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Landslide Hazards Zonation Using the Overlap Index and AHP Method (Case Study: Sattarkhan Dam Watershed)

Somayeh, Nemati*, Naser, Abdi
Department of Geology, Ahar Branch, Islamic Azad University, Ahar, Iran
*)Corresponding Author: Somaye_6966@yahoo.com
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Abstract:
Sattarkhan Dam is constructed on Aharchai Stream in 15 km west of Ahar in East Azerbaijan province. Considering the susceptibility of the dam to landslide hazard, it is critical to determine factors effective on such natural phenomena in this area. Different methods are applied to identify places with high landslide susceptibility in order to prevent and reduce causalities of such natural phenomena. In this investigation, two methods including Overlap Index and Analytic Hierarchy Process (AHP) are implanted for landslide hazard zonation. In this regard, first, the map of landslide occurred in the area was prepared using the available landslide occurrence maps, images, and field studies. Next, the thematic maps and then the associated susceptibility maps were prepared in GIS using eight effective factors including lithology, slope angle, slope direction, land use, average monthly rainfall, distance from faults, distance from streams, and elevation. The role of these factors was divided into several classes and the weight of each class was assigned to the corresponding raster layer and classes of each layer. Based on the obtained results, the study area was divided into four zones with different landslide occurrence hazards by overlapping different layers in GIS environment and preparing landslide occurrence hazard. The data evaluation and processing show that around 38% and 4% of the area is located in zones with high and very high landslide occurrence hazard, respectively. The result also reveals the susceptibility of the study area to such natural phenomenon, which must be considered in the dam lifetime for preventing damages and causalities.

Keywords: zonation, Sattarkhan Dam watershed basin, landslide, Overlap Index, AHP

1. Introduction

Landslide is defined as the mass movement of rock or soil naturally due to the effect of different factors such as gravity in steep slopes (Ghobadi 2011) and (Shabani et al. 2016). Hazard zonation of landslides is generally defined as dividing the study area into zones with almost similar hazard levels (Memarian 2014) and (Hatamifard et al. 2014). The study area is located on Aharchai Stream in 15 km west of Ahar in East Azerbaijan province (northwest of Iran). The study area (Sattarkhan Dam watershed) is adjacent to Songoon copper mine in the north, Goradaraq village, Masqaran village in the east, and Alaviq village in its west. The watershed is located in 110 km of Tabriz and is limited within the latitudes 38° 23′ 31″N and 38° 41′ 23″N and longitudes 46° 34′ 16″E and 47° 01′ 32″E. The surface area of the study area is 60,188 hectares (601.8 km^2). The average elevation of the study area is 2,062 m.a.s.l with its highest and lowest points being 2,760 and 1,380 m.a.s.l, respectively. As shown in Fig. 1 and Fig. 2, the average annual precipitation and temperature of the area are 320 mm and 10.6, respectively; indicating its semiarid cold climate.

2. Materials and methods

2.1 Research materials

2.1.1 Topography maps

For topography and geomorphology evaluation, digital elevation map (DEM) preparation, slope angle estimation, and geographical position of the watershed and its precise zonation and drain network evaluation, we used 1:25,000 topography maps of the study area (Table 1).

2.1.2 Geological maps

To investigate geological characteristics and the lithology of the study area and the relative strength of lithological units, the following 1:100,000 geology maps of the study area were used:

1. The 1:100,000 quadrangle map of Ahar (prepared by Geological Survey and Mineral Explorations of Iran, 1988).
2. The 1:100,000 quadrangle map of Khajeh (prepared by Geological Survey and Mineral Explorations of Iran, 2006).
3. The 1:100,000 quadrangle map of Varzaghan (prepared by Geological Survey and Mineral Explorations of Iran, 1992).

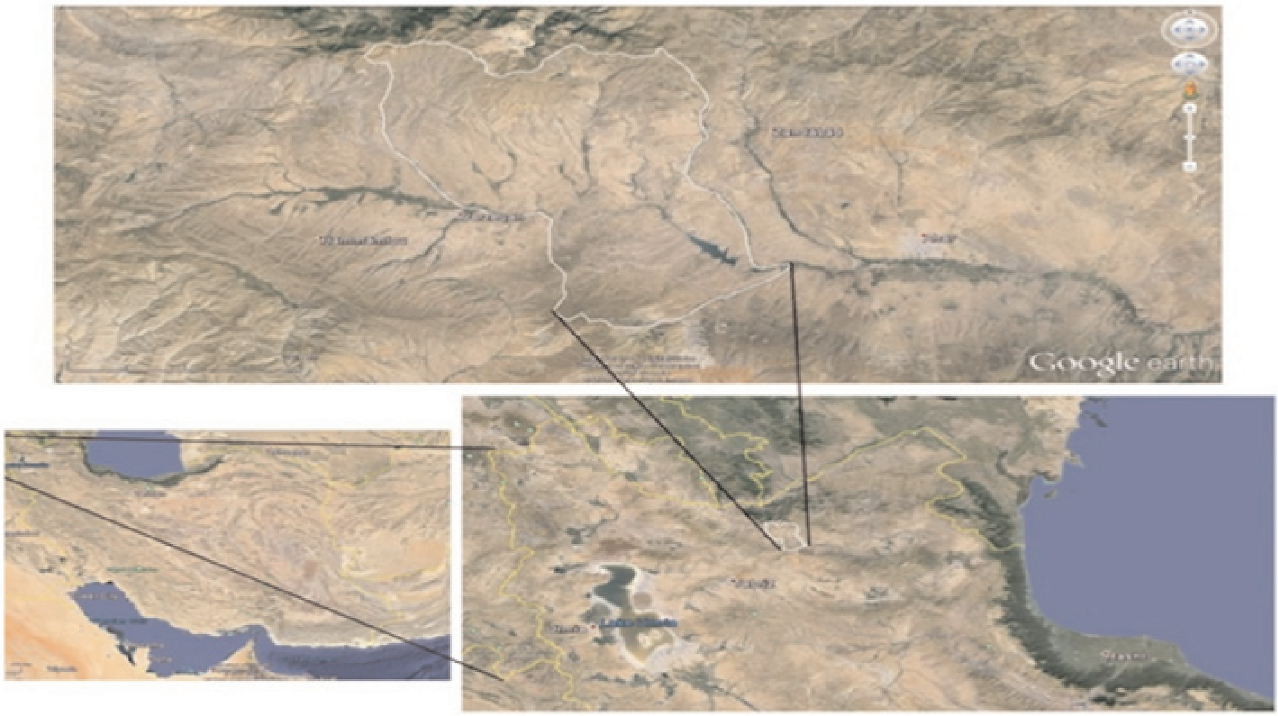

Figure 1. The satellite image of Sattarkhan Dam watershed

2.1.3 Specialized software

The software packages utilized in the present research are ArcGIS 10, SPSS 23.0 (to plot various diagrams), Expert Choice 11 (for AHP weighting of the parameters), and Google Earth Pro 7.1 to study satellite images.

2.2 Research method

In this study, first, the map landslides occurred in the study area was prepared using the aerial photos and field surveys. Next, to prepare thematic maps in GIS environment and prepare susceptibly map, 8 controlling parameters were selected based on their distance from the studied watershed. These parameters are slope angle, aspect, land use, average annual precipitation, distance from faults, distance from streams, and elevation. After selecting these parameters, each parameter was categorized into several classes. To prepare layers of different factors and thematic maps in GIS environment, we used topography and geology maps, satellite photos, precipitation data, aerial photos, and field surveys. The thematic maps of slope angle and elevation were prepared in RASTER format directly from DEMs of the study area. In comparison, the thematic maps including a map of faults, distance from faults, distance from streams, lithology, and land use were prepared in vector format and then rasterized to mix the layers.

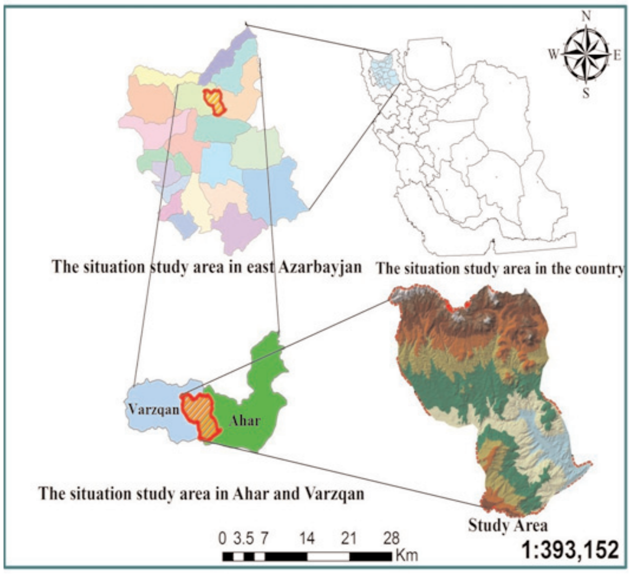

Figure 2. The geographic setting of Sattarkhan Dam watershed.

