studies provide varying results. For instance, some research considers aspect to be one of the primary indicators of landslide hazard (Galli *et al*. 2008; Yalcin, Bulut 2007), while others restrict its influence to only certain types of landslides (Atkinson, Massari 1998). Other studies argue that aspect plays no role in landslide formation (Ayalew, Yamagishi 2005; Çevik, Topal 2003).

There is no unified agreement on the role of aspect in landslide formation, nor has a precise conclusion been reached regarding which aspects are associated with a higher landslide potential. This uncertainty stems from the varying results of different studies and analyses. For example, in the Northern Hemisphere, Lee *et al*. (2002) identified southeast, Nagarajan *et al*. (2000) identified west and northwest, Choi *et al*. (2012) identified east and southeast, Turan and Dengiz (2017) identified north, and Pourghasemi *et al*. (2013) identified northwest as directions with the highest landslide potential. These differences indicate that evaluating aspect alongside other regional parameters and considering its position is essential to understanding which aspect has the greatest influence on landslide occurrence.

Despite the large total area of south-facing slopes in the Middle Araz Basin, landslide processes occur significantly more frequently on north-facing slopes. The main reason for this is the weaker solar heating on north and northeast-facing slopes. Reduced solar influence allows moisture to be retained in the soil for longer periods after rainfall. Additionally, north and northeast-facing slopes tend to have more stable and prolonged snow cover. Most importantly, the combination of heavy rainfall and intense snowmelt during the first ten days of April and May leads to faster and more hazardous development of landslide processes on these slopes.

Elevation

The role of the elevation in assessing landslide susceptibility is multifaceted. First and foremost, climate changes with elevation (Türkesh 2010), and these climate changes, in turn, lead to alterations in vegetation cover (Donmez 1985). Both climate and vegetation changes affect soil properties and soil formation processes (Atalay 2011). These environmental components, which vary with elevation, also impact the formation and development of landslides. For example, climate influences factors such as the type, amount, and duration of precipitation; vegetation cover varies with forest, shrub, mountain xerophyte, and grassland types; and soil characteristics, such as thickness, permeability, and texture, play a crucial role in landslide activity.

In addition to changes in natural components, human activities also vary with elevation. Elevation limits the extent of agricultural fields and settlement areas (Türkan 2016). In this context, changes in land use with elevation also influence landslide activity. Furthermore, the construction of road networks parallel to the spread of settlements and agricultural fields increases slope susceptibility (Uzun, Uzun 2003).

Considering all these factors, it is clear that the elevation parameter can influence landslide activity in various ways. However, it is not possible to make a general judgment about this potential. A more precise approach involves evaluating each area based on its physical and geographical characteristics to accurately determine the relationship between elevation and landslides.

In the Middle Aras Basin, the elevation ranges from 600 to 3904 meters. More than 66% of the area lies at elevations above 1000 meters. Most landslides have developed on slopes at elevations between 1500 and 3000 meters (Pashayev 2018). Above 3000 meters, areas with exposed bedrock dominate the landscape, with soil cover appearing only as scattered patches amidst these outcrops. In these regions, atmospheric precipitation does not have the opportunity to infiltrate, resulting in surface runoff and soil erosion. The prevalence of steep, rocky slopes with exposed bare rock contributes to a gradual decrease in landslide potential. However, these conditions create favourable environments for other slope processes, such as rockfalls and screes.

Slope curvature

To assess the impact of slope morphology on landslide occurrence, slopes are classified into different categories (Lee, Min 2001). Positive pixel values indicate a convex relief, zero values correspond to a flat surface, and negative values represent a concave relief. These forms significantly influence water flow. Convex areas distribute water flow more evenly and have less impact on landslide occurrence, whereas concave areas promote water accumulation at the base, creating favourable conditions for landslide formation (Senouci *et al*. 2021). Some researchers combine curvature, plan, and profile curvature components in their landslide susceptibility studies, while others focus on only one of these components. In this study, the curvature component was selected as the primary parameter.

