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Impact of Large Landslides on River Environments Using Satellite Imagery and Field Data (Case Study: Jajrud River)

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ABSTRACT

Landslides often result in the formation of dammed lakes along rivers. This study aims to explore the correlation between landslides occurring in the Jajrud region and the subsequent creation of dammed lake. To achieve this objective, a combination of remote sensing techniques, geomorphometry, DEM imagery, GPS, ArcGIS software, MATLAB, Global Mapper, and GMT wereutilized. Radar interferometry and SPL methods were employed to analyze the influential factors contributing to landslides. The SBAS method was utilized to determine the amount of displacement while the SPL method involved analyzing basin morphometry and geomorphology through the Tec DEM model. Additionally, morphometric analysis was conducted to assess and correlate terrace sequences. Finally, based on the findings, the extent of the dammed lake was reconstructed The interferometry results revealed an approximate uplift of 40 mm in the landslide area over a span of three years, leading to long-term rupture and landslides TheSPL analysis demonstrated the active presence of morphotectonic changes in the basin, with faults causing amplitude fragmentation. Furthermore, upstream drifting flows, the valley became obstructed, forming a substantial lake along the Jajrud River.

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1.Introduction

Dammed lakes, particularly those resulting from landslides on a large scale, are fairly common and perilous occurrences in mountainous areas worldwide. However, many of these lakes remain unknown an unrecorded, often displaying temporary characteristics as they quickly deteriorate or become filled with sediment when their reservoir has limited capacity (*Costa and Schuster, 1988; Canuti et al., 1998; Korup, 2002; Evans et al., 2011; Bonnard, 2011; Stefanelli et al., 2015; Stefanelli et al., 2018*).

The convergence of various processes on steep mountain slopes gives rise to landslides, which can occur gradually (at a few millimeters per year) or suddenly and rapidly (reaching speeds of 160 kilometers per hour). In most instances, landslides result in fatalities (*Selby, 1970*). Research findings on landslides that form natural dams reveal that these dams are primarily triggered by falling rocks and soil, with approximately 50% of their composition consisting of mud deposits and flows. Additionally, around 25% of cases involve sediments or rocky avalanches. Furthermore, approximately 6% of dams are formed due to the flow of sensitive clay. The presence of clay provides a substrate for falling rocks and coarse materials. Rainfall and snowmelt contribute to approximately 60% of these processes, while earthquakes account for roughly 30%, and volcanic activity and other factors contribute to the remaining 10% of the dams formed by landslides (*Costa & Schuster, 1991*).

Situated in thesouthern part of central Alborz, Jajrud Valley features predominantly mountainous and steep topography, with slopes varying significantly in height compared to the canals. Moreover, the area is classified as having a high seismic risk due to its proximity to the construction site of the Mosha-Fasham fault. According to Iran's tectonic maps (*Nabavi, 1976*), the study area falls within the Alborz-Azarbaijan zone. The region's stratigraphic divisions encompass geological units ranging from the oldest, Precambrian, to Quaternary sediments. However, the majority of formations in the region belong to the Eocene Epoch. The formations in the area, from oldest to newest, include Binder, Barut, Zagun, Laloun, Mila, Jiroud, Mobarak, Ruteh, Nesen, Elika, Shemshak, Delichai, Lar, Fajan, Ziarat, Karaj, Kand, Ghermez Paiyni, Hezar Darreh, Kahrizak, and alluvial deposits of Tehran, respectively. During the early Carboniferous period, extensive layers of limestone were deposited in the northern parts of Iran, while the coal formation in the region is associated with the favorable conditions for plant growth during the early Jurassic period. In the northern margin of the Jajrud-Damavand Rivers, there are tuff rocks within the Karaj Formation, which constitute one of the main synclines in the middle of the zone and an anticline in the eastern part. Numerous faults have emerged in the study area, resulting from the Laramide, Pyrenees, and Pasadena phases (*Darvishzadeh, 1991*). These faults exhibit different orientations due to variations in the forces at play, the heterogeneous nature of the formations in the region, and the prevalence of compression and thrust faults (*Mehrpooya, 1992*). Noteworthy faults the region include the Mosha-Fasham fault, the North Tehran fault, and the Dizin-Darbandsar fault, with several sub-faults concentrated in the northern part of the Catchment (Figure 1).

Furthermore, the studied area is characterized by a variety of hard-to-erode formations. Factors such as high rainfall, dense vegetation, sparse rangelands, agricultural and horticultural activities, unregulated constructions on steep slopes, and the crossing of the Jajrud River and its tributaries contribute to the natural conditions that promote different types of landslides. The research conducted has identified more than ten landslides spread across the region, covering a total area of 2.53 square kilometers. It is worth noting that while small-scale landslides occur annually along communication paths in the area, no previous studies have reported the formation of a landslide dam in the Jajrud region, resulting in the creation of a lake. Therefore, this study aims to explore the historical development and reconstruction of the Jajrud landslide dammed lake.