Afterward, the weight values were assigned to the raster layers and their corresponding classes through the analytic hierarchy process (AHP) in Expert Choice software. In the next step, based on the overlap of the thematic maps, the susceptibility map of the study area was prepared using the obtained weights. To evaluate the reliability, accuracy, and precision of the prepared model, the obtained results were validated using the map of an active landslide in the study area.

3. Discussion

Considering the high susceptibility of the study area to landslide and presence of numerous landslides in the study area, detecting factors effective in this phenomenon seems to be an essential requirement. For this purpose, we made an attempt to detect and investigate landslides occurred in the study area and

Table 1. Number topography maps of the study area.

NO.	1:25,000 sheet number	1:50,000 sheet number	Status	Executer
1	5366-4-1	5366-4	Completed	Iran National Cartographic Center
2	5366-1-4	5366-1	Completed	Iran National Cartographic Center
3	5366-1-1	5366-1	Completed	Iran National Cartographic Center
4	5367-3-3	5367-3	Completed	Iran National Cartographic Center
5	5367-3-2	5367-3	Completed	Iran National Cartographic Center
6	5367-2-3	5367-2	Completed	Iran National Cartographic Center
7	5367-2-2	5367-2	Completed	Iran National Cartographic Center
8	5367-3-4	5367-3	Completed	Iran National Cartographic Center
9	5367-3-1	5367-3	Completed	Iran National Cartographic Center
10	5367-2-4	5367-2	Completed	Iran National Cartographic Center

extract parameters importance is slide triggering. In a general view, factors effective in landslide occurrence are classified into three classes: geological causes; geomorphological causes, and human causes (Ariapoor et al. 2015). Each of mentioned causes affects landslide occurrence in different ways. Studying factors effective in landslide occurrence and to prepare susceptibility map of the study area, 8 controlling factors were extracted based on their relationship with landslide occurrence in the study area; i.e., lithology, slope angle, aspect, land use, average annual precipitation, distance from faults, distance from streams, and elevation.

3.1 Factors effective in landslide occurrence

3.1.1 Lithology

Because lithology changes lead to a difference in strength and permeability of rocks and soils, it is widely accepted as a landslide-triggering parameter. In this study, the basic information used for the preparation of vector geology map was extracted from the 1:100,000 map of Geological Survey of Iran and Mainlining Explorations. To prepare such a map, all rock groups (i.e., igneous, metamorphic, sedimentary, and loose sediments) were classified into 10 strength groups with respect to their strength, physical, formation conditions, and texture (Fig. 4). Eventually, the area of each landslide occurred in each rock unit was estimated (Fig. 3 and Table 2).

3.1.2 Slope angle

One of the main parameters for slope stability analysis is slope angle (Jahani et al. 2015) and (Bogaard 2012). Because slope angle directly affects landslide occurrence, it is majorly used in landslide hazard zonation (Zamanipoor et al. 2015). Slope angle controls the velocity and flow of groundwater and the moisture content of soil. Moreover, when slope angle is increased, shear stress in the surface of disconnected soils is generally increased. The slope angle values in the study area, which vary between 0.01 and 35.5°, can be classified into five classes (Fig. 6): a) very gentle (0.01 to 4°); b) gentle (4 to 12°); c) average (12 to 24°); steep (24 to 32°); and scarp (>32°). The results show that about 63% of the landslides occurred within slope angles of 4 to 12° (Fig. 5).

3.1.3 Aspect

Because aspect is related to parameters such sunlight absorption, drying winds, and rainfall, it is consid-

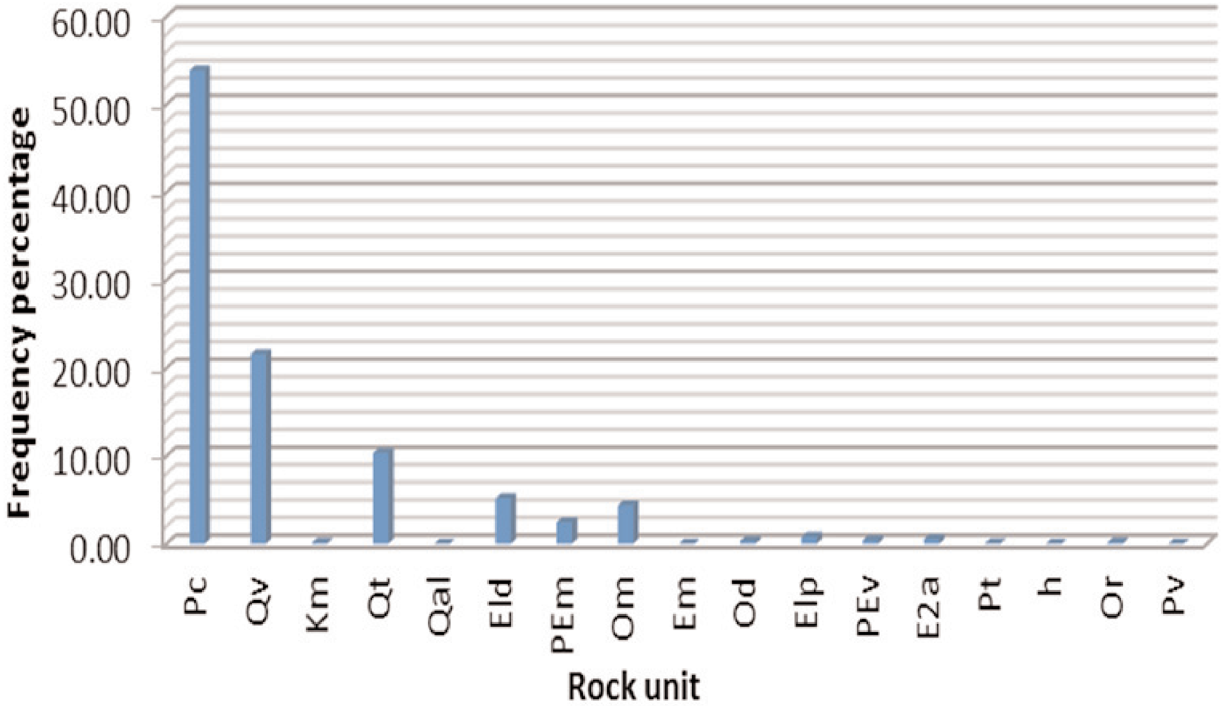

Figure 3. Frequency of landslides for different geological units.

Table 2. Susceptibility classification of rock and soil units in the study area.

Abbreviation	Lithology description	Class name	class
Pc	Conglomerate and siltstone	Extremely weak	9
Qv	Alkaline andesite and basalt	Weak	7
Km	Marl, molasses, and sandstone	Very weak	8
Qt	Silt, conglomerate, and travertine	Extremely weak	9
Qal	Quaternary alluviums	Separate and completely loose	10
Eld	Dacite, trachi andesite, and ignimbrite	Average	5
PEm	Marl, limestone, and sandstone	Weak	7
Om	Micromonsonite and the related trachi andesite dykes	Weak to average	7
Em	Marl and nomolite limestone	Weak	7
Od	Brecciate dacite	Average	5
Elp	Mega porphyritic lalite	Strong to average	4
PEv	pyroxene Andesite, analcim tephrite, and trachyte	Strong to average	4
E2a	Lathite and andesite	Strong to average	4
Pt	Trachy andesite dome	Strong	3
H	Hydrothermal alteration zone	Average	5
Or	Rhyolite dome and ignimbrite	Strong	3
Pv	Pyroclastic conglomerate	Very strong	2
E2l	Lathite and ignimbrite	Very strong	2
Pi	Ignimbrite	Very strong	1

