Research Article

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Spatial modeling of ground subsidence susceptibility along Al-Shamal train pathway in Saudi Arabia

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Abstract: Al-Shamal train pathway, which is extended between Saudi Arabia and Jordan, is prone to geo-hazards due to the geological features, proximity to faults, earthquake epicenter, and the human activities along the pathway. The objectives of this study are to shed light on the ground subsidence susceptibility along Al-Shamal train pathway in Qarrayat city in Saudi Arabia and develop a ground subsidence susceptibility model to determine the prone areas to the impacts of ground subsidence to mitigate and avoid the loss of life and property. This study integrated the various data types to map the subsidence susceptibility along Al-Shamal train pathway. Nine ground subsidence causative parameters were selected as subsidence controlling factors in the study area including lithology, land cover/land use, elevation, slope, aspect, annual average rainfall, distance to faults, distance to earthquake epicenter, and distance to streams. The analytical hierarchy process is applied to obtain accurate weight

to each criterion through the distribution of online Google form questionnaire to experts in different expertise and get their judgments on the weights of ground subsidence causative parameters in the study area. A subsidence susceptibility index was derived by classifying susceptible maps into five classes, namely, very low, low, moderate, high, and very high using the statistical distribution analysis. The results revealed that the study area is subjected to moderate susceptibility with about 32.56. A total of 29.8 and 11.52% of the study area had very low and low susceptibilities, respectively, and 8.44 and 17.68% had very high and high susceptibilities, respectively. The results were validated using the receiver operating characteristic using previous ground subsidence locations. The area under the curve showed 0.971, which is equivalent to 97.1%. Consequently, the findings of the study are thought to be beneficial to managers and decision makers for future planning, mitigating, and preventing subsidence in the study area.

Keywords: geohazards, multicriteria decision analysis, Al-Shamal train pathway

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1 Introduction

Subsidence is the sinking of the Earth's surface relative to surrounding terrain due to ground collapse resulted from subterranean voids or a decrease in subsurface materials [1]. The earth fissures and the associated land subsidence can be attributed to the lowering of groundwater, refs [2–4] found that the decline in the aquifer level is one of the causes of land subsidence occurrence. Intensive rainfall is considered as an important factor in the occurrence of land subsidence [5–7]. According to ref. [8,9], the most prominent cause of land subsidence is the structural weakness of the underground layers, which is usually caused by human activities, such as mineral extraction. The land subsidence damages include the loss of life, human

injuries, infrastructure, and urban facilities in addition to water intrusion and cracking of underground services lines [10]. Moreover, the damages can occur either suddenly or gradually [4] and begin with thin short cracks and later increase in the size and depth. Subsidence has negative impacts on the economic status of the society [7]. Several techniques have been applied to map ground subsidence including frequency ratio [11,12], weight of evidence [13], logistic regression [11], artificial neural network [4,11,14–16], fuzzy logic and neuro-fuzzy [4,12,17–19], support vector machine [20,21], geographic information system (GIS) [4,7,10,13,14], multi-criteria decision analysis (MCDA) [4,7,12,22], and machine learning algorithms [23]. The InSAR method has been used to map the subsidence susceptibility [12,22,24–30].

Saudi Arabia is vulnerable to several geomorphological/geological hazards due to physical characteristics. These hazards include rockfalls/rockslides, subsidence, sinkholes, landslides, sand accumulations, flash floods, faults, volcanic activities, and earthquakes [31–33]. The earthquakes can trigger many other geological hazards and can crash down and cause loss of life and significant damages to infrastructures and property [34]. The national center for earthquakes and volcanoes that followed the Saudi Geological Survey (SGS) (www.sgs.org.sa) declared many geohazards due to earthquakes: (1) an earthquake has occurred in Tabuk in 1995 with a magnitude of 7.2 on the Richter scale, which caused subsidence and landslide along the earthquake fault and (2) an earthquake has been arisen in Al-Eis city in Al-Madinah Al-Munawwarah region in 2009, with 5.4° on the Richter scale. It causes damage to the houses of Al-Eis city, sinkhole, and landslide of an 8 km in the northern part of Al-Harrah. A closer look at the earthquakes' announcements of SGS in Saudi Arabia from 2010 to 2015 revealed that the following. (1) 5,450 earthquakes have been occurred in the Kingdom in 2015 compared to 11,000 in 2014 with a decrease of 54%. (2) Most of the earthquakes were below 2 on the Richter scale. (3) About 2,670 of earthquakes were ranged between 2° and 3° on the Richter scale, accounting for 4% of the total number of earthquakes. (4) Nearly, 156 earthquakes have occurred with a magnitude of 4–5° on the Richter scale, which represents 0.2% of the total earthquakes. (5) Forty-nine earthquakes had a magnitude from 5° to 6° on the Richter scale, which may generate damages near the epicenter. (6) Six earthquakes reached the magnitude of 6–7° on the Richter scale, which damages the weak infrastructures and buildings within a buffer zone of 10 km near the epicenter. Refs [35–38] have been documented and discussed a variety of geohazards in Saudi Arabia either natural or man-made. The geohazards in Saudi Arabia can be grouped into earthquakes, land subsidence, sinkhole,