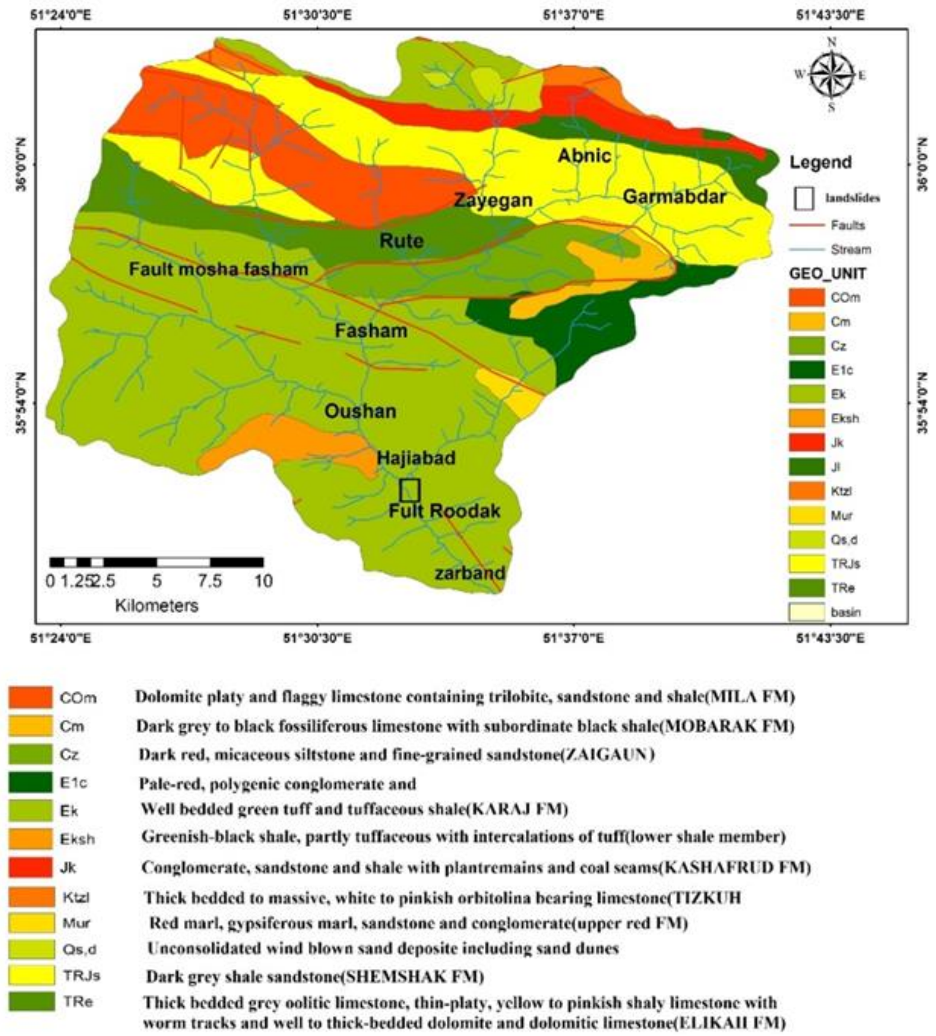

Fig. 1. Geology and tectonics of the study area

Previous research has indicated that the formation of landslide dammed lakes can be influenced by various factors. For instance, *Jian et al. (2013*) conducted a study in the upper reaches of the Jinsha River in the southeast of the Tibetan Plateau, revealing that earthquakes and active faults were the primary causes of landslides that formed dammed lakes. Similarly, *Sharfi et al. (2016)* identified geomorphic evidence of a saline slide dam lake in Khuzestan province, attributing the formation of the Salt Dam lake to the Se Tanan mountain landslide, which blocked the flow of the Shore River in the Dozvil Valley due to the valley's narrow width and the large size of the landslide debris. *Yamani et al. (2015*) focused on the role of the Damavand lavas in creating lake dams, employing an analysis and reconstruction method to study changes over time. The results indicated that the Haraz, Lar, and Delichai lakes were formed simultaneously, with the lava flows separating the lakes and being sequentially adjacent to each other Based on the research background and field observations, this study aims to reconstruct and analyze the extent and depth of the Jajrud landslide dammed lake using satellite image analysis, morphometry, and sedimentology of the terraces. Additionally, the investigation seeks to explore the relationship between landslide occurrence and the factors that influence its development.

2. Material and methods

The Jajrud landslide is situated in close proximity to Rudak Village in the southern region of the Jajrud Catchment, located in the northeast of Tehran City. It falls within the geographical coordinates of 51 degrees and 22 minutes to 51 degrees and 52 minutes east longitude, and 35 degrees and 45 minutes to 36 degrees and 50 minutes north latitude (Figure 2).

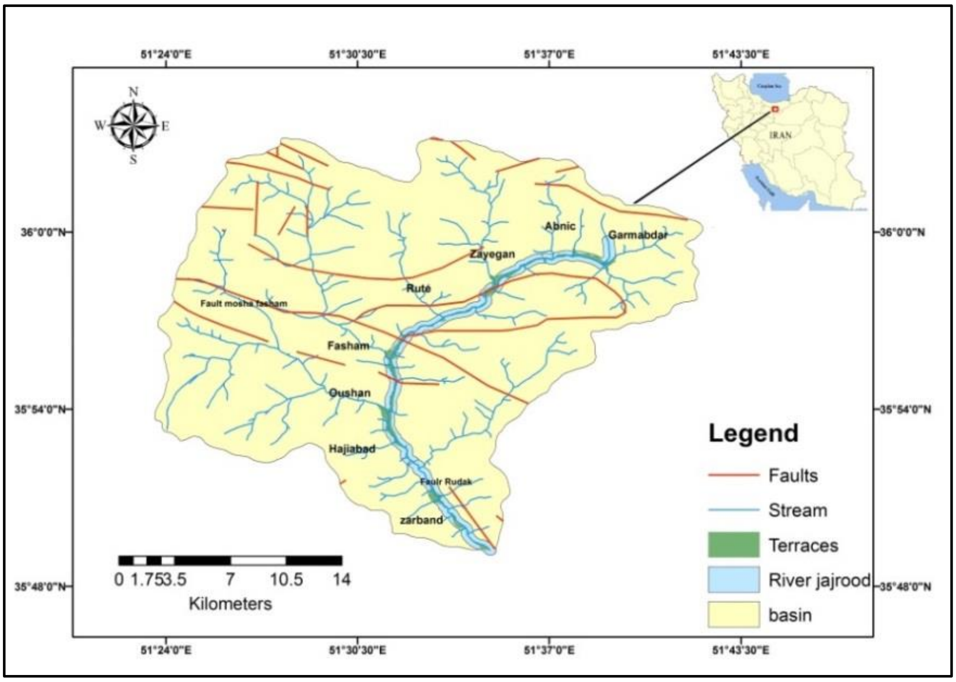

Fig. 2. Geographical location of the study area and landslide in the direction of the Jajrud River

In order to reconstruct the historical development and underlying causes of the long-standing dammed lake, various documentary sources such as articles, dissertations, and projects were carefully examined. Following this, comprehensive fieldwork was conducted to gather morphometric and sedimentological data. Based on these findings, cross-sectional profiles and stratigraphic sections of the terraces were plotted. To enhance precision and conduct more intricate analyses, several software programs including Google Earth, global mapper, ArcGIS, and digital elevation models, along with aerial photographs from 1961 and satellite images from Landsat ETM (2002) and IRS were utilized.

The Landsat and IRS images were instrumental in identifying and mapping the extent of landslides, studying changes in vegetation and land use patterns, and evaluating the impact of landslides on the river environment. These assessments encompassed surface alterations, modifications in the river bed and its quality, as well as sedimentation and water erosion. Additionally, these images were employed to identify potential hazards and risks associated with landslides, such as variations in slope stability and the likelihood of future landslides.

The morphometric indices of the landslide. were studied and analyzed using various data sources, including Liss III sensors from 2004 and 2006, 1:25000 and 1:50000 topographic maps, and a 1:100000 geological map. To obtain specific measurements, a digital DEM elevation model was utilized, providing information on the landslide area (A), depth (D), width of the rupture surface (Wr), length of the displaced mass (Ld), length of the rupture surface (Lr), width of the displaced mass (Wd), depth of the rupture surface (Dr), and depth of the displaced mass (Dd). Calculations were performed using equations such as Dr/Wr to determine the transverse deformation coefficient, Lr/Dr to examine the ratio between the depth and length of the rupture surface, Lr/Wr to assess the deformation coefficient, and V (cubic meters) to measure the landslide volume.

role of tectonic factors in the occurrence of landslides. two methods were employed: radar interferometry and the SPL method. In the radar interferometry method, the vertical displacement of the region was evaluated using the SBAS time series method. This involved analyzing 27 images captured by the Sentinel 1 satellite between October 14, 2014, and October 27,2016. The selection of these images was based on the research objective and their relative baseline to each other. VV polarization was used for all 27 images. The interferometry method, combines radar images with phase values and amplitude of the wave, producing an interferogram that provides information about the difference in distance between the complication and the sensor during imaging times. By analyzing the phase difference, variables such as surface displacement and topographic information with an accuracy of 10 meters can be extracted. However, due to the large area covered by each interferometer and its low correlation, the results alone are unreliable. To overcome this challenge, the SBAS time series method was employed. This method only utilizes pairs of images with a vertical baseline component below a critical value and a minimal temporal baseline.