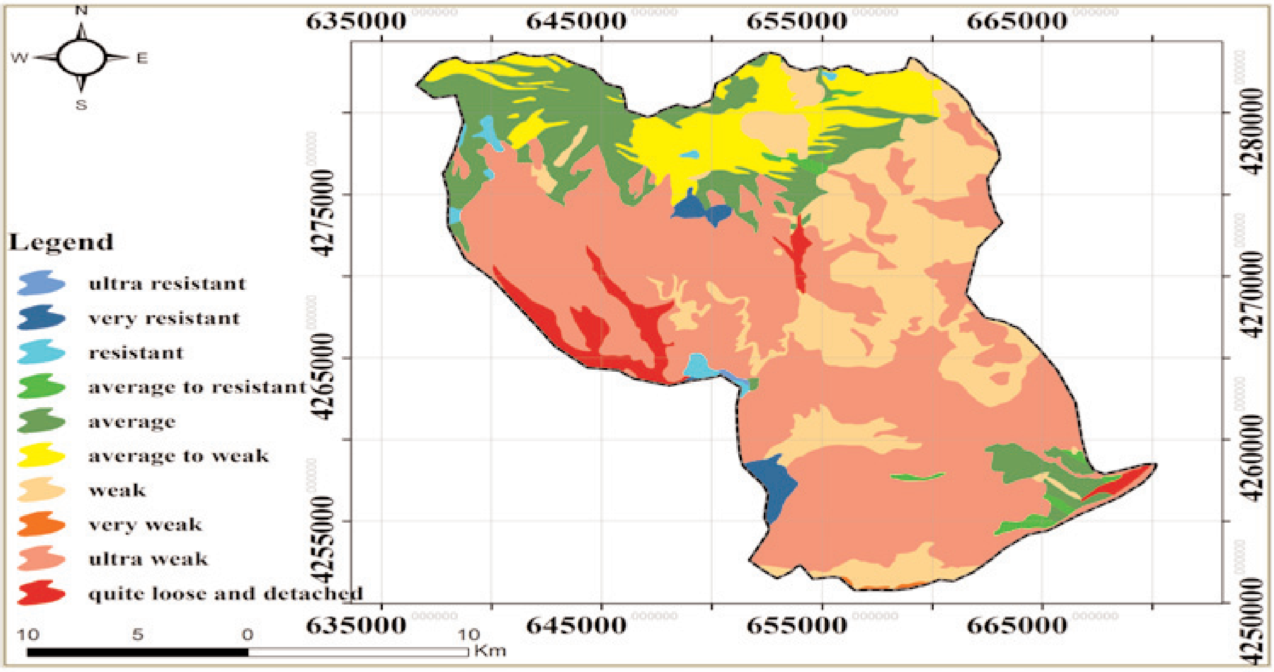

Figure 4. Susceptibility map of the classified lithological units existing in the study area.

ered as an important factor in landslide susceptibility map preparation (Fathi and Sadri 2015). Based on this parameter, the study area was categorized into nine classes. Based on an analysis of aspect and the occurred landslides, it was revealed that the maximum and the minimum number of landslides have occurred in southeast and northwest directions, respectively. Fig. 7 and Fig. 8 present the frequency percentage of the corresponding these nine aspect classes.

3.1.4 Land use

The effect of soil cover on slope stability can be explained by hydrogeological and mechanical effects. In this regard, cover serves as a protective barrier and reduces its susceptibility to erosion, slid-

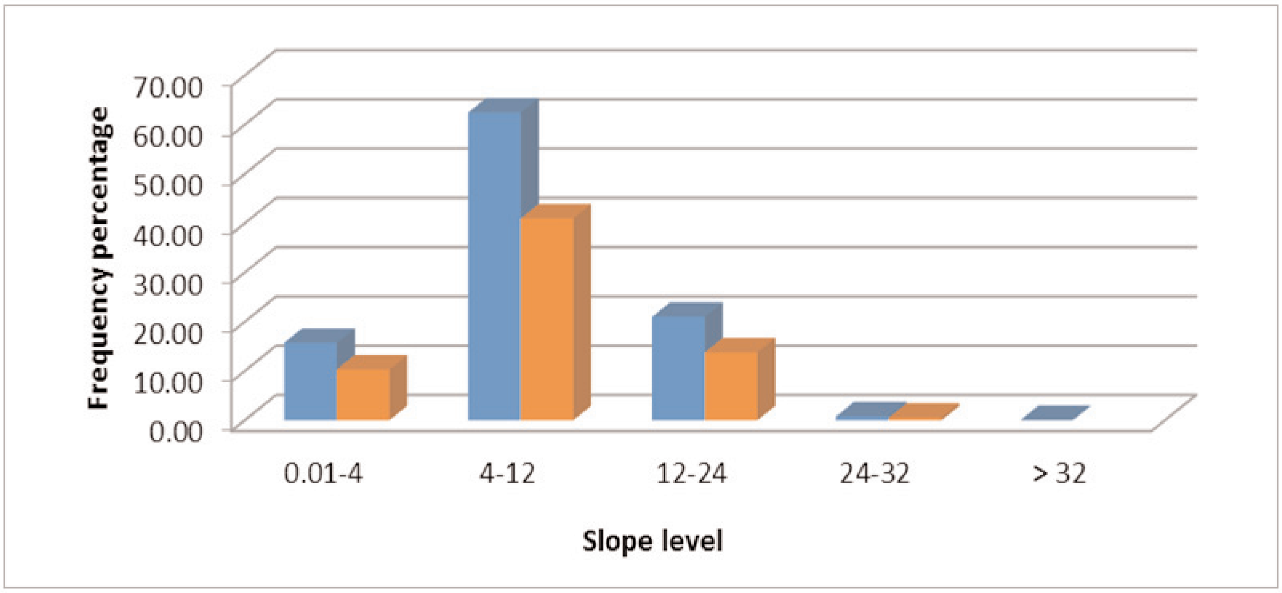

Figure 5. Surface area and frequency percentage of landslides for different slope angles.

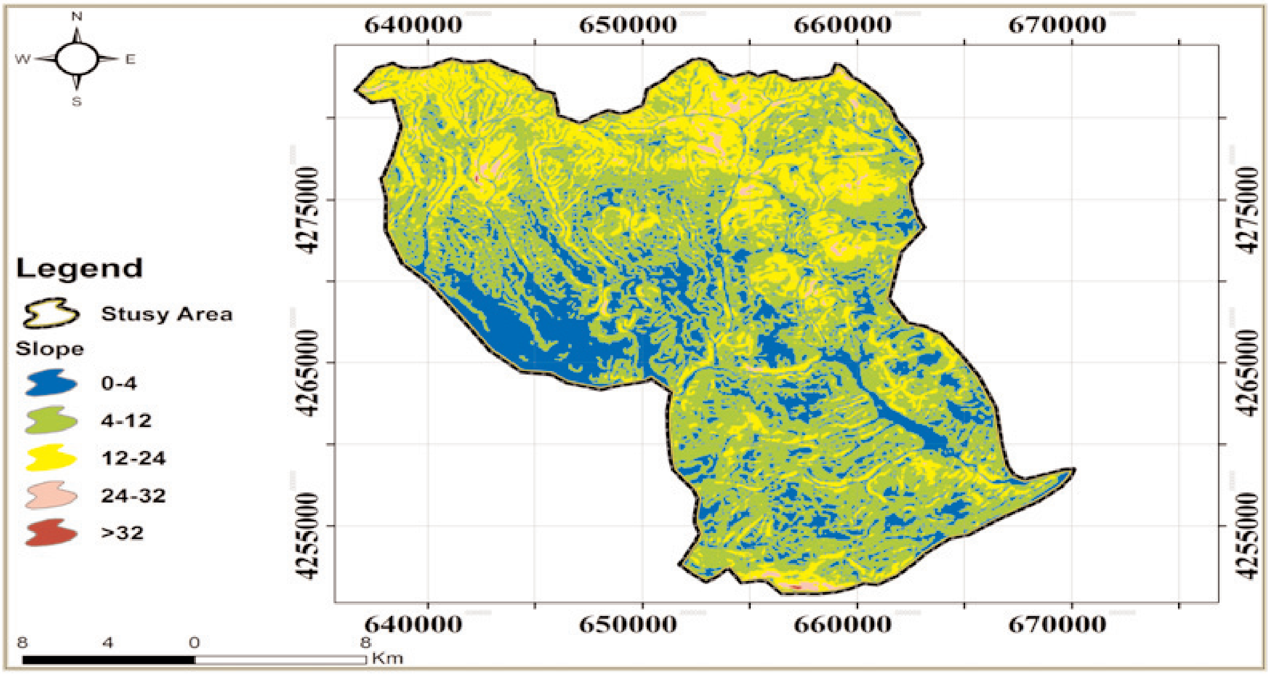

Figure 6. Classification map of topographic slope angle in the study area.

ing, and rainfall water absorption. Vegetation considerably affects soil hydrology by increasing interception, penetration, and evapotranspiration. Interception and evapotranspiration reduce the amount of water which reaches or stored in the soil. Soil cover does not play a critical role during the heavy short rainfalls, unlike the long heavy rainfalls water. Roots increase soil permeability and, in turn, their seepage and hydraulic conductivity, leading to water accumulation in the soil during two periods of short-term and long-term rainfalls. Vegetation also affects mechanical properties of the slopes through soil stabilization and loading on the slope. Also, it results in the enhanced strength of soil because of its stabilization by plant roots, which reduce landslide occurrence rate. Through the land use map prepared using the satellite and aerial photos, the study area was classified into eight land use classes. The results