earth fissures, landslides, flash floods, and volcanic hazards. Many studies have focused on subsidence, fissures, and sinkholes in Saudi Arabia, including refs [38–55]. Land subsidence has occurred in Saudi Arabia due to the reduction of the water table because of the experienced extensive expansion in agriculture. Refs [39,40] found that land subsidence took place in many areas close to the volcanic terrain (harrat) such as villages of Tabbah and An-Na'ay. Refs [39,41,44] observed land subsidence in areas of karstic rock terrains at El-Aflaj, El-Kharj, and near Sulayyil. Ref. [42] manifested the land subsidence in Hail in Saudi Arabia due to water withdrawal from a volcanic crater. Ref. [43] studied the effect of geological features, geotechnical properties, and soil in Jazan city. The author manifested that the subsidence arises from the dissolution of the salt rocks through water infiltration. Ref. [45] revealed that groundwater exploration in Wadi Nafia and Wadi Alitma in Saudi Arabia caused subsidence hazard. Ref. [46] presented the formation of many ground cracks of different scales with a total length of 3,560 m in the south of Al-Madinah Al-Munawwarah in 1992. Ref. [47] studied the reasons for land subsidence in the Saudi Arabia and classified the land subsidence into natural and human induced. Natural land subsidence in Saudi Arabia is attributed to the karst phenomenon (carbonate and evaporite rocks and salt diapirs, lowering of groundwater, and soils instability). Human-induced subsidence in Saudi Arabia is occurred due to extraction of groundwater from aquifers, water intrusion to unstable soil, and water rises in urban areas. Ref. [48] investigated the land subsidence in Wadi Al-Yutamah in the west of Saudi Arabia. The findings manifested that the subsidence is induced due to the decline in water by the uncontrolled aquifer pumping, and the subsidence increases after flooding or rainfalls. Ref. [49] used the Landsat, QuickBird satellite images, and GIS analysis to map the subsidence hazards in Jazan in Saudi Arabia. The authors attributed the subsidence to the presence of sabkha, loess soil, salt rocks, and sand dunes drifting and movement. The degree of subsidence is correlated with the characteristics, the bearing capacity of sabkha, dissolution of salt rocks after water infiltration, and the soil stability. Ref. [33] classified causes of subsidence and sinkholes in the Saudi Arabia: (1) geological structures and groundwater extraction such as in Wadi Najran, Wadi Al-Dawather, Hail, El-Qasim, and El-Jouf region; (2) clay deposits such as in Hail, El-Qasim, and Al-Jouf regions; (3) Khabra deposits such as in El-Jouf, Hail, and El-Qasim regions; and (4) earthquake such as in El-Shaqa area in Al-Madinah Al-Munawwarah. Ref. [35] studied the formation of land subsidence in Wadi Najran in Saudi Arabia due to land use changes, cultivation activities,

and groundwater depletion. The authors recommended the necessity to detect incipient earth fissures that are not reached the surface yet to be mapped and mitigated. Furthermore, the subsidence will continue if the groundwater extraction surpasses the aquifer safe yield. Ref. [51] reported that many areas in Saudi Arabia are prone to earth fissures and land subsidence due to the excessive extraction of groundwater. The authors expected the depletion of Saudi Arabia's groundwater reserves in the next 25–30 years due to the extensive agricultural development that irrigated with groundwater. The results indicated that the land subsidence in Saudi Arabia is related to the soluble sediments of evaporite, carbonate rock formations sabkha deposits, and salt diapirs. Ref. [52] revealed that land deformation including sinkholes, subsidence, fissures, and earthquakes are correlated spatially with cultivation activities and extraction of groundwater. Leakage of irrigation water to cultivated lands increases the carbonate dissolution and consequently resulted in sinkhole formation. Pumping from limestone aquifers could result in the development of sinkholes. Furthermore, the presence of faults is considered a stone