Proximity to river and stream networks

Another important factor frequently considered in landslide susceptibility analysis is the proximity of slopes to river and stream networks. Numerous studies have shown that landslide susceptibility increases as one approaches river and stream networks and decreases with distance from them (Ersayın 2021; Jaafari *et al*. 2014; Mandal, Mondal 2018). In areas near river and stream networks, processes such as valley erosion caused by water flow and saturation should not be considered the sole contributors to landslides. Other factors, such as slope, vegetation cover, and regolith thickness, play a crucial role in determining landslide susceptibility in these regions.

In the Middle Araz Basin, landslides primarily occur along riverbanks and, to a lesser extent, at the base of slopes where atmospheric precipitation infiltrates through deluvial deposits and weathered rocks, eroding these materials. They are especially prominent on the steep left-bank slopes, which are composed of ancient relief surfaces and fourth-period deluvial deposits predominantly made up of clay and gravel. Over time, erosion and weathering processes cause the accumulation of materials in valleys influenced by gravitational flows. This accumulation alters the dynamics of surface runoff, impacting the area's morphology and resulting in the formation of new topographic features. When the debris at the valley base becomes saturated with water, it reaches a critical point where the solid landslide mass begins to move under gravitational forces, leading to various types of landslide flows. Bedrock formations, such as those in the Paraghachay and Nakhchivanchay river basins, occasionally experience landslides. Landslides on steep slopes and ravines typically involve the breakage and displacement of surface formations affecting the upper horizons and are associated with the saturation of rocks on very steep slopes during rainfall events.