It is worth noting that the geometric registration of two images is performed accurately and approximately in two steps. Additionally, to address the issue of unreliable results, various methods have been proposed one of which is the SBAS time series method introduced by Zhou in 2013. By considering the specific criteria for image pairs and their baselines, this method helps to overcome the limitations of radar interferometry and provides more reliable results.

Therefore, only interferences of high quality are generated. Once these interferences are formed, they create a network of images. The displacement of each pixel is then estimated using the least squares method, as outlined by Dong et al. in 2014. To assess the displacement of the region, the temporal and spatial baseline status of the images is analyzed using the SBAS time series method. This involves selecting a pair of images to create an interferogram. The desired interferogram maps are generated using the GMT software in the LINUX operating system, following the selection of the desired image pair

The DEM map of the region is prepared as Depression using the Tec DEM software developed by *Gloauen and Shahzad in 2011*), as part of the SPL method. Once the digital elevation map of the region is ready, the indices are calculated, and the tectonic situation of the area is analyzed. Aerial photographs and maps the terrace levels. is examined. Based on the gathered information, the correlations of the terraces are determined, considering their geometry (pattern and terrain) as observed in the aerial and satellite photographs.

Furthermore, the position, height, and distance of each terrace relative to the current riverbed and landslide level are calculated using field data and GPS.Multiple sections are sampled toensure the layering of the terrace is accurately matched and adjusted to different locations. The layers are then organized according to their relative height , resulting in the reconstruction of the terrace levels Sequential profiles and sedimentary stratigraphy of the terraces are derived from the data for further analysis.

Another aspect of the fieldwork focuses on studying the landslide mass.This involves examining the process of landslide formation, its height, extent of expansion, and its influence on the formation of a lake. Based on the findings, the landslide dam and the resulting Jajrud landslide lake are reconstructed (Figure 3).

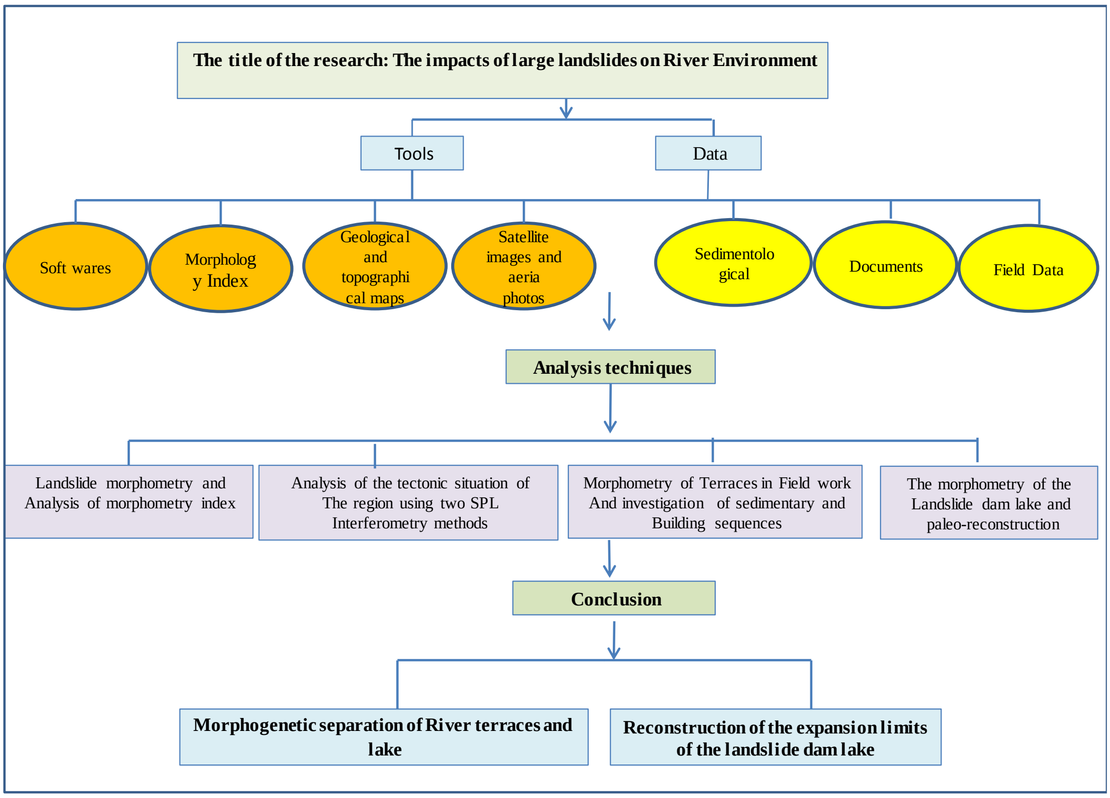

Fig. 3. The methodology flowchart of the research

3. Results
The study's finding are presented in three sections. The initial section examines the morphometry of the Jajrud landslide, encompassing factors such as the area and surface rupture of the landslide, its lengthand width, well as the displacement of water, longitudinal and transverse deformation coefficients, and an analysis of morphometric indices related to the landslide. The second section .focuses on the morphometric characteristics of the landslide dam lake, including its historical reconstruction. Lastly, the third section delves into the tectonic positioning of the region, employing interferometry and SPL as two methods of analysis.

3.1. Impact of fault rupture
Faults can contribute to landslide occurrence from two perspectives. Firstly, faults serve as seismic sources, and slopes in close proximity to fault lines receive a higher concentration of seismic energy during an earthquake, increasing the likelihood of rupture. Moreover, faults can lead to rock fragmentation. The Rudak fault line, located downstream of Rudak, cuts through an area characterized by non-layered and weaker rocks compared to other regions. As a result, this discontinuity diminishes the shear strength of the domain, rendering it more susceptible to instability.

Furthermore, the Mosha-Fasham fault intersects with the upstream area of the landslide, causing fragmentation and disintegration of the mass on the western slope of the Jajrud Valley. These fault systems play a pivotal role in shaping the region's current and past morphology, inducing deformation that disrupts the relative balance of slopes. Consequently, they reactivate the slopes, prompting the movement of materials at varying speeds, such as creeping, falling, and sliding.

3.1.1. Cirque drift deposits as the dominant sliding mass

The impact of Pleistocene glacial cirques in the elevated regions of the Jajrud Catchment is extensive, depending on latitude, slope orientation , and location. Clearly recognizable are the substantial accumulations of drift material found at the outlets of these cirques, as well as in the majority of the high valleys surrounding them. Within this context, three glacial cirques upstream of the landslide were investigated, and it was observed that drift till had accumulated on the dominant sliding slope, adding to its weight following the Wurm glacial period. It is likely that the landslides occurred approximately 8,000 to 10,000 years ago, after the glaciers retreated. The melting of ice between the slope deposits and drifts caused by the warming climate after the Wurm glacial period exacerbated the slope's instability, despite the presence of the Rudak fault rupture (Figure 4 D).