corner in the land deformation development. Ref. [53] focused on subsidence in Saudi Arabia that is triggered by groundwater withdrawal. The authors attributed the subsidence to the overexploitation in the aquifer, which lead to compaction and subsequent subsidence. The study recommended minimized land deformation by reducing groundwater extraction by 3.5–4 km³/year and the optimum utilization of fossil aquifers. Ref. [38] reported that subsidence and sinkholes can be attributed to karst morphology and changes in soil structures. The authors documented that sinkholes have been found in the north-eastern region of Al-Khafji, An-Nariyah cities, Layla, and As-Sulayyil towns. Ref. [54] studied the land subsidence in Dammam city using the soil geotechnical parameters. The authors indicated that the weak soil conditions and lowering the groundwater levels with pumping from Dammam aquifer are the main causes of subsidence. The most common subsidence and sinkholes in Saudi Arabia included the cover collapse (Al-Jouf region in 2006 with 40 m width and 15 m depth), caprock collapse (Al-Issawiah in Al-Jouf region with 27 m diameter and 23 m depth), and bedrock collapse (Aba Alwrood area in Al-Qasim

Figure 1: Recorded subsidence in Saudi Arabia. (a) Al-Jouf region, (b) Al-Issawiah in Al-Jouf region, (c) Aba Alwrood area Al-Qasim region, (d) Al-Maizalia district in Riyadh, (e) Dammam road, (f) Al-Mudriba district in Jazan.

Figure 2: Areas of potential subsidence.

region in 2010 with 10.5 m long and 7.5 m wide). Figure 1 shows examples of subsidence in Saudi Arabia, and Figure 2 shows areas prone to subsidence in Saudi Arabia.

This study is an important study in subsidence susceptibility in Saudi Arabia as Al-Shamal train pathway are situated between two Saudi Arabia and Jordan. Furthermore, the study area along the train pathway with 2,750 km is proposed to be vulnerable to subsidence geohazard due to its proximity to faults, an earthquake epicenter, and a historic volcanic eruption from 1,400 years ago. Figure 3 shows the Al-Shamal train pathway. The objectives of this study are as follows: (1) to investigate the causative parameters for ground subsidence in the Qarrayat Saudi city; (2) to use the analytical hierarchy process (AHP) pairwise comparisons to get weights for the causative parameters by sending the AHP matrices to eight experts and aggregating the obtained weights using

the geometric mean; (3) to integrate the AHP with GIS-MCDA to develop a ground subsidence susceptibility (GSS) along Al-Shamal train pathway in the Qarrayat Saudi city; (4) to identify the ground subsidence prone areas in five rank classes to explore the degree of susceptibility in the study area; (5) to propose recommendations for preventing and mitigating the future subsidence hazards in the susceptible areas. These findings of this research are assumed to be useful for land planners and decision makers to estimate the threats to population, infrastructures, and transportation network along Al-Shamal train pathway in general and in Qarrayat city in Saudi Arabia as particular.

2 Study area

This study area is located between 30° to 31.5° N and 36.5° to 38° in Qarrayat city in Al-Jouf region in Saudi Arabia. It is bounded by Jordan Kingdom in the north and west, Tarif Saudi governorate in the east, and Al-Jouf region in the south as shown in Figure 4. It is about 1,200 km, 310 km, and 350 km from the Riyadh, Sakaka, and Arar cities, respectively. The study area follows the climate of Saudi Arabia, which is characterized by high temperature and rare precipitation due to the location in the desert zone. The annual average temperature is 53°C, and June is the hottest month over the year. The annual average rainfall is less than 150 mm/year, it increases in the southwestern regions due to the topography and wind path to reach more than 488 mm annually, and it decreases in the interior regions to reach 125 mm annually. The study area is populated in the northern part only along the paved highway that connected with Tabuk in the southwest and with Arar in the northeast. The study also included a paved highway in the northwestern region and continues

Figure 3: Al-Shamal train pathway between Saudi Arabia and Jordan.

Figure 5: Methodology flowchart.

epicenter, and distance to streams. Soil and lithology are one of the backbones controlling factors for the occurrence of subsidence and susceptibility rate [56–59]. Several researchers [60–62] focused on the effect of soil and lithology on subsidence susceptibility. Refs [60–62] revealed that clay and silt structures increase the rate of subsidence and gypsum, and carbonates rocks are influenced by water presence due to dissolution, which also increases the rate of subsidence.

The land cover is the physical land type and is considered another causative driver of subsidence susceptibility [58,62]. Land use is related to human activities and how they use the land and changed according to population needs. Changes in land cover and land use due to either natural or anthropogenic forces are a subsidence contributory factor [22] particularly in agricultural activities [25].