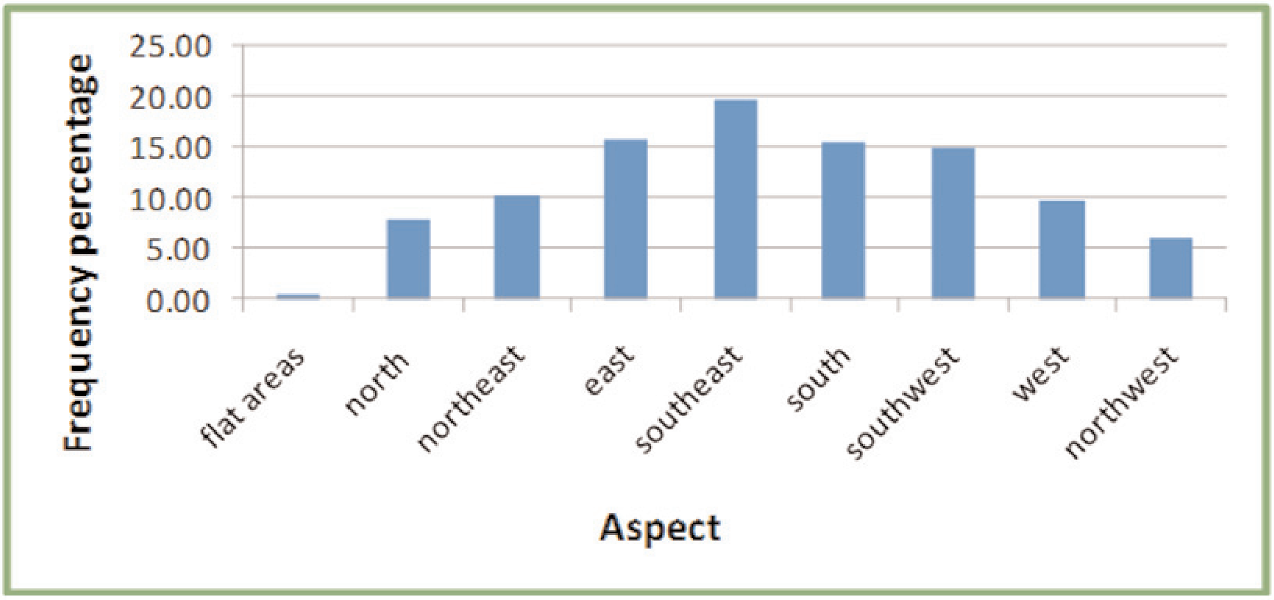

Figure 7. Frequency percentage of occurred landslides for different aspect classes.

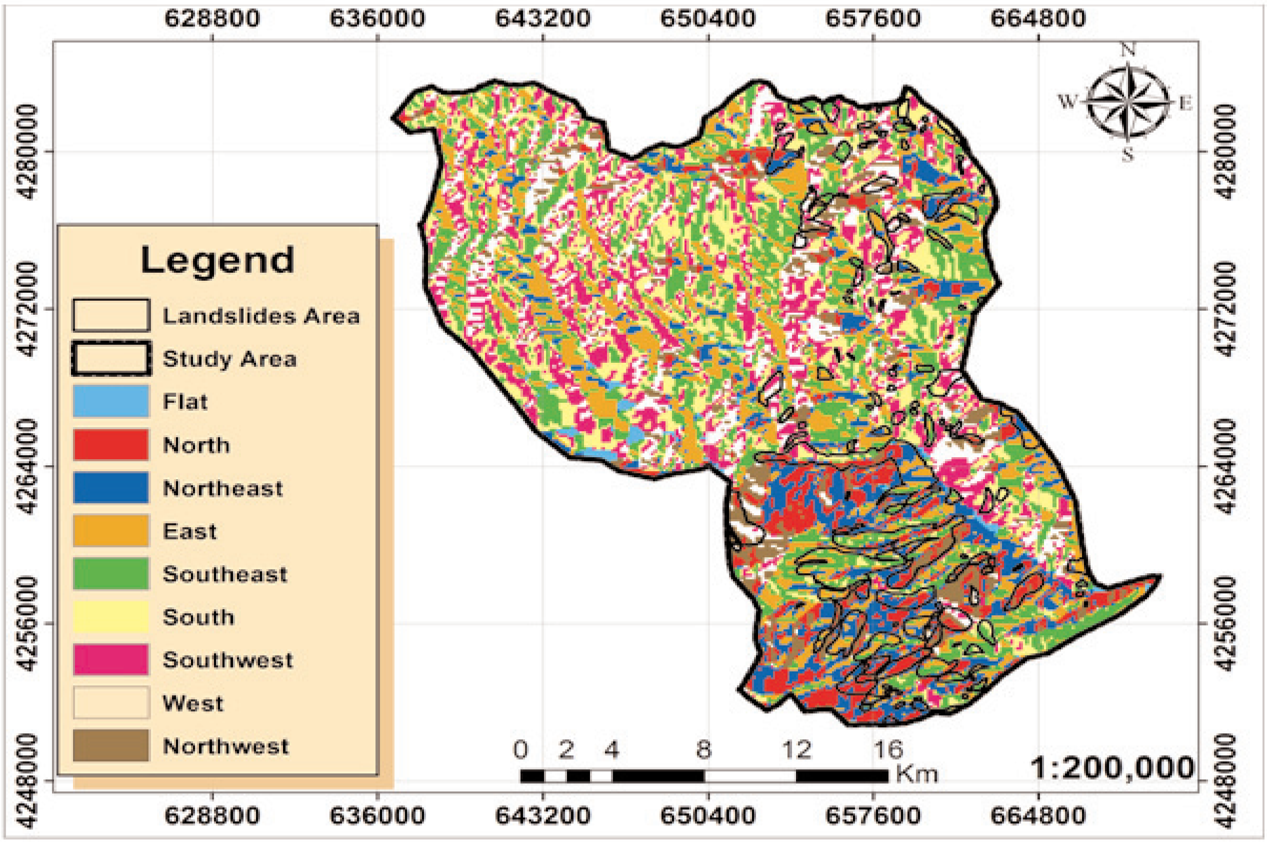

Figure 8. Classification map of topographic aspect in the study area.

show that the slides mainly occur in agricultural and dry farming lands (Fig. 9 and Fig. 10).

3.1.5 Rainfall

To study the effect of rainfall on landslide hazard increase, rainfall data of 22 stations within the case study and its surrounding areas were collected and analyzed. The data show that rainfall values have an almost similar pattern for the entire study area and indicate a slight change with elevation variations and reach 500 mm at the heights. The thematic map of this factor in the study area, then, was prepared and

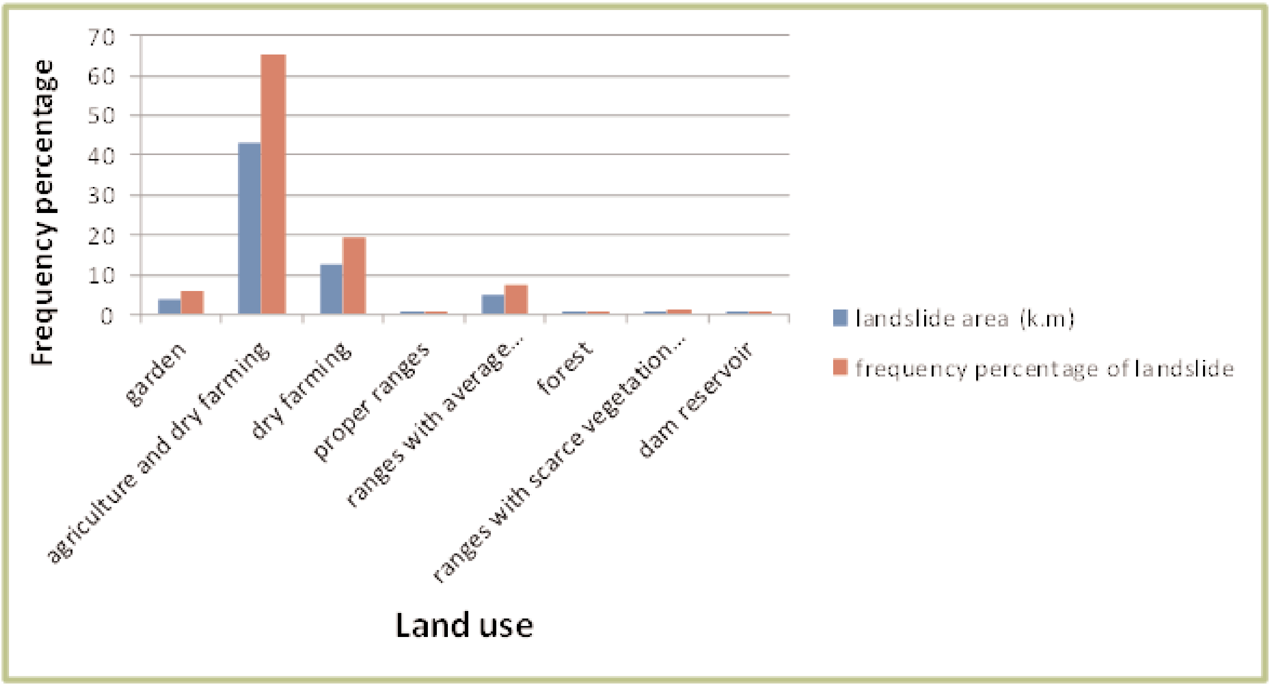

Figure 9. Area and frequency of landslide occurrence in lands with different uses.
(Dam reservoir; ranges with scarce vegetation cover; forest; ranges with average vegetation cover; proper ranges; dry farming; agriculture and dry farming; garden)