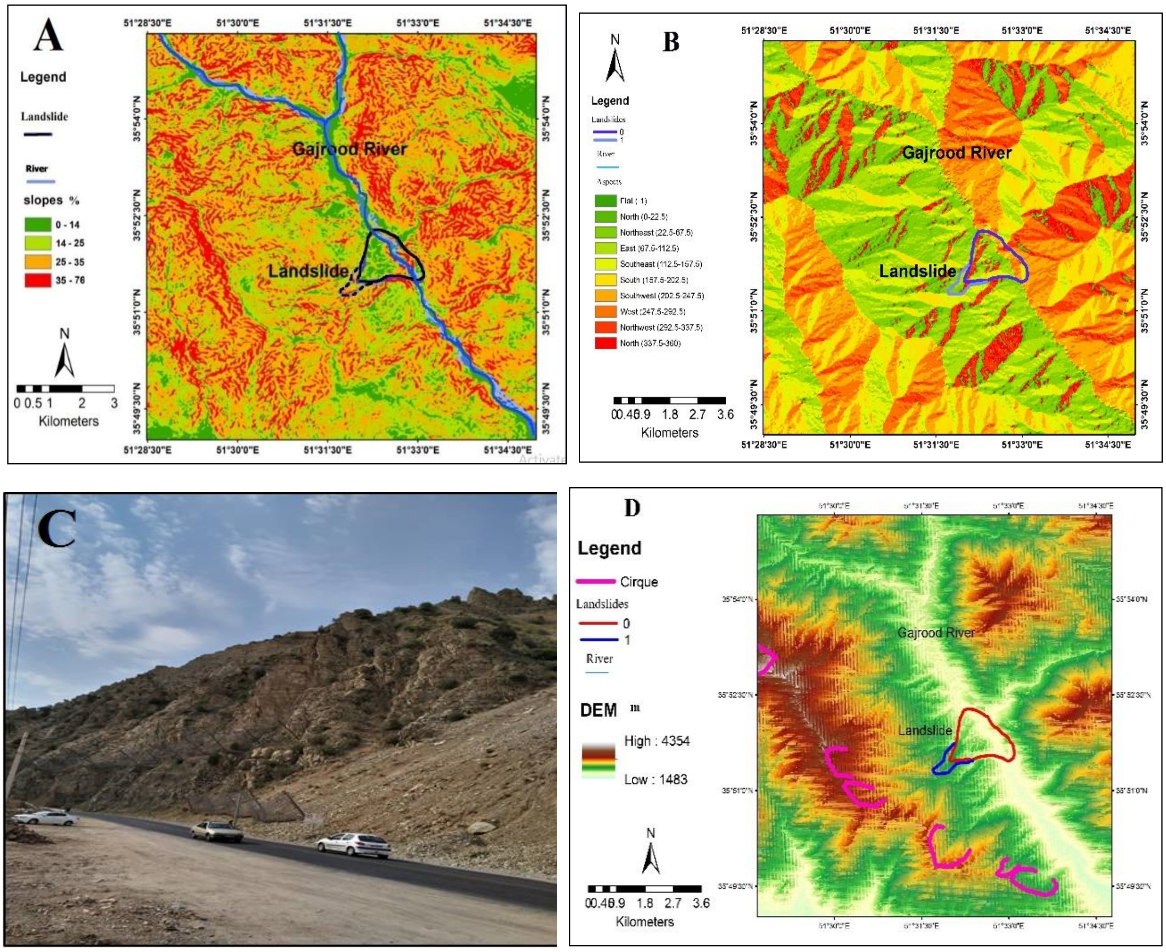

Fig. 4. A. slope, B Aspect Slope, C. Rudak fault zone (stratification disruption due to crossing the Rudak fault line), D. Position of dominant cirques upstream of the Jajrud landslide.

3.2. Morphometric parameters of slope amplitude

Theoretically, an increase in slope amplitude always leads to a corresponding increase in shear stress amplitude, resulting in an expected rise in slope instability potential The Jajrud Valley exhibits steeply sloping layers, which have been further accentuated by the erosion caused by the flow of the Jajrud River and the deepening of the Jajrud synovial valley.To classify the slope in the landslide region, GIS software was employed, categorizing it into four classes, with the steepest region having slopes between 76 and 35 degrees. The average slope at the landslide site measures 32 degrees. The slope, along with the presence of green tuff and lime masses (Karaj Formation) containing marine layers, has been a significant contributing factor to landslide occurrence in the area. Another intrinsic factor influencing landslides is the direction, which indirectly reflects the influence of various factors such as soil thickness, vegetation, and moisture (*Amani 1999*). When considering the occurrence of landslides based on different slope directions, the northern slopes appear to have the highest percentage of landslides Geologically, the region is situated within the Central Alborz tectonic unit. Factors such as weathering intensity, join systems, and rock fragmentation are influenced by the lithology, which is closely linked to the prevailing climate conditions (*Meamarian 1996*). The landslide formations, ranging from old to new, include Barut, Zagun, Laloun, Mila, Jiroud, Mobarak, Doroud, Ruteh, Nesen, Elika, Shemshak, Delichai, Lar, Tizkooh, Fajan, Ziarat, Karaj, Sinit Lavasan, Ghermez, Hezar Darreh, and present-day deposits. The Karaj Formation is composed of Chilean rocks, marl, and tuff, alongside alluvial sediments and recent deposits, which constitute the majority of the region, including the basin formations. Notably, the extension of this formation plays a pivotal role, as 78% of the area comprises rocks with a high level of sensitivity, making them more prone to landslides compared to other types of rock (Figure 4 A, B, C).

3.2.1. Morphometry of the Jajrud landslide

The morphometric characteristics of the Jajrud landslide were analyzed, including its area, depth, volume, width of the rupture surface, length of the displaced mass, length of the rupture surface width of the displaced mass, depth of the rupture surface, and depth of the displaced mass. Additionally, the deformation coefficients of the landslide, such as the transverse deformation coefficient and the ratio of depth to length of the rupture surface, were examined (*Dewitt et al., 2005*) (Table 1).

Table 1. Morphometric features of the Jajrud landslide

	Rupture surface area	1700 km^2
Landslide Surface	$\frac{Lr}{Dr}$	39.950
	Lr	1598.000 km
	Wr	700.780 m
	Dr	40.000 m
	$\frac{Dr}{Wr}$	0.597
	$\frac{Lr}{Wr}$	2.280
Landslide mass	VOLr = $\frac{1}{6}\pi$ * Dr* Wr*Lr	23442103.000m^3
	A	1.864 km^3
	Ld	2.068 m^2
	Wd	1.864 k
	VOLd = $\frac{1}{6}\pi$ * Dr * Wr * Ld	30317536.000 m3

The transverse deformation coefficient of the studied landslide. was calculated using the equation (Dr / Wr), where Wr represents the width of the rupture surface and Dr represents the depth of the rupture surface (*Dewitte et al., 2005*) (Table 2).