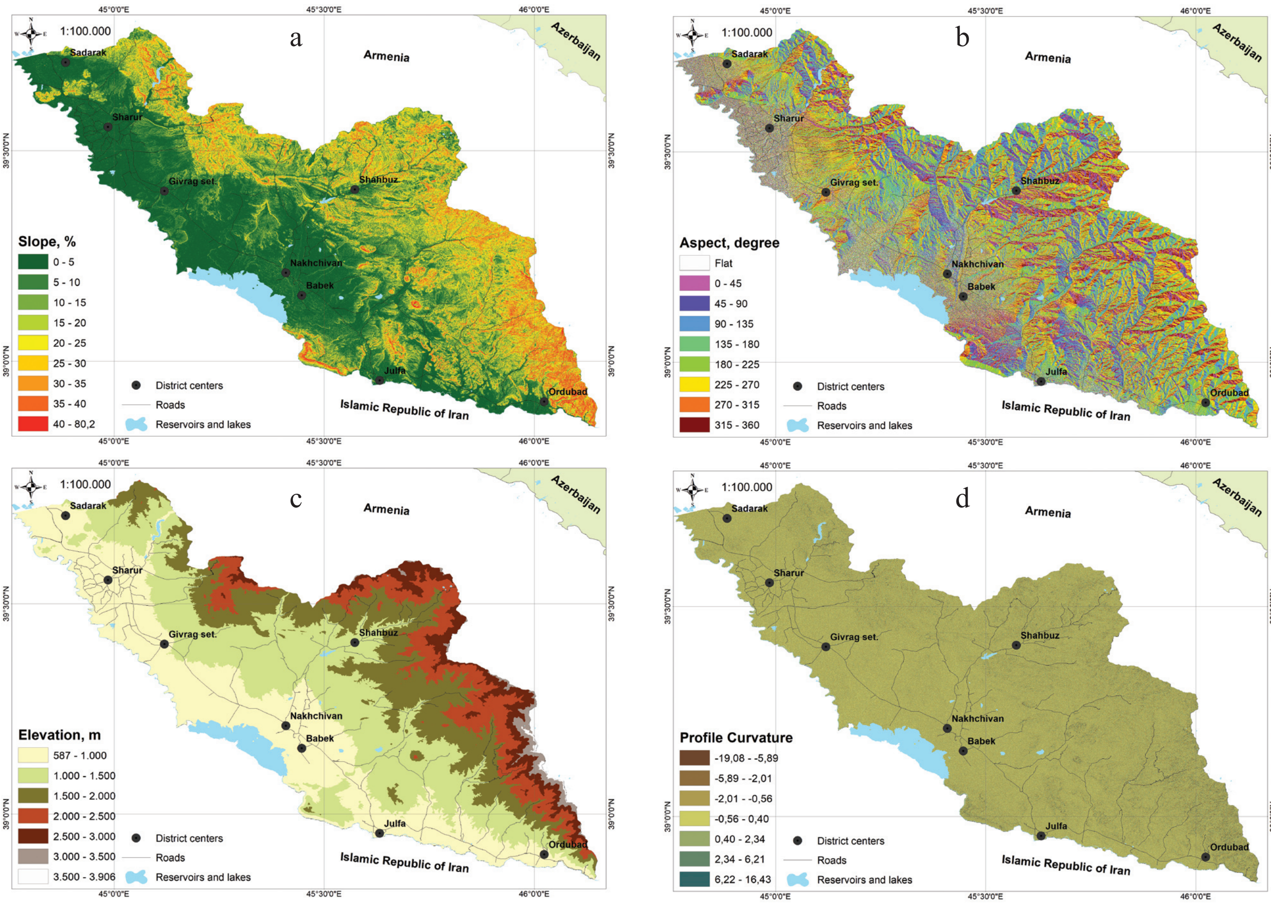

Fig. 3 The maps of conditioning factors: slope (a), aspect (b), elevation (c), curvature (d), proximity to streams (e), proximity to roads (f), NDVI (g), proximity to fault lines (h), and precipitation (i)