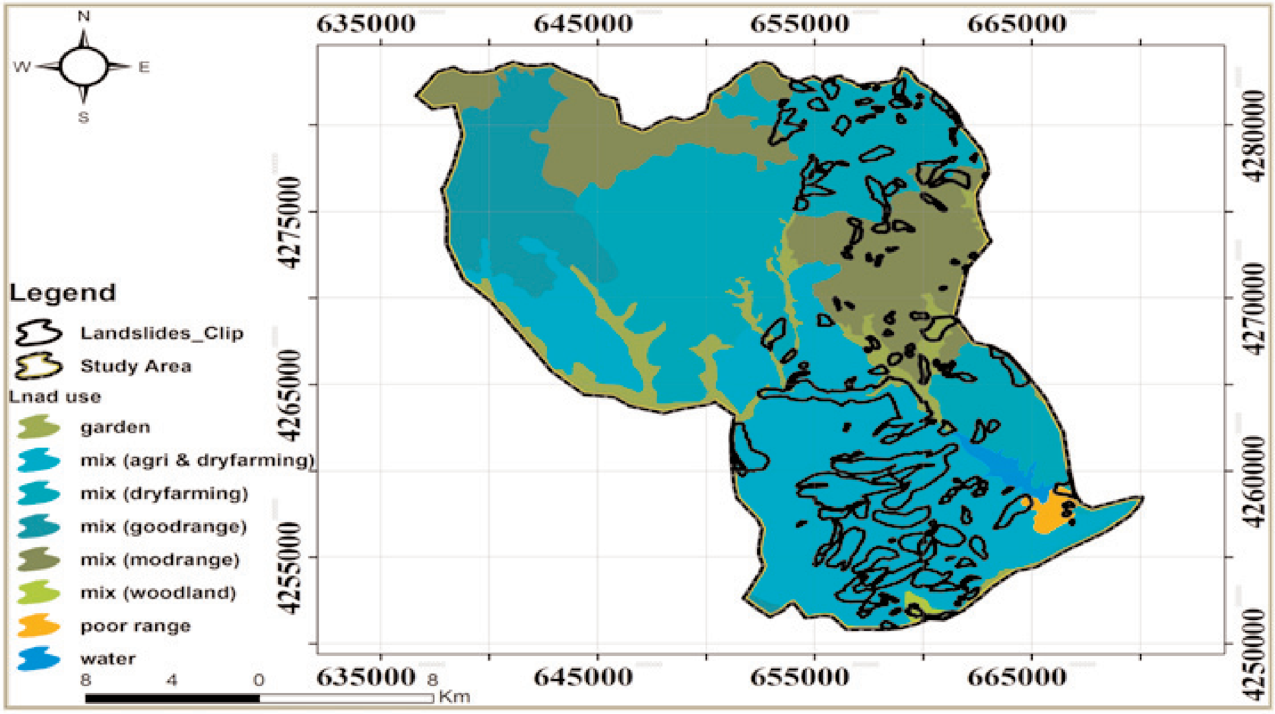

Figure 10. Land use map of the study area.

categorized into seven classes with different average monthly rainfall (Fig. 11). Potentially, the higher rainfall rate is a positive factor in landslide triggering. The effect of rainfall has been proved in both water moisture increase (leading to the increased slide potential) and as a slide-triggering factor (under heavy and long rainfall).

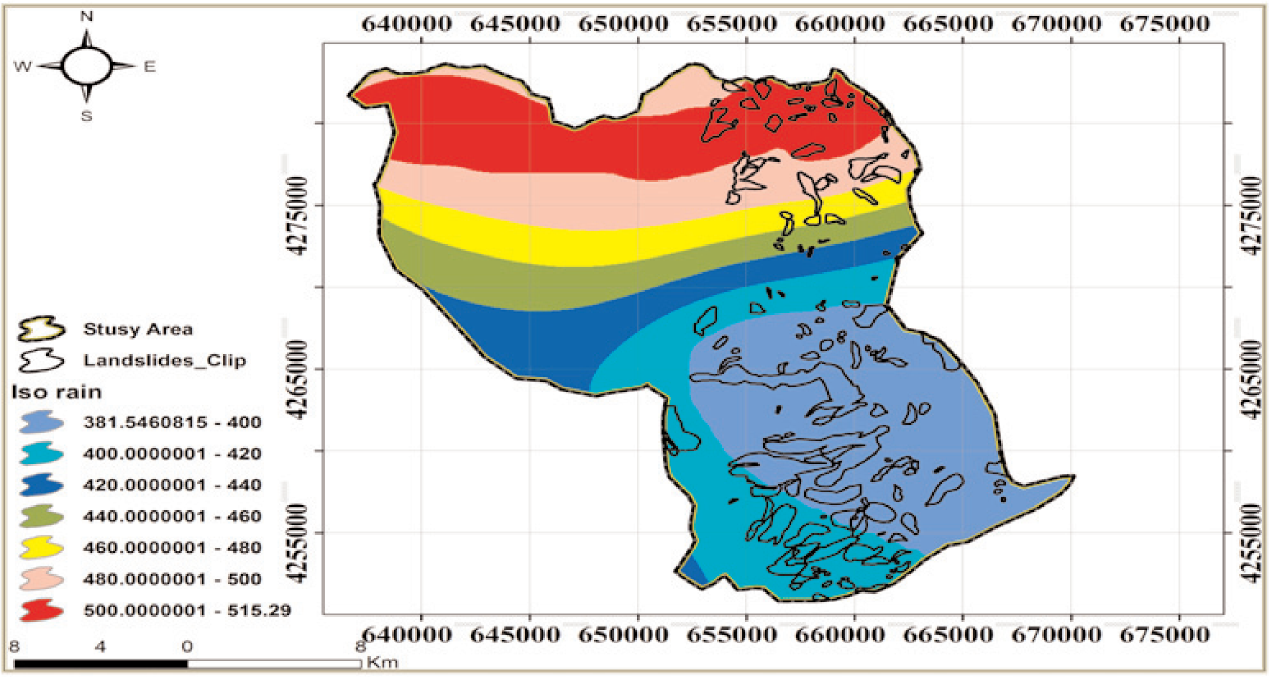

Figure 11. The map of isorain zones in the study area (in millimeters).

3.1.6 Distance from streams

The distance of slopes from drainage features directly affects their saturation level and stability. Drainage pattern poses negative effects on slope through their erosion or saturating its toe, leading to the raised water table (Mansoori et al. 2015) and (Saha et al. 2013). The main streams in the study area were divided into six zones with offsets of 0-200, 200-400, 400-600, 600-800, 800-1000, and above 1000 m (Fig. 12). Generally, an increase in the distance from drainage pattern leads to the reduced landslide hazard. According to our surveys, the maximum number of landslides in the study area occur in the offset distance of 0-200 m (Table 3).

3.1.7 Distance from faults

The faulting areas intensify landslide occurrence potential through creating steep slopes, weakened shear zones, and fractured rocks. Landslide occurrence is the result of the development of some low-preamble rocks overlain by highly permeable rocks. This feature is typically detected by the creation of spring opening. In this work, the main faults and thrusts of the study area were extracted, digitalized, and presented as a vector layer. Then, using this

Table 3. The area and frequency percentage of landslides occurred in different offsets of streams.

Offset (m)	Overall landslide surface area	Accumulative landslide frequency
0-200 m	12.3	31.44%
200-400 m	8.9	22.71%
400-60 m	7.17	18.33%
600-800 m	5.69	14.53%
800-1000 m	5.08	12.97%

layer, the distance function was represented along the structural discontinuities and six buffer zones with a distance of 400 m were created on each discontinuity (Fig. 13). According to our surveys, the structural phenomena have a considerable effect on landslide occurrence, as an increase in the distance from tectonic lineations leads to the reduced landslide occurrence hazard.