Table 2. The landslide condition studied in the classes of transverse deformation coefficient

Landslide mass status	Dr/Wr
Very weak transverse deformation	18.58≤D≤3.22
Weak transverse deformation	33.94≤Wr/D≤18.59
Medium transverse deformation	48.30≤Wr/D≤33.95
Severe transverse deformation	64.66≤Wr/D≤49.31
Very severe transverse deformation	80≤Wr/D≤64.67

The calculated transverse deformation coefficient ($\frac{Dr}{Wr}$= $\frac{40}{700}$=0.057 indicates that the landslide exhibits very weak transverse deformation compared to .its depth. This coefficient falls within the range of 18.58≤D≤3.22, as shown in the table above.

To determine the ratio of depth to length of the rupture surface, the equation (Lr / Dr was utilized, with Dr representing the depth of the rupture surface and Lr representing its length (Table 3)

The obtained ratio ($\frac{Lr}{Dr} = \frac{1598}{40} = 39.95$ indicates that the landslide demonstrates very weak longitudinal deformation compared to.its depth. This coefficient falls within the range specified in the table above.

Table 3. The landslide status studied in longitudinal deformation coefficient classes

Landslide mass status	Lr/Dr
Very weak longitudinal deformation	61.13≤Lr/D≤1.43
Weak longitudinal deformation	120.83≤Lr/D≤61.14
Medium longitudinal deformation	180.53≤Lr/D≤120.84
Severe longitudinal deformation	240.23≤Lr/D≤180.54
Very severe longitudinal deformation	300≤Lr/D≤240.24

3.2.2. Landslide deformation coefficient

The landslide deformation coefficient was calculated using the equation (Lr / Wr , with Lr representing the length of the rupture surface and Wr representing its width (*Dewitte et al., 2005*) (Table 4).

The calculated landslide deformation coefficient ($\frac{Lr}{Wr} = \frac{1598}{700} = 2.280$) falls within the second range of the table above, indicating that the landslide belongs to the category of elongated landslides.

Tab 4. The landslide status studied in landslide deformation coefficient classes

Landslide mass status	Lr/Wr
Landslide with lateral expansion	Lr/Wr<1
Elongated landslide	Lr/Wr≤1

3.2.3 Calculation of landslide volume

The volume of the landslide(V) can be determined in cubic meters using the following, formulas:

1. The initial landslide volume , denoted as VOLr is calculated prior to the movement of the material (Cruden et al., 1996).

VOLr= 1/6π*Dr*Wr*Lr

VOLr= 1/6*3.14*40*700*1598= 23442103m^3

This equation, considers the width of the rupture surface (Wr), the length of the rupture surface (Lr), and the depth of the rupture surface (Dr).

2.Calculating the volume of the displaced material during fast movements is not possible using VOLddue to the unknown. value of Dd. However, VOLd can be estimated by assuming Dd = Dr. Therefore, the equation to obtain the volume of the displaced material is as follows (*WP/WLI, 1999*).

VOLd= 1/6π*Dr*Wr*Ld=30317536m^3

equation takes into account the width of the rupture surface (Wr), the depth of the rupture surface (Dr), and the length of the displaced mass (Ld).

3.3. Morphometric characteristics of the Jajrud Dammed Lake

Morphometry involves determining and measuring the geometric features and quantifiable aspects of a feature, such as its length, width, height, and particle diameter (*Moghimi et al., 2004*). The morphometry analysis of the Jajrud landslide Dammed Lake allows for the assessment of the lake's expansion during its formation subsequent changes leading up to the discharge stage.

3.3.1. Determining the area and extent of the Jajrud Dammed Lake

The Jajrud Lake area has formed behind the mass of the landslide near Fasham city, as indicated by the 1:100,000 geological map of eastern Tehran. The area of the lake, marked on the geological map, measures approximately 4.17 square kilometers, with a depth of around 50 meters and a volume of approximately 70 million cubic meters.

3.3.2. Reconstruction of the Jajrud dam and the extent of the Dammed Lake

Through field observations and analysis of sedimentary evidence, remnants of the Jajrud landslide and the resulting accumulated sediments forming a terrace behind the dam were identified and measured in terms of height. The block diagram of the Jajrud Valley can be divided into two parts: A. Reconstruction of the lake during the time of the landslide and the formation of the landslide-dammed lake. B. Rupture of the landslide dam and the remaining lake terraces as ancient remnants of the lake formation process(Figure 5).

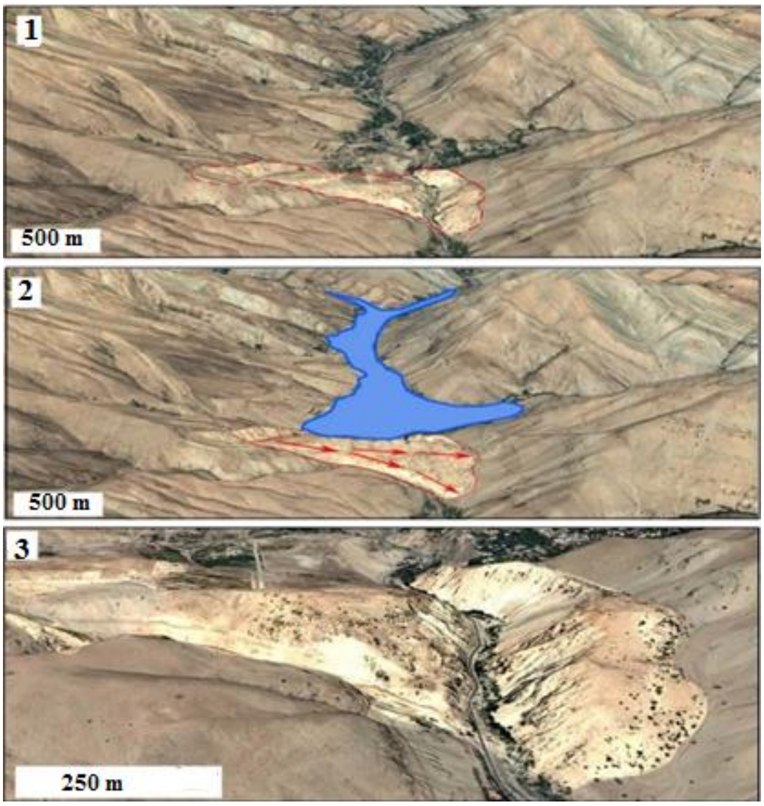

Fig. 5. 1) Cutting off the landslide dam and the drainage of the dam lake and remaining lake terraces. 2) Reconstruction of the dam lake at the time of the landslide and the formation of the landslide dam lake. 3) The landslide mass in the current conditions (Google Earth).

Provides evidence-based reconstructions depicting the entire process, from the initial landslide stage and the formation of the dam lake to the subsequent rupture and draining of the dam lake. The landslide covered the surface of the eastern amplitude, reaching a height of 1920 meters and creating a lake with an area of 4,171,843 square meters (Figure 6).