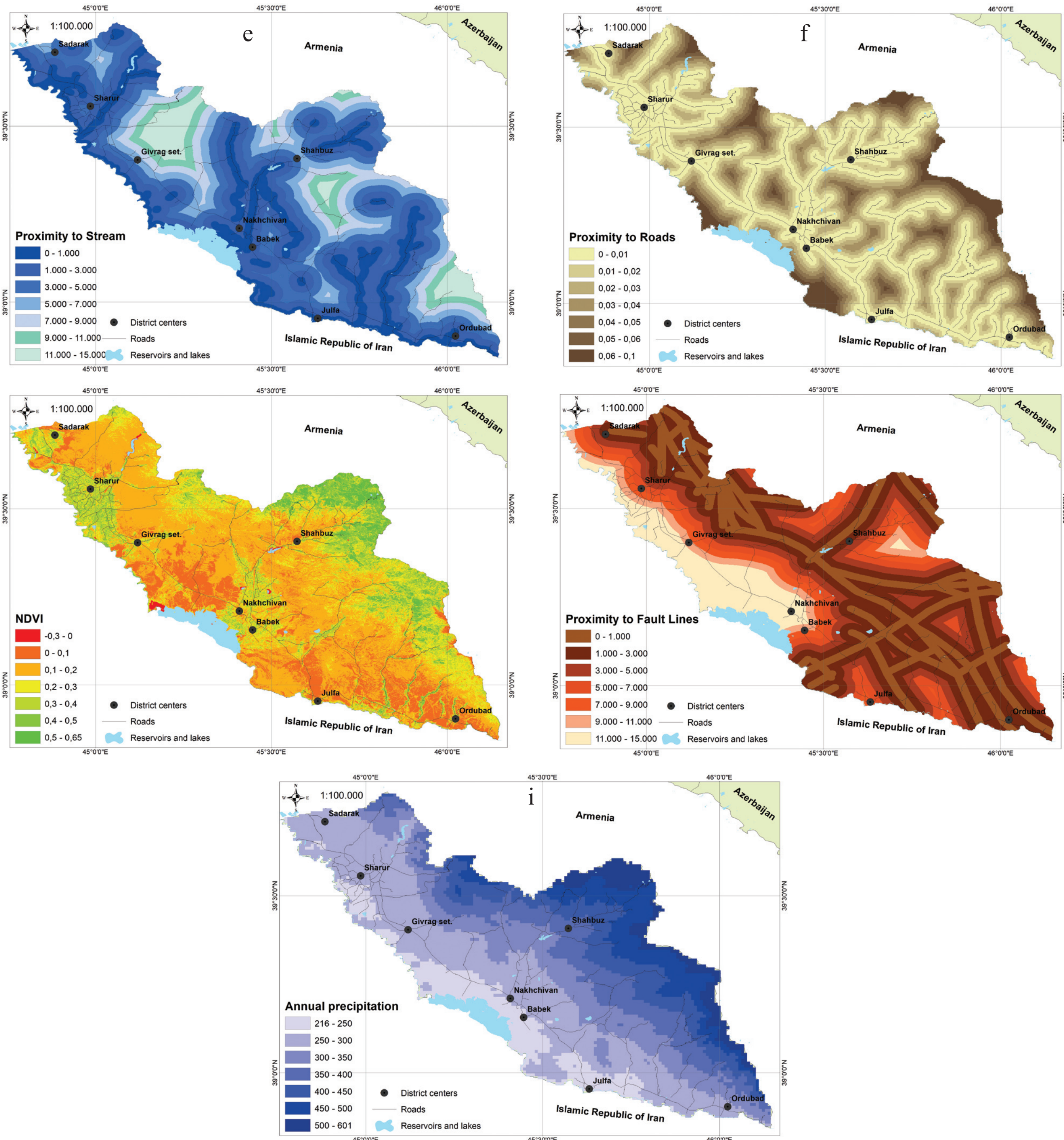

Fig. 3 (continuation) The maps of conditioning factors: slope (a), aspect (b), elevation (c), curvature (d), proximity to streams (e), proximity to roads (f), NDVI (g), proximity to fault lines (h), and precipitation (i)

Proximity to roads

Anthropogenic activities have a significant impact on landslides, with some human-induced factors potentially having a stronger influence than natural ones. Roads, in particular, constructed in steep-slope areas, can disrupt the natural equilibrium, compromising slope stability. Heavy rainfall following road construction further exacerbates the risk of landslides in these already vulnerable areas. The movement of heavy vehicles on these roads can induce vibrations in the upper rock layers, simulating artificial seismic activity, which, in turn, increases the gravitational load on the layers. Observations show that landslides can occur not only in the upper parts of slopes affected by roads but also in the lower sections. For example, material removed from the upper slope areas is often used to reinforce the lower sections of slopes to stabilize the road foundation and prevent surface deformations or subsidence. However, when drainage is inadequate and water from the slopes accumulates in soft, fragmented rocks on the road, especially after heavy rains, this can create conditions conducive to landslide formation (Devkota *et al.* 2013; Eker, Aydin 2014).

Construction work in mountainous areas is technically challenging and expensive, often leading to economic considerations taking precedence over thorough investigations of geological and hydrological conditions. As a result, long-term risks and issues may be unintentionally introduced. Currently, landslide susceptibility and risk are notably high on several roads connecting settlements, including Bilav-Bist-Khurs-Nurgut, Bist-Nasirvaz, Bilav-Paraghachay, Saltag-Goydara, Lakatagh-Arafsa-Teyvaz, Nursu-Kulus, Kulus-Kechili, Yukharı Gıshlaq-Ashaghı Gishlag, Aghbulag-Gomur, Bichanak-Ashaghı Gishlag, Kuku-Gizil Gishlag, Jahri-Gulshanabad, and Yukharı Buzgov-Ashaghı Buzgov-Garmachatag (Pashayev 2018). Except for certain sections of these roads, there are generally no mitigating measures in place – such as retaining walls, drainage systems, or vegetation – to reduce landslide risks. Given these challenges, the proximity of roads to landslide-prone areas was considered an important parameter in this study. Road data for the area was sourced in vector format from OpenStreetMap and included in the analysis.