3.1.8 Elevation

Height variations affect weathering of rock units as an increase in elevation and water content of slopes accelerate chemical reactions, which consequently lead to the intensified weathering and the increase in landslide occurrence hazard. Based on the height variation ranges in the study area, the thematic map of the elevation parameter was divided into eight classes

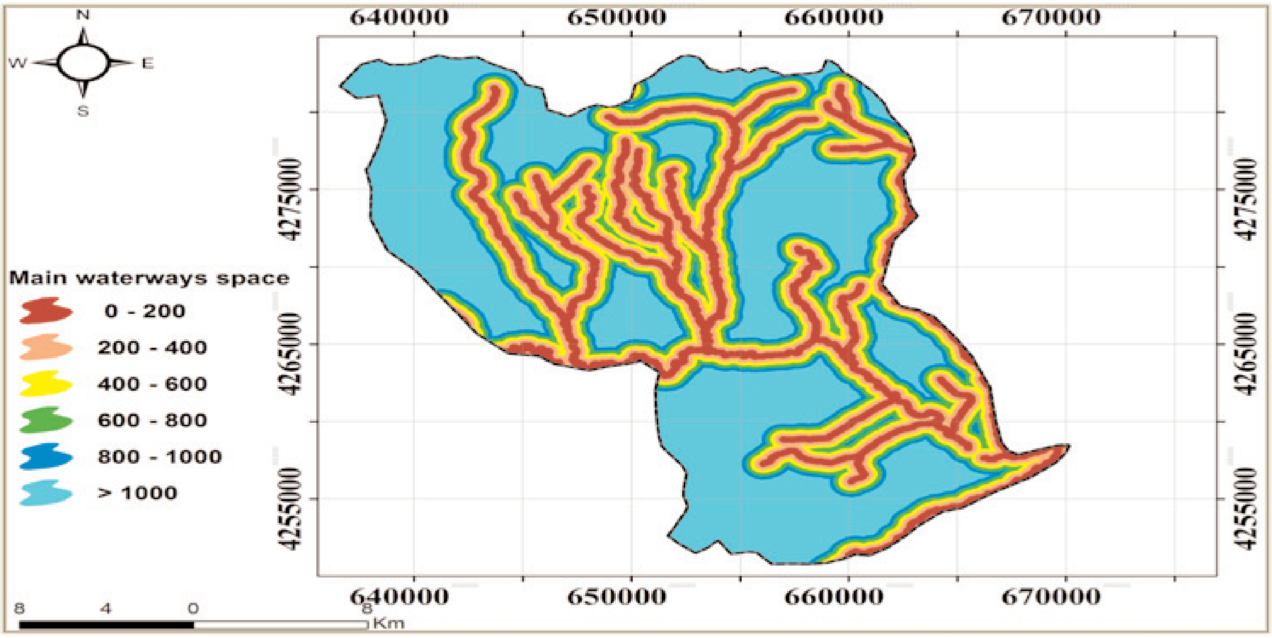

Figure 12. Stream offset map of the main streams in the study area (in meters).

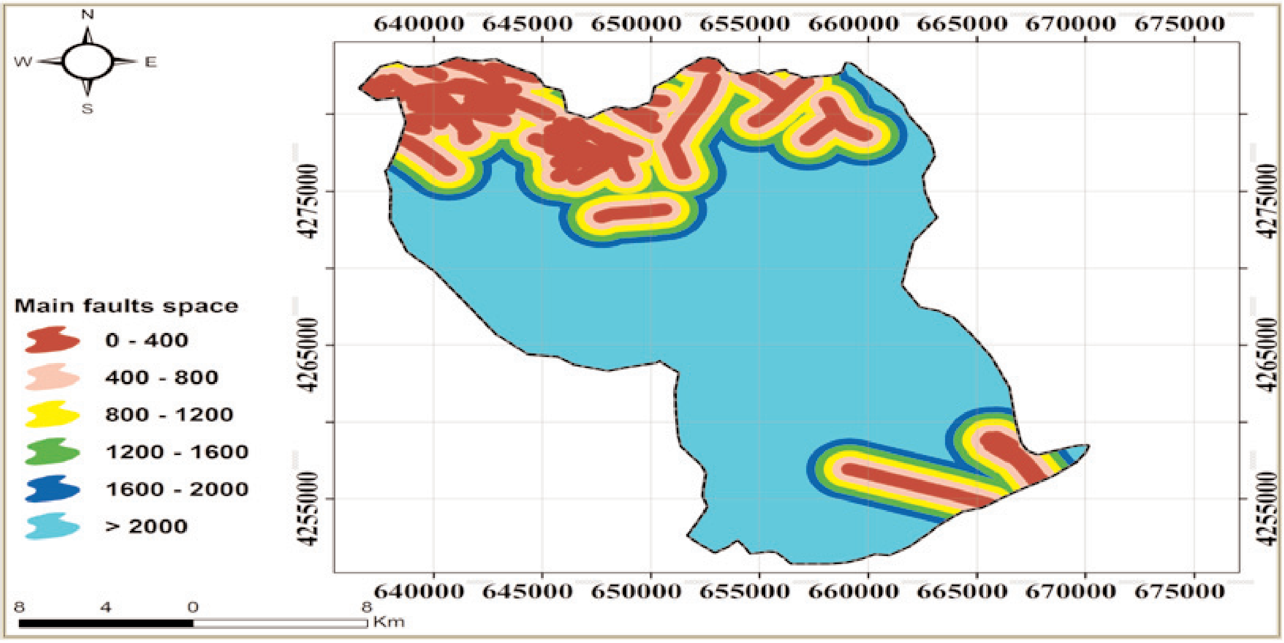

Figure 13. Offset map of main faults in the study area (in meters).

with 200 m height ranges (Fig. 14). The results show that about 65% of the slides have occurred within height range 1,550-1,950 m (Table 4).

3.2 Occurred landslides

After preparing information layers of factors effective in landslide occurrence, the distribution map of these landslides in the study area was prepared using the 1:20,000 aerial photos and Google Earth satellite maps of Sattarkhan Dam watershed (Fig. 15). Moreover, to control accuracy of the prepared map, we made some field trips in the study area. Fig. 16 and Fig. 17 illustrates some images from the detected landslides in the studied watershed.

3.3 Integration and modeling

Integration of information layers is among the key parts in landslide hazard zonation, as applying an inappropriate method for data integration may lead to an erroneous result. For weighting the information layers, two overlap index and AHP methods were applied in the present work.

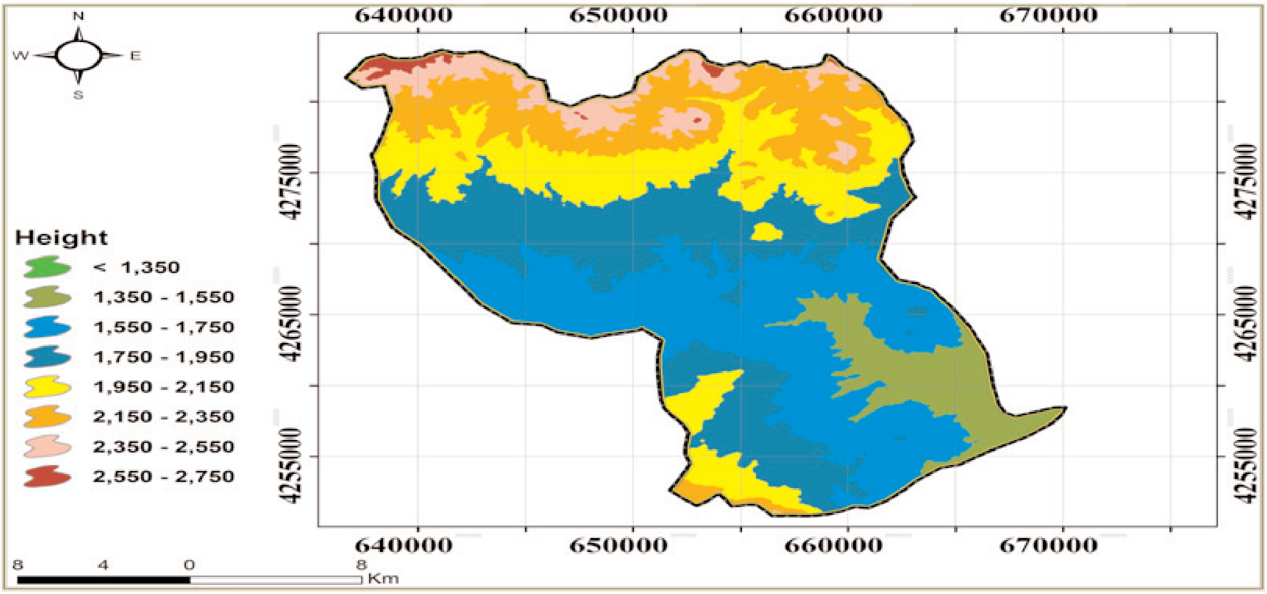

Figure 14. Height zonation map of the study area.

Table 4. Area and frequency percentage of slides occurred with different height ranges.