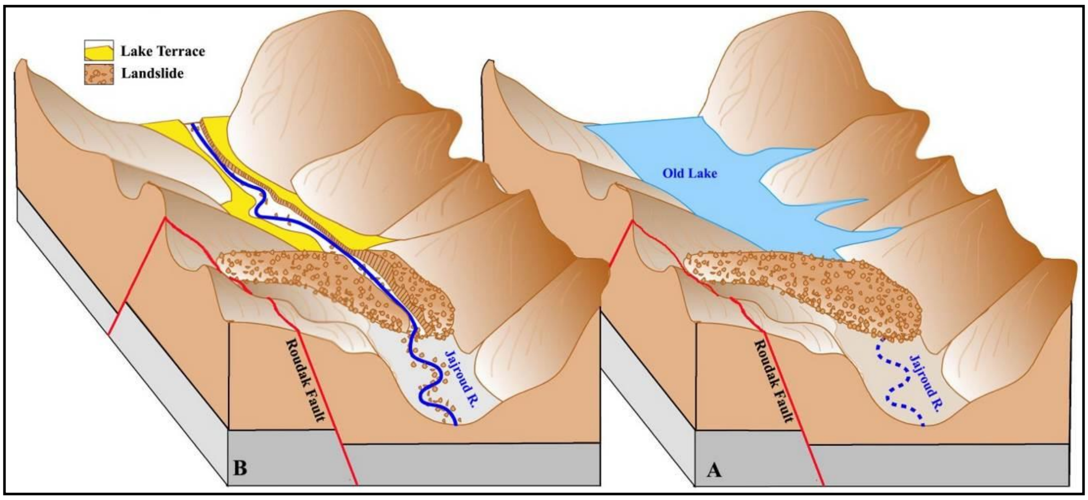

Fig. 6. Block diagram of the Jajrud Valley A. Reconstruction of the lake at the time of landslide and formation of the landslide Dam Lake B. Rupture of the landslide dam and remaining lake terraces as ancient legacies of lake formation.

3.4. Analysis of the tectonic position of the region using interferometry and its role in landslide evolution

Alborz , located in Iran, is recognized as one of th tectonically active regions , and the studied landslide has been influenced by these activities. In this study, we assessed the vertical displacement of the region over a span of three years using radar images. The findings revealed that the study area experienced vertical displacement ranging from +80 to -51 mm during the three-year period. This displacement was characterized by an uplifting of approximately 80 mm in the northern part and a subsidence of around 50 mm in the southwestern part. Additionally, the landslide area underwent an uplifting of approximately 40 mm. The cumulative results of this analysis demonstrate that the region is tectonically active , exhibiting significant vertical displacement. This factor has contributed to amplitude rupture, instability, and ultimately the creation of conditions conducive to landslides over an extended period (Figure 7).

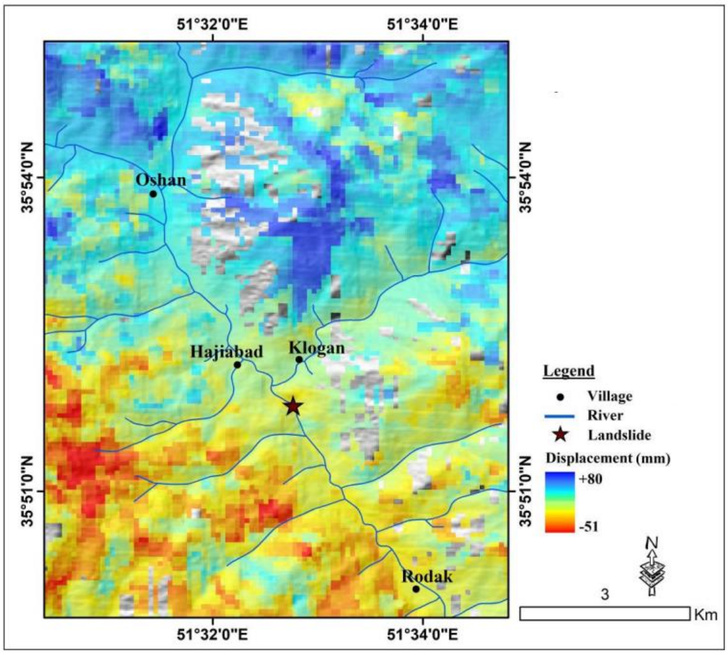

Fig. 7. The vertical displacement of the region from 01/06/2016 to 12/21/2018

3.5. Analysis of the tectonic position of the region using the SPL method

Field studies have been conducted in the area based on the obtained indices , employing tectonic geomorphological indices and the Iso base of the indentation indices, namely ϴ, Ks slope (Table 5), river slope gradient index (Table 6), transverse topographic symmetry factor (Table 7), hypsometric curve (Table 8), and a tantamount map of the study area (Figure 8. These analyses, along with tectonic evidence supporting active tectonics in the basin, have been utilized to assess the tectonic position of the region. The findings reveal that sub-basin 4 of the Garmabadr basin exhibits the highest level of activity, while the Meygon basin displays the lowest tectonic activity, as indicated by the concavity, slope, and river slope gradient index. Sub-basins 1 and 3 exhibit the greatest tilt in terms of tectonic activity, as determined by the transverse topographic symmetry factor. Additionally, the tantamount map of the area confirms the influence of tectonics on topographic changes and subsequently the alteration of basin canals. The hypsometric curves of all sub-basins also demonstrate the youthful conditions in the Jajrud Catchment area and support the notion that sub-basin 4 displays the highest degree of convexity.

These averages highlight the prevalence of active tectonics in the region and the youthful nature of the basin, despite variations in the examined indices.

Table 5. Values of the indentations (θ) indicators and slope (Ks) of sub-basins

Sub-basins												
End sub-basin			Garmabdar sub-basins						Meigun	Emameh	Ahar	
9	8	7	6	5	4	3	2	1	0.32	0.80	0.23	Min amount depressions
-0.24	-0.04	-0.09	-0.02	-0.20	-0.41	-0.13	2.00	1.00	0.86	0.30	0.34	Max amount depressions
-0.15	0.45	0.45	0.06	-0.05	-0.21	-0.43	0.26	0.69	197.32	227.71	195.5	Min amount slope (ks)
84.39	73.30	116.80	97.15	92.29	73.14	101.63	138.39	216.80	279.28	240.80	263.30	Max amount slope (ks)
171.69	186.43	231.39	139.89	241.68	387.17	271.29	221.05	319.8				

Table 6. Values of the river slope gradient of sub-basins

Sub-basins												
End sub-basin			Garmabdar sub-basins						Meigun	Emameh	Ahar	
9	8	7	6	5	4	3	2	1	0.32	0.8	0.23	Min amount depressions
-0.24	-0.04	-0.09	-0.02	-0.20	-0.41	-0.13	2.00	1.00	0.86	0.30	0.34	Max amount depressions
-0.15	0.45	0.45	0.06	-0.05	-0.21	-0.43	0.26	0.69	197.32	227.71	195.5	Min amount slope (ks)
84.39	73.3	116.80	97.15	92.29	73.14	101.63	138.39	216.80	279.28	240.8	263.3	Max amount slope (ks)
171.69	186.43	231.39	139.89	241.68	387.17	271.29	221.05	319.80				