NDVI (Normalized Difference Vegetation Index)

The role of vegetation in landslide prevention cannot be overlooked. Research indicates that the presence of trees and shrubs on slopes can significantly hinder the development of landslide processes. However, in highly susceptible areas, the influence of vegetation may not be sufficient to prevent landslides. The region's sharply continental climate, marked by low precipitation, dry conditions, and hot, rainless summers and autumns, coupled with cold winters and significant temperature fluctuations between day and night, favours arid-adapted vegetation (Talibov *et al.* 2017). In the lower mountainous areas of the study region, various grass species coexist with mountain xerophyte shrubs, along with plants such as broom, wormwood, topalotu, and stonecrop. Higher up, in the middle mountainous zone, the arid shrubland complex transitions to arid forests and merges with mountain-grassland-steppe complexes. Extensive mountain forests, once widespread, have significantly diminished due to anthropogenic activities, particularly since the early medieval period, and are now preserved mainly in the northern parts of Bichanak, Khurs, and Nurgut villages.

The prevalence of cold, dry summer conditions in the mountainous zone limits the natural distribution of plants suited for forest cover. As a result, the establishment and maintenance of forest cover in the middle mountainous zone present considerable ecological challenges. The deep root systems of arid forests and forest-shrublands are vital for providing horizontal and vertical connections between rocks, effectively performing an engineering function that stabilizes the landscape.

To protect various environmental components, state-protected areas such as the Zangazur National Park (named after academician Hasan Aliyev), Shahbuz and Arpachay state reserves, and Arazboyu protected areas have been established. In the upper reaches of the Nakhchivanchay River, particularly in the Nursu and Kukuchay basins, vegetation protection efforts have resulted in the recovery of dense grasslands and forested areas (Gurbanov *et al*. 2024). To assess this factor, the dynamics of vegetation in the study area were monitored by processing satellite images from Landsat 5 (June 1987) and Landsat 8 (June 2022). Data from 3rd (red) and 4th (near-infrared) bands of Landsat 5, as well as 4th (red) and 5th (green) bands of Landsat 8 were used in image processing. A comparison of these processed satellite images reveals that the NDVI index increased from a minimum value of -0.5 in 1987 to -0.2 in 2022. However, it is important to note that only vegetation with robust, deep root systems can effectively reduce landslide susceptibility on slopes. Observations show that forest plantations mainly consist of pine trees, along with species like hawthorn, rosehip, and pear, whose shallow root systems are less effective in preventing landslides. As a result, the role of vegetation in mitigating landslide risks remains a topic of debate in the scientific community (Collinson, Anderson 1996).

Proximity to fault lines

The Middle Araz Basin and its adjacent border areas are located in a seismically active region. With three tectonic fault lines within this relatively small area, this factor has been incorporated into susceptibility analyses (Bababayli, Gurbanov 2020).

The density of fractures and fault lines in rocks significantly contributes to the potential instability of slopes, playing a key role in the formation of landslides (Lan *et al*. 2004). In addition to the direct impact of deep fractures, there are also indirect effects from fractures in various directions surrounding these faults. These fractures lead to the displacement, fragmentation, and weakening of rock blocks. When intense precipitation or snowmelt infiltrates these fractures, it facilitates the movement of hydrothermal solutions, which can trigger landslides. Consequently, as one moves farther from fault lines, the frequency and intensity of landslides tend to decrease.

Major landslides in the area are often triggered by earthquakes. The Middle Araz Basin is situated in a region known for strong and destructive earthquakes, with magnitudes of 8 or higher being observed. According to Azerbaijan's most recent seismic zoning map (1989), 40% of the area is classified within the highly dangerous seismic zone for earthquakes of magnitude 9 (FHN Atlas 2017). Landslide-generated reservoirs, such as Batabat and Qanlıgöl, serve as examples of how earthquakes can induce rock block movements and surface deformations.

The fault line map used in this study was digitized from Azerbaijan's national atlas. Using GIS tools, multiple buffers were created at 100-meter intervals, categorizing distances to faults into nine distinct classes.

Precipitation

One of the most significant factors contributing to the occurrence of landslides is precipitation, as it directly affects the stability of soil and slopes. Particularly, frequent and short-duration rainfall events have a heightened effect on the formation of landslides (Mallick *et al*. 2021).