Elevation (m)	Landslide area	Frequency percentage	Accumulative frequency
< 1350 m	0.00 km^2	0.00%	0.00
1350-1550 m	8.93 km^2	13.58%	13.58
1550-1750 m	27.28 km^2	41.46%	55.04
1750-1950 m	16.14 km^2	24.52%	79.56
1950-2150 m	6.07 km^2	9.22%	88.78
2150-2350 m	5.70 km^2	8.66%	97.44
2350-2550 m	1.54 km^2	2.33%	99.78
2550-2750 m	0.15 km^2	0.22%	100.00

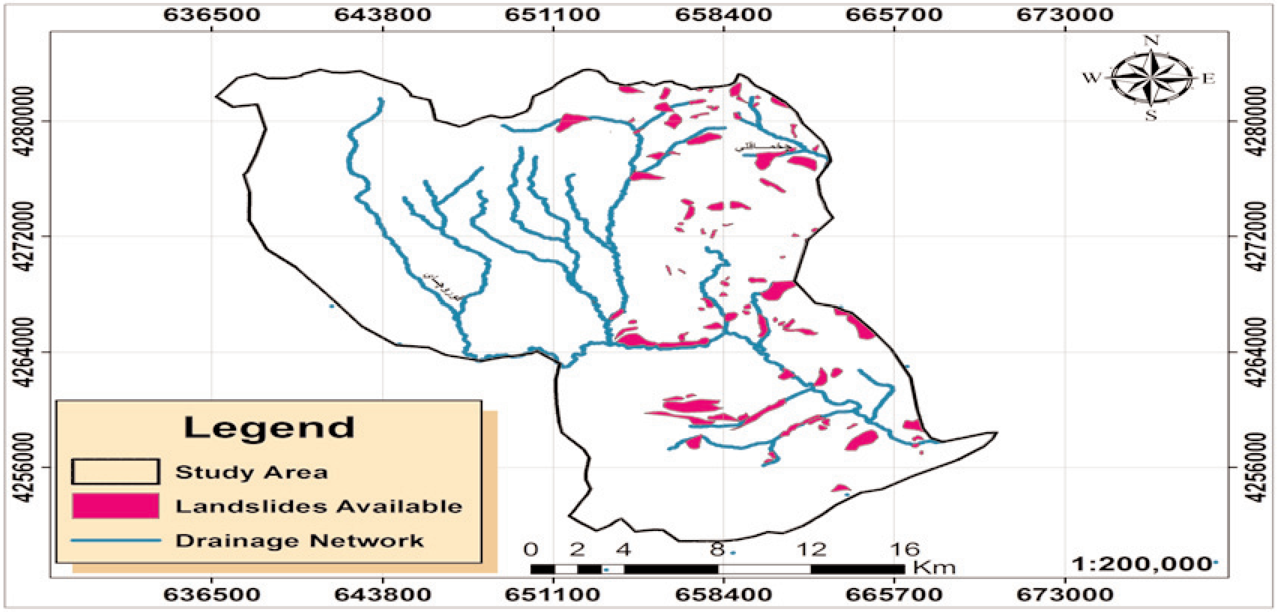

Figure 15. Distribution map of landslides occurred in Sattarkhan Dam watershed.

Figure 16. A landslide occurred in the study area (viewed from the south).

Figure 17. A photo from Sattarkhan Dam watershed (viewed from the south).

3.3.1 Overlap index method

In this approach, weighting is performed based on the accuracy and precision of different layers and their data collection validity. Each information layer contains different scores and the layer itself has a special independent value called as weight. The score value and weight of layers are determined by an expert. Eventually, to integrate the data and prepare zonation map, the following equation is applied:

$$\bar{S} = \frac{\sum_i^n s_j W_i}{\sum_i^n w_i} \quad (1)$$

where, S is the ultimate score of each pixel for the ith output map, wi is the weights applied to the ith output map, and Sij is the ith score of ith output map. Finally, after calculating all pixel values (the summed weight of all layers multiplied to their corresponding score), the ultimate output is divided by the summed score of different information layers, and the final score is reported as S for each pixel. As shown in Table 5, the weight and score of each layer varies between 1 and 10.

3.3.2 Analytic hierarchy process (AHP)

Applying AHP method, first, factors effective in landslide occurrence were selected and each factor was divided into several classes. Next, the weight values were assigned to the raster layers (factors) and

Table 5. The weight of different information layers.

Layer name	Lithology	Slope angle (°)	Aspect	Land use	Precipitation	Distance from streams	Distance from fault	Elevation	Total
Layer weight	10	9	6	10	7	6	7	5	60

Table 6. The area and percentage of different slide zones in the study area.

Landslide occurrence probability	Area (km2)	Area percentage
Very high	0.24 km2	0.04%
High	226.67 km2	38.17%
Average	295.95 km2	49.84%
Low	70.98 km2	11.95%

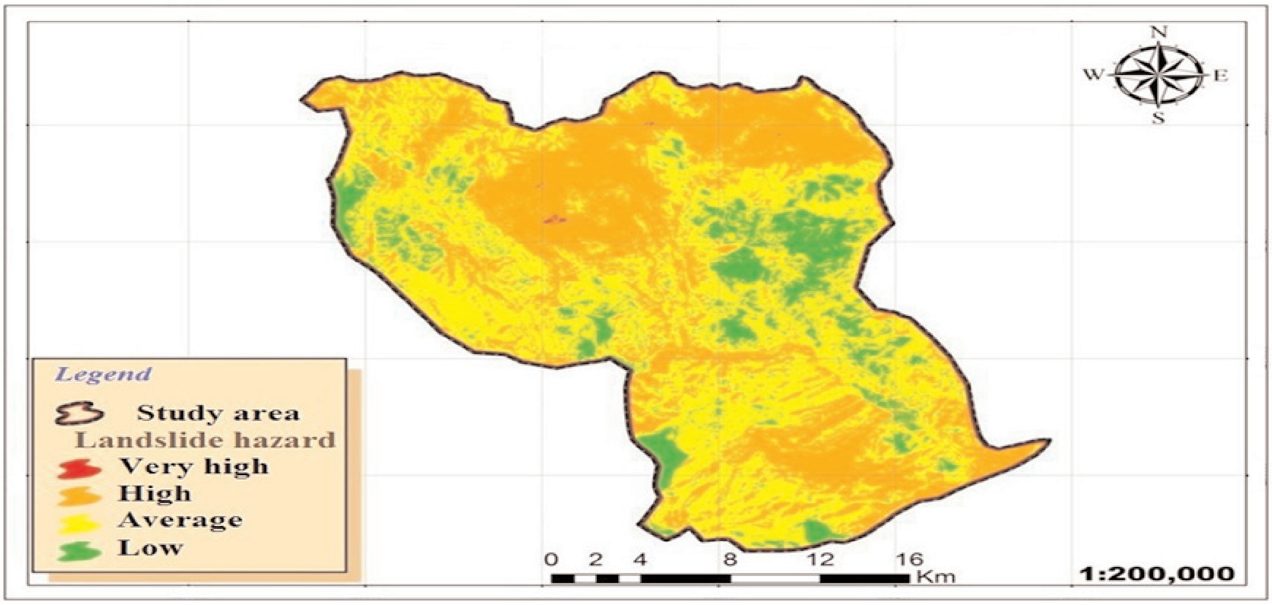

Fig 18. Zonation map of landslide hazard in the study area.

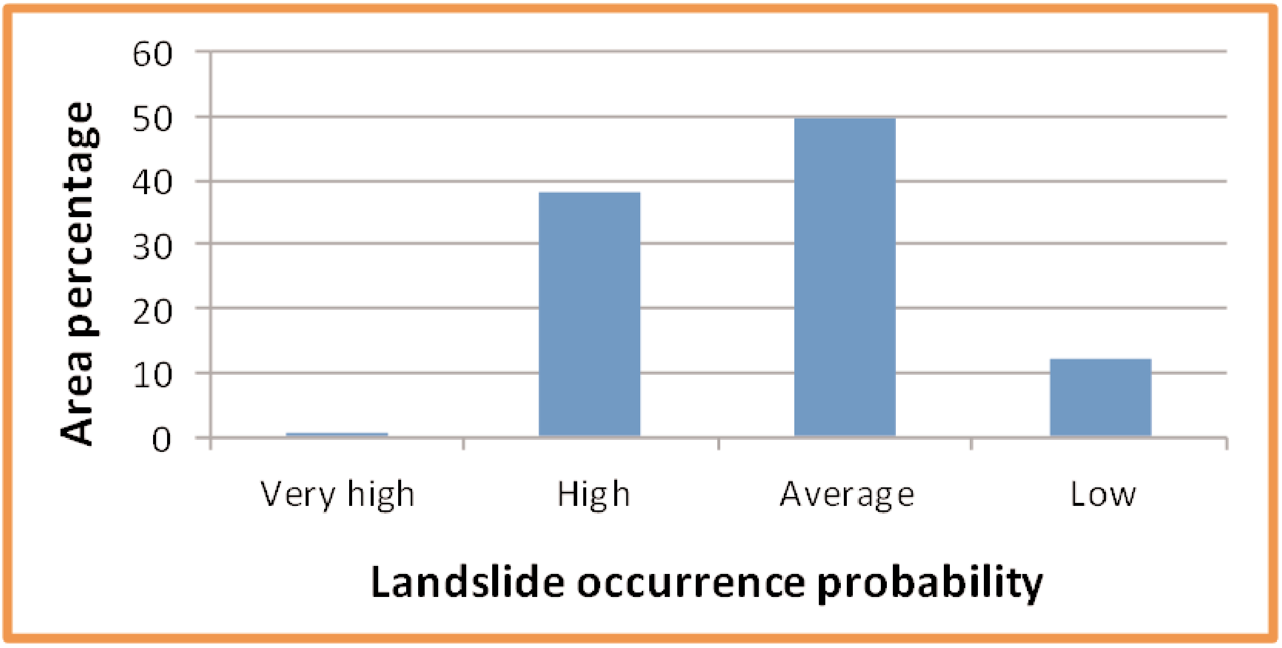

Fig 19. Area percentage of zones with different landslide occurrence probability in the Sattarkhan Dam watershed.

to corresponding classes these layers through AHP method. To prioritize the classes related to the layers effective in a landslide, first, this map was prepared in GIS environment and then area percentage of the occurred landslides for the corresponding classes was estimated. Hence, using this method prioritization is done based on the characteristics of the landslides occurred in the considered area and, thus, provides more accurate results. Eventually, by overlapping the thematic maps using "Raster Calculator" tool in GIS, the information layers of factors effective in landslide occurrence were detected and the susceptibility map of the study area was prepared using the obtained weights (Fig. 20).