Table 7. Values of the transverse topographic symmetry index of sub-basins

	Sub-basins											
	Ahar basin	Emameh basin	Meigun basin	Garmabedar sub-basins						End sub-basins		
				1	2	3	4	5	6	7	8	9
Transverse topographic symmetry factor	0.22	0.20	0.35	0.67	0.29	0.67	0.15	0.32	0.25	0.21	0.54	0.54
Direction tilting	NW-SE	NW-SE	NW-SE	NW-SE	NW-SE	NW-SE	NW-SE	NW-SE	NW-SE	NW-SE	NW-SE	NW-SE

Table 8. Values of the hypsometric curve indices of sub-basins

	Sub-basins											
	Ahar basin	Emameh basin	Meigun basin	Garmabedar sub-basins						End sub-basins		
				1	2	3	4	5	6	7	8	9
Skewness	0.48	0.50	0.21	0.29	0.24	0.66	-0.85	0.09	0.46	0.26	0.10	-0.11
Kurtosis	2.67	2.07	2.57	2.04	2.50	3.16	2.69	2.13	2.75	2.11	1.82	2.15
Histometric Integral	0.21	0.23	0.21	0.20	0.19	0.18	0.25	0.09	0.16	0.23	0.19	0.21

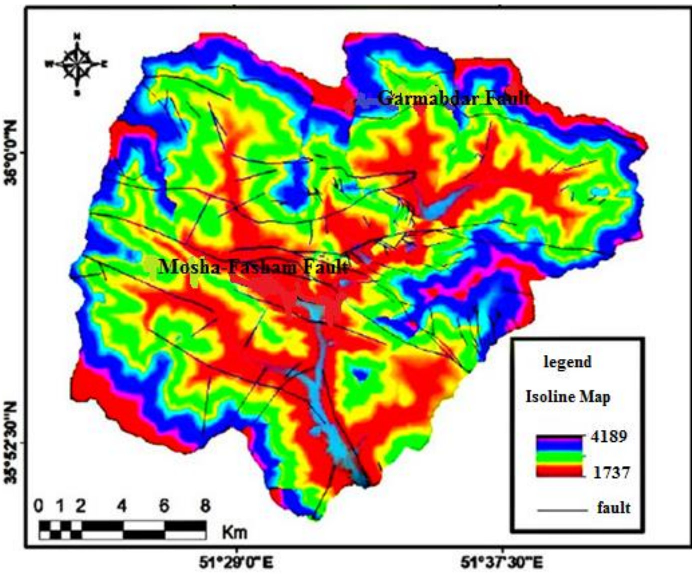

Fig. 8. Isoline Map of the study area

4. Evidence of the formation of the Jajrud landslide Dammed Lake

The Jajrud Landslide Dam Lake, located slightly above the Rudak site, covers an area of 4.17 square kilometers, resulting from the obstruction of the Jajrud River. The remaining sediments can be considered a lake terrace above the landslide dam (Figure 9).

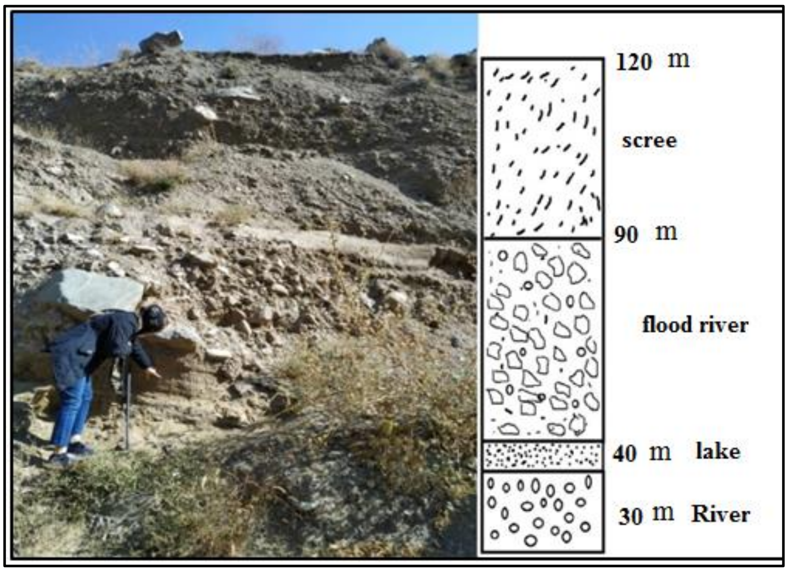

Fig. 9. Sedimentary sequences with lake-river alternation

4.1. Lake sediments

Coarse-grained sediments (sand) found in the lake environments are associated with hot and dry periods when the lake's water level decreases. Conversely, fine-grained materials (silt and clay) are linked to wet periods and are deposited following an increase in the lake's water level (Maghsoudi et al., 2014). The examined terraces display a stratigraphic alternation of lake and river sediments, characterized by flood alternation. Alluvial sediments, primarily consisting of sand and rubble (from floods), cover the river up to 30 meters above the current riverbed at the terrace base. These sediments formed prior to the creation of the dam lake. The lake sediments, with a thickness of 1 to 2 meters, mainly comprise sand, exhibiting a high degree of sorting. Recent alluvial sediments have formed on top of these lake sediments, displaying significant thickness. The lateral extent of these sediments is considerably greater than that of the lake sediments and consists of fine to coarse sands and rubble in varying dimensions. Consequently, the highest terrace is the most recent terrace, contrary to the typical pattern of river terraces in terms of surface topography. The Jajrud Lake terrace is situated at an elevation of 1856 meters above sea level, and its relative height from the current riverbed is approximately 90 meters (Figure 10). It is important to note that the highest terrace is covered by deposit flows.