Studies have shown that it is possible to predict landslide occurrences based on the amount of precipitation in many regions (Okamoto *et al*. 2004; Dai *et al*. 2001). Although high mountainous areas typically receive heavy and intense precipitation, this does not always correlate with an increase in the extent or intensity of landslides. This suggests that there is no absolute correlation between precipitation levels and landslide occurrences, and that landslide risk is also influenced by other factors. For instance, the high mountainous southern watershed, consisting of the intrusive rocks of the Ordubad pluton, is characterized by its rocky nature (Alizade *et al*. 2017). In such areas with lithologically sensitive layers, precipitation can create instability, thus increasing the risk of landslides.

For this study, rainfall data for the basin was obtained from meteorological information provided by worldclim.org.

In the Middle Araz Basin, atmospheric precipitation increases with altitude, though it remains significantly lower compared to other mountainous regions of Azerbaijan. The basin's location surrounded by high mountains on three sides and its distance from large water bodies contributes to this relatively low precipitation. Precipitation ranges from 250–270 mm at elevations of 800–1000 meters, 410–520 mm at 1500–2000 meters, and up to 600 mm above 2000 meters. Despite a low total annual precipitation, rainfall during the warmer months tends to be torrential in nature. Approximately 54% of the precipitation in the region comes from these intense rain events (Nabiyev 2017). Consequently, torrential rains are a major factor in triggering landslides, both in terms of frequency and intensity. Notable landslide-prone areas, such as Aghyurd, Kuku, Kechili, and others, have experienced significant landslides, particularly following periods of heavy rainfall.

Key climatic parameters influencing landslide development in the Middle Araz Basin also include the regime and amount of solid precipitation. The region experiences relatively cold winters, with stable and long-lasting snow cover. On steep slopes, large snow flows often occur, triggered by intense snowfall and the force of gravity. This typically happens in early spring when the weather begins to warm, causing the snow cover to melt and transport moisture-saturated soil masses down into the valley. Such snowmelt-induced landslides are frequently observed in the upper reaches of the Gilanchay and Vanandchay river basins. A recent example occurred in late June at the source area of the Saqqarsu River, a left tributary of the Gilanchay, at the summit of Gazangoldagh (3829 meters).

Sensitivity analysis for landslides

The weighted overlay method (WOM) is a widely used tool in GIS environments for landslide susceptibility mapping. This method involves multi-criteria evaluation by overlaying multiple raster layers, each weighted based on expert judgment (Shit *et al*. 2016; Ahmed *et al*. 2014). The factors used in this study were chosen for their known influence on landslide formation, as identified in prior research and field observations (Basharat *et al.* 2016; Roslee *et al*. 2017). Table 2 presents the weight factors assigned to each parameter, reflecting their relative importance in the analysis.

Each factor's contribution to landslide formation is justified as follows. Proximity to fault lines (10%) is critical as it indicates zones of crustal weakness often associated with ground movement and seismic activity. Areas near active faults are more susceptible to landslides due to vibrations and fracturing of slope materials. Proximity to river networks (12%) captures the influence of river erosion, which can destabilize slopes by undercutting their bases, especially in areas

Table 2 Weight factors for parameters used in the analysis

Raster parameter	Influence, %
Proximity to fault lines	10
Proximity to river networks	12
Proximity to roads	8
NDVI	6
Slope curvature	10
Aspect	9
Precipitation	15
Slope	15
Elevation	15

with steep banks. Proximity to roads (8%) accounts for anthropogenic triggers, as road construction often involves excavation and slope modifications that weaken natural stability.

The Normalized Difference Vegetation Index (NDVI) (6%) reflects vegetation cover, which influences slope stability by reducing surface erosion and strengthening soil through root systems. Sparse vegetation or deforestation increases susceptibility to landslides. Slope curvature (10%) is included because it affects water flow and sediment deposition. Convex slopes are more prone to erosion due to overland flow concentration, while concave slopes may accumulate sediments that, under certain conditions, can destabilize slopes. Aspect (9%) determines slope orientation to solar radiation and prevailing winds, which affects soil moisture and vegetation cover, both of which influence stability.