(2) ("lithology" × 0.3129)+ ("slope" × 0.2289)+ ("fault" × 0.1737)+ ("river" × 0.1098)+ ("landuse" × 0.0733) + ("rain" × 0.0642) + ("height" × 0.0216) + ("aspect" × 0.0153) / 100

Examining the maps obtained by integrating different information layers of factors effective in landslide occurrence show that about 11.33% (67.90 km^2) of the study area is posed to a "very high", 23.92% to a "high", 23.55% of an "average", 35.84% to a "low", and 5.36% to a "very low" landslide occurrence hazard (Fig. 21). The results also show that the maximum share of the study area has a "low" landslide occurrence hazard. Because the probability of "low" landslide occurrence hazard is about 35%, it is recommended making the needed predictions for future plans and applying the necessary measures, prior to increasing this probability.

4. Conclusion

According to the susceptibility map of the study area (Sattarkhan Dam watershed):

1. The maximum share of watershed area (49.84%) is located in a zone with "average" and "low" landslide occurrence probability while its minimum share is posed to a "high" landslide occurrence hazard.
2. Among eight factors effective in landslide occurrence, slope angle, lithology, and land use (by the order of their appearance) have the highest control over landslide occurrence.
3. Studying the relationship between slope angle and landslide occurrence shows that the majority of slides occurred in slope angles between 4 and 12°.
4. Streams, which are the passage for water flow, contain a high volume of water during rainfall seasons and may lead to loosening and collapse of rock units and, eventually, landslide occurrence. Hence, the stream offsets might be considered as

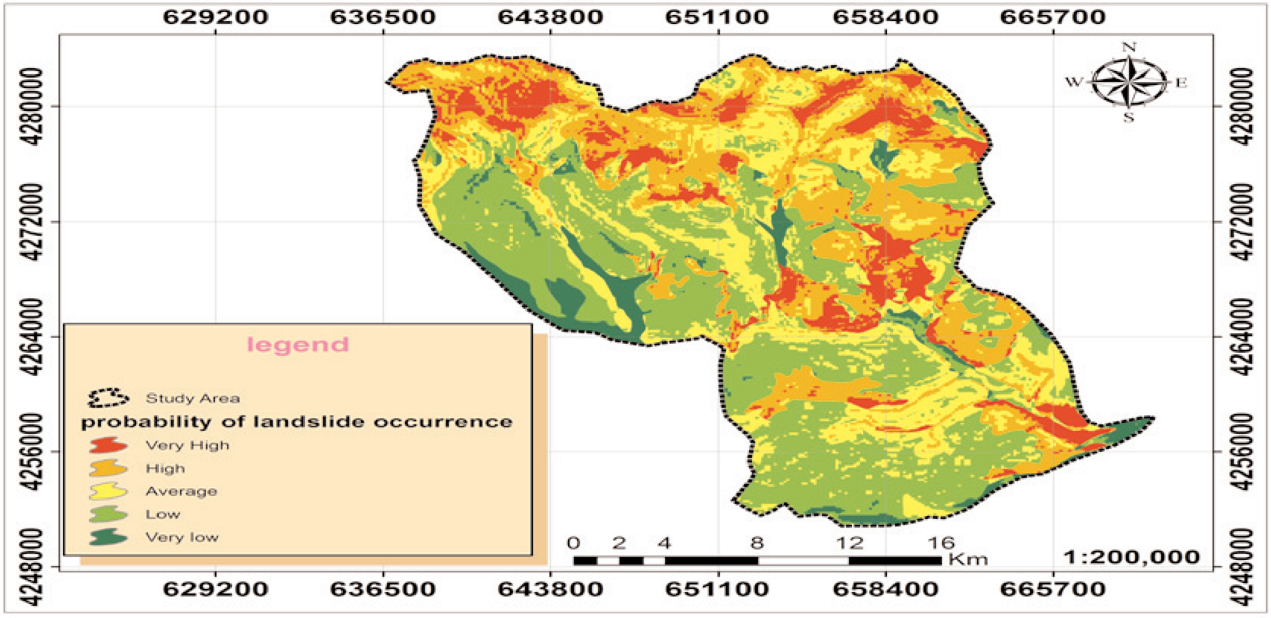

Figure 20. Zonation map of landslide occurrence probability in Sattarkhan Dam watershed.

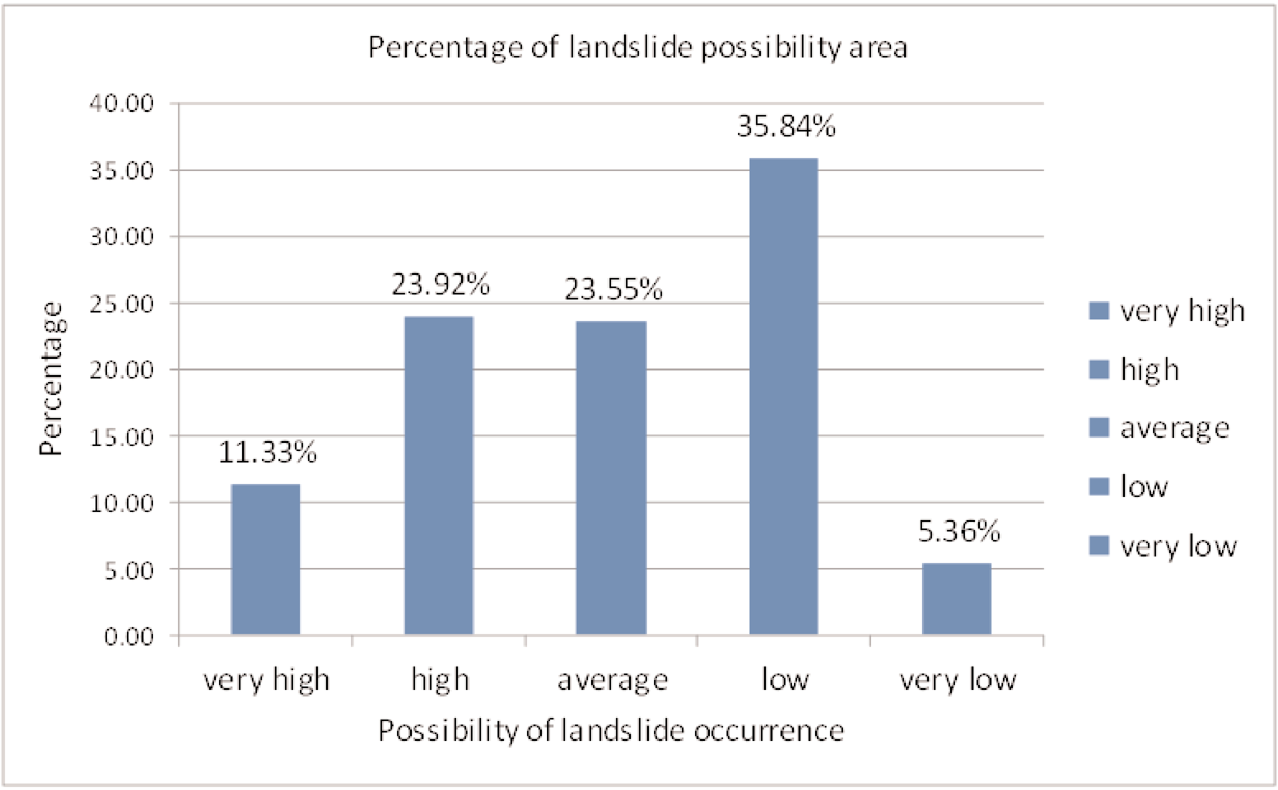

Figure 21. The area percentage of zones with landslide occurrence probability in the study area.

areas with high sliding probability. Thus, the larger the distance from streams, the lower the landslide occurrence hazard.

5. Considering the prepared zonation map and locating the majority of study area in zones with "average" and "high" sliding hazard, it is suggested to implement the results of the present study for the optimum choice and expert decisions prior to any planning about the land use changes and expanding dwelling areas and constructing any engineering structure.

6. Due to the landslide occurrence probability and the increased erosion and sedimentation in the study area, it is proposed to install gabion in the downstream of streams joining to the dam lake to prevent sediment accumulation in the dam. Also, to prevent landslide occurrence hazards in areas susceptible to sliding, it is proposed to implement stabilization measures in slopes with "high" landslide occurrence hazard to prevent any potential life and property loss.

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