Agriculture activities (due to groundwater withdrawal required for irrigation), rangelands, and urban areas are considered the most water-consumed areas. The increased water consumption can be a causative for lowering groundwater levels, which increase the likelihood of subsidence.

Topographic factors include elevation, slope, and aspect control subsidence susceptibility [63]. The topographic factors were extracted from the 30 m ASTER-GDEM image acquired from the study area. Slope is defined as the inclination degree of any feature with respect to the horizontal surface plane [64]. Aspect is the direction of the slope, and it affects hydrological processes because of evapotranspiration [10] and then influences soil moisture and vegetation cover [60,62]. Rainfall decreases the rate of land subsidence as intensive rainfall

causes higher infiltration of water to the groundwater, which in turn increase the groundwater table. Faults are another subsidence triggering factor as the strength of rocks declines due to tectonic breaks [10]. The active faults play a significant role in initiating subsidence as the rocks near the faults are weaker than other rocks farther from faults [63]. Closeness to faults increase the likelihood of the occurrence of subsidence [60].

Earthquakes are considered one of the most destructive events, which cause injury, loss of life, extensive infrastructure damages, and serious economic losses. Earthquakes are a basic triggering factor for subsidence susceptibility [59,61]. Saudi Arabia experienced earthquakes in 1995 and 2009, with a surface wave magnitude of 7.2 and 5.4, respectively, on the Richter scale and suffered losses of life and property. The earthquake in 2009 ruptured large faults with 8 km long in the northern part of Al-Harrah.

The stream networks are key chief in subsidence occurrence, and the susceptibility increases as distance to streams decreases. Many subsidence occurred in close to the streams network [60]. The streams can harmfully affect the stability by the slope erosion, saturating the lower part of the soil and resulting in increasing the water level [62].

3.4 GSS

The GSS was developed according to four steps:

- (1) The nine selected criteria are classified separately where the lithology was classified into six classes according to the lithology in the geological map. The land cover/land use criteria were classified according to the supervised classification into four land cover types, while the land use was classified into five urban uses and the green areas were classified into farms, parks, grass, and orchards. The distance to faults, earthquake epicenter, and streams were classified using the Euclidean distance to five distance classes. Elevation, slope, and rainfall criteria were classified using the statistical distribution analysis to subdivide the classes of each criterion into five classes.
- (2) An online Google form questionnaire was sent via e-mail to eight experts' to fill in a pairwise matrix of the nine criteria. Multiple experts were chosen to get rid of bias in their judgments. The results of the eight questionnaires were aggregated into single pairwise matrix using the geometric mean presented in equation (1). The consistency of the aggregated pairwise

comparison matrix was assessed using the consistency ratio in equation (2), which was calculated using the consistency index given in equation (3) and the consistency ratio (RI).

$$\text{Consistency ratio (CR)} = \frac{\text{CI}}{\text{RI}}, \quad (2)$$

$$\text{Consistency index (CI)} = \frac{(\lambda_{\max} - n)}{n - 1}, \quad (3)$$

where “ n ” is the number of criteria in the pairwise matrix and $\lambda_{\max}$ is the largest eigenvalue in the matrix. According to ref. [54], the pairwise matrix is consistent if the CR value was less than 0.1.

- (3) The AHP was integrated with GIS to systematically assign weights to the selected multicriteria based on the numerical scale proposed by ref. [54].
- (4) The GSS was calculated by multiplying each raster criteria layer by the weights obtained from AHP in the previous steps as presented in the following equation.

$$\text{GSS} = \sum_{f=1}^n W_f S_f, \quad (4)$$

where “GSS” is the ground subsidence susceptibility, “ f ” is the criteria number, “ W_f ” is the weight assigned to the criteria, “ S_f ” represents the criteria raster layer, and “ $n = 9$ ” is the total number of criteria.

3.5 Reliability analysis

The results of the ground subsidence susceptibility map have to be validated, so the data required for this step were obtained from the Saudi Geological Survey (SGS) (www.sgs.org.sa). The data covered different locations in the study area. The TerrSet software version 18.31, developed by Clark Labs at Clark University, was used to draw the receiver operating characteristic (ROC) curve to check the reliability of the ground subsidence results. The false positive rate (FPR) is drawn along the x -axis to show the points in the susceptibility map, which is classified as low ground subsidence likelihood and in fact had no previous ground subsidence. The true positive rate (TPR) is drawn to y -axis to demonstrate the points in the susceptibility map, which is classified as high ground subsidence likelihood, and they had prior ground