Precipitation (15%) is a major triggering factor for landslides, as it increases soil pore water pressure and reduces cohesion, with areas of high rainfall being significantly more susceptible to slope failures. Slope gradient (15%) directly affects gravitational forces acting on soil and rock, with steeper slopes experiencing higher shear stress. Elevation (15%) influences climatic conditions, such as precipitation patterns and geomorphology, and high-elevation areas may experience frost weathering further contributing to instability.

The weight percentages in Table 3 were determined through expert judgment and supported by existing research to reflect the relative importance of each factor in landslide susceptibility. For instance, proximity to fault lines (10%) was assigned a significant weight due to its strong association with seismic hazards, which directly impact slope stability. Conversely, NDVI (6%) was given a lower weight, as its influence is more indirect, primarily related to vegetation's role in reducing surface erosion. Similarly, slope curvature, though less impactful than precipita-

Table 3 Landslide susceptibility distribution by area and percentage

Landslide susceptibility degree	Area	
	Thousand square kilometres	Percentage (%)
• Very Low	1.3	23.6
• Low	1.9	34.6
• Moderate	1.4	25.5
• High	0.8	14.5
• Very High	0.1	1.8
Total	5.5	100

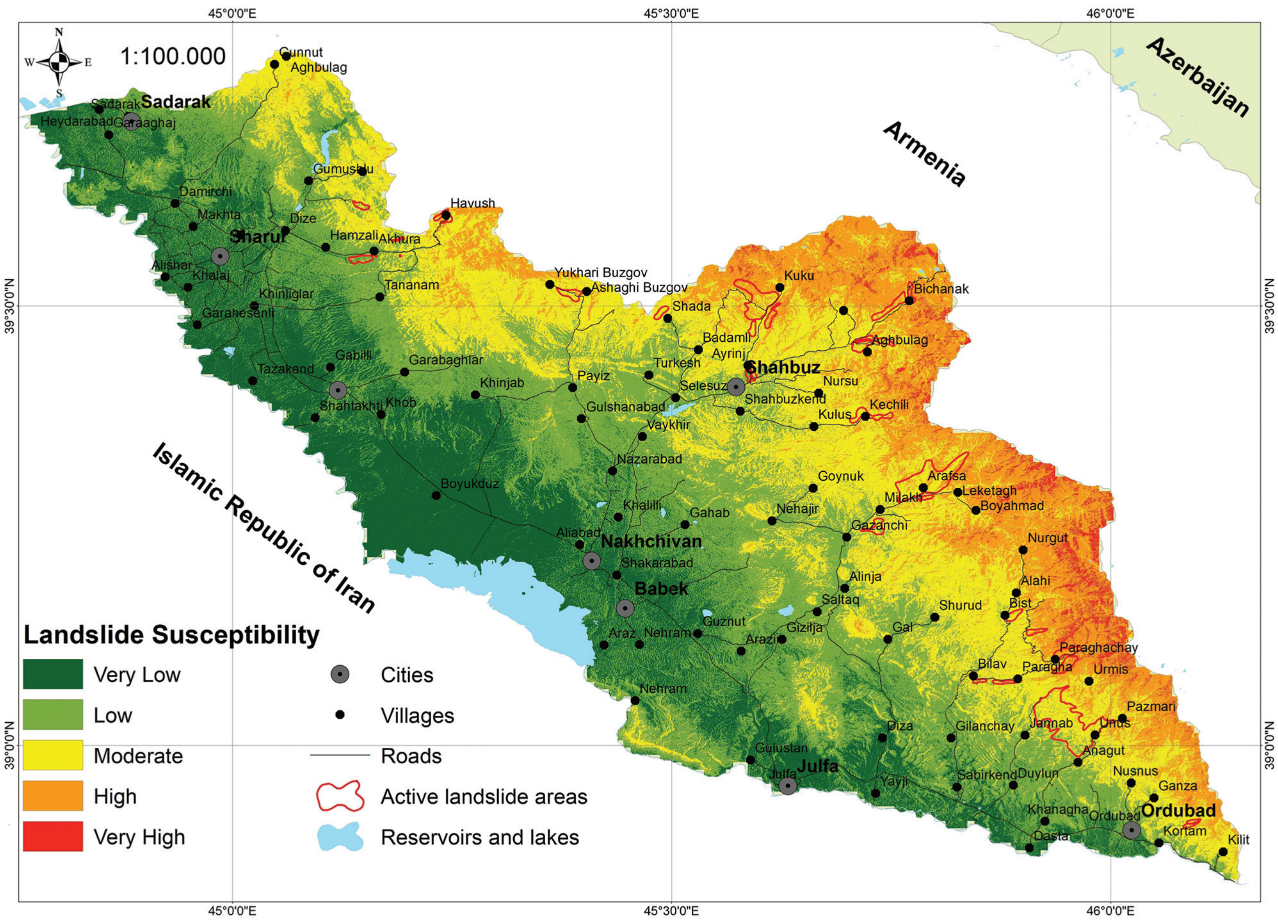

Fig. 4 Landslide susceptibility map of the Middle Araz Basin

tion or slope gradient, plays a crucial role in controlling water flow and sediment deposition, which are essential in understanding localized slope stability. Each factor's weight reflects its contribution to the complex interplay of processes governing landslide formation.

RESULTS AND DISCUSSION

As a result of this study, a comprehensive landslide susceptibility map for the Middle Araz Basin has been generated for the first time. This map (see Fig. 4) highlights areas with varying levels of landslide risk, providing valuable insights for land-use planning, infrastructure development, and disaster risk management in the region.

As shown on the map, areas with very high and high landslide susceptibility include the Nakhchivanchay River valley and its tributaries, particularly the Kukuchay River basin, as well as the high mountainous regions extending from the mid-course of the Akhurachay, Alinjachay, and Gilanchay rivers to the watersheds of the Daralayaz and Zangazur ranges. A high energy of the terrain, its deep fragmentation, seismic activity (with magnitudes of 8–9), longitudinal and transverse tectonic fractures, poor vegetation development, and intense convective processes that generate thunderstorm clouds and heavy rainfall have created favourable conditions for landslides. Frequent landslides and debris flows occur regularly in these landslide-prone areas.