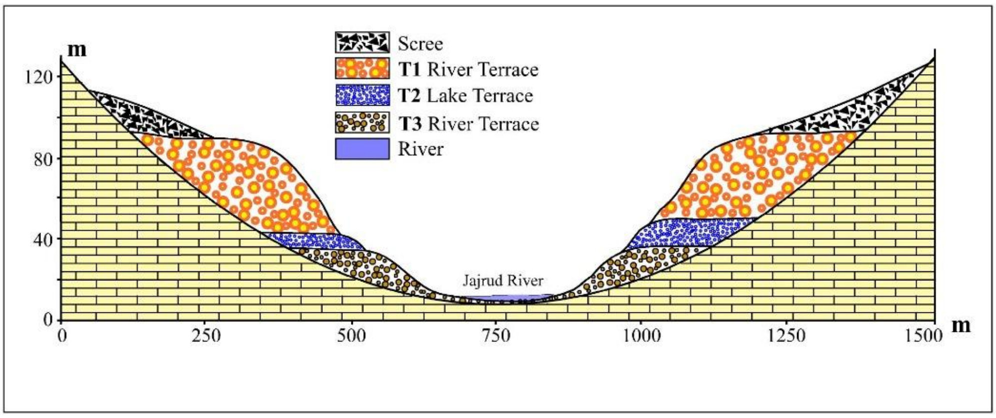

Fig. 10. Transverse profile of Lake Terrace surfaces

4.2. Terrace levels

The mountainous regions of Iran are characterized by expansive alluvial terraces, which are indicative of the activity of flowing water (Mahmoudi, 1988). One prominent feature that identifies the landslide-dammed lake of Jajrud is the presence of Lake Terrace, which spans a wide area within the Jajrud Valley. Three distinct levels of terraces have been formed, with Jajrud Lake terrace positioned at an elevation of 1856 meters above sea level. These terraces stand approximately 90 meters higher than the current river level. Interestingly, the absence of similar terrace levels in other parts of the Jajrud River suggests the potential involvement of landslides in the formation and development of these terraces. Moreover, the Jajrud River, acting as a dynamic geomorphological factor, has significantly influenced the shaping of these terraces (Figure 10).

5. Discussion

Identifying the location of ancient dam lakes along river valleys holds great significance. Several researchers in Iran have focused on studying terraces, including Hai-mei liao et al. (2018, who proposed a fuzzy comprehensive method for assessing the risk of landslide-dammed lakes. Ahmadi et al. (2021) analyzed the morphogenetic sequences of Haraz Valley in the Esk Watershed, investigating the processes behind the formation of defenses in the Haraz Valley and the role of Damavand pyroclastic sediments in altering water behavior, leading to the creation of a dammed lake in the Esk water area. To achieve their objective, they employed an analytical approach and reconstructed temporal changes. Their technique, involved segmenting the study area, comparing the height and thickness of alluvial sediments, determining the expansion limits of lacustrine sediments, and establishing the height boundaries of the terraces that enclose the Haraz Valley.

Haowang et al. (2019) studied the evolution of a landslides-dammed lake in the southeastern Tibetan plateau and its impact on river longitudinal profiles. Dingzhu liu et al. (2021) conducted an assessment of the local outburst flood risk resulting from successive landslides, focusing on the Baige landslide-dammed lake in the upper Jinsha River of eastern Tibet. Their research quantitatively analyzed the influence of dam geometry, resulting from successive landslides, on the process of outburst floods and associated risks.

Yamani et al. (2014) reconstructed the paleosurfaces of Lake Urmia during the Quaternary period through an examination of the lake fortifications. The primary objective was to identify and investigate Quaternary terraces in Lake Urmia, in order to determine their elevation and reconstruct the ancient water levels and affected areas influenced by fluctuations in the lake's water level.

Given the significance of landslides occurring along rivers, the formation of dammed lakes, and the subsequent environmental and human impacts, numerous studies have been conducted in this field. Sharfi et al. (2019) conducted a study on the paleogeomorphological reconstruction of the Dela landslide and the formation of Shimbar dammed lake in Andika city, located in Khuzestan province in the southwest of Iran. Geoarchaeological studies were conducted in the study area using topographical and geological maps, Digital Elevation Model (DEM), and GIS satellite imagery. The outcomes of this research contributed to the reconstruction of the paleogeomorphology of the Dela landslide and Shimbar dammed lake.

Haowang et al. (2023) conducted a study on the reconstruction of a landslide-dammed lake in the Yalong basin, located in the eastern Tibetan plateau. Their research aimed to investigate the formation of dammed lakes during the early Holocene as a result of large landslides. These findings were compared to a previous study by Zhang et al. (2015, which focused on dating a significant landslide-dammed lake in the upper region of the Yellow River in the northeast Tibetan Plateau.

The results of Zhang et al.'s (2015) study indicated that the formation of dammed lakes during the early Holocene was caused by large landslides. In a similar vein, Haowang et al. (2022) examined the spatial and temporal distribution of landslide-dammed lakes in the Purlung Tsangp area. They observed that climate driven factors, such as intense rainfall and increased river incision after the Last Glacial Maximum (LLGM, played a crucial role in preconditioning the occurrence of these landslides.

The innovative aspect of Haowang et al.'s (2023) research lies in the utilization of two methodologies, namely interferometry and SPL, to investigate the tectonics of the study area and the role of tectonics in the formation of the Jajrud landslide and subsequent creation of the landslide-dammed lake. Additionally, their research introduced a novel approach by employing sedimentological studies of terraces and their anomalous age sequence in the Jajrud river valley. These findings may indicate the presence of paleo-lakes, setting it apart from previous studies conducted by other researchers.

6. Conclusion

The study findings reveal the following:

1. Results obtained from interferometric analysis show that there is vertical displacement ranging from +80 to -51 mm. Analysis of the displacement indicates that the northern regions experience uplift of about 80 mm, while the southwestern regions show subsidence of approximately 50 mm. The areas with landslides exhibit uplift of around 40 mm. Overall, these

results demonstrate the tectonic activity in the area and significant vertical displacement, which could have led to the conditions for amplitude rupture and long-term landslide instability.

2.Field studies in the area utilized the SPL method, considering the obtained indices and employing tectonic geomorphological indices and equivalent maps derived from indentation indices such as ϴ, slope Ks (Table 5), river slope gradient index (Table 6), transverse topographic symmetry index T (Table 7), hypsometric curve (Table 8), equivalent map of the study area (Figure 9), and tectonic evidence confirming active tectonics in the basin. Additionally, the equivalent map of the region validates the influence of tectonics on topographic changes and consequently, the classification alteration of basin waterways. Hypsometric curves of all sub-basins indicate youthful conditions on the surface of the Jajrud Catchment. Despite variations in the values of the studied indices, the averages indicate the prevailing influence of active tectonics in the area and the basin's location in youthful conditions.

3.The upper part of the slope experiences imbalance due to initial fault rupture and accumulation of moraine at the terminal moraine cirque, leading to increased weight and slope imbalance. Landslides commonly occur in the study area due to the alternation of hard and soft beds. The following outcomes were observed based on the examined evidence: 1) The path of the Jajrud River changed due to the flow of the landslide mass; 2) The formation of a lake behind the landslide mass was primarily influenced by factors such as a narrow valley width (450 m), large volume of the landslide mass, landslide intensity, size of landslide sediments, and low shear strength of the Jajrud River. The gradual drainage of the lake in the direction of the Jajrud River resulted in the creation of a shear surface in the landslide mass at each stage. A comparison of the terrace surfaces reveals a direct relationship in this process. although there are variations in thickness and volume of the terrace masses. These differences are influenced by the height and volume of the landslide dam and the stability of the lake over time. Consequently, the deposition of alluvial sediments on the lake terrace corresponds to the timing of the landslide dam rupture and lake drainage. The surface topography of the terrace sequences indicates that the tallest terrace is the youngest, contrary to the usual pattern observed in terrace sequences.

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