The middle mountainous areas, especially the middle reaches of the Alinjachay, Garaderechay, and Gilanchay rivers, as well as the basins of the Duylunchay, Vanandchay, Aylischay, and Ganzachay rivers show moderate landslide susceptibility. Considering the main natural components, it is evident that certain conditions favour landslides in these areas.

Low and very low landslide susceptibility is observed in the Arazboyu sloping plains, broad smooth-bottomed mountain basins, and central parts of flat surfaces. In these areas, where the slope is less steep, small-scale and localized landslides occur rarely, mainly as a result of heavy rainfall or human activities.

As a result of the observations conducted by us in the field research, the active landslide areas identified have also been added to the map. It has been determined that such areas predominantly correspond to medium and high landslide susceptibility zones.

CONCLUSIONS

Based on the information provided by landslide susceptibility map of the Middle Araz Basin, various mitigation measures can be selected to prevent existing landslide events and enable timely intervention for potential future landslides. The data presented by the map reflects the precise locations, risk levels, and influencing factors of landslide-prone areas, thus facilitating the planning and implementation of appropriate measures. Utilizing this information, the following actions can be implemented:

- ***Establishing detailed monitoring systems*** in areas with high landslide risk, as identified on the map, to allow for continuous observation of changes in the area and potential hazards.
- ***Strengthening and improving existing infrastructure*** (such as roads, buildings, and other structures) in risk-prone areas to minimize the harmful effects of landslide events.
- ***Developing emergency plans*** for regions with high landslide risk, ensuring prompt and effective interventions (such as rescue operations, evacuations, and other critical measures) when landslides occur.
- ***Revising safety regulations and standards*** based on the map's data and imposing relevant restrictions on construction and other activities in high-risk areas.
- ***Educating the population*** living in landslide-prone areas to raise awareness and ensure they are informed about how to respond to landslide events.
- ***Utilizing the map's data*** as a foundational resource for ongoing research and development projects, helping to facilitate more accurate future assessments of landslide risk in the region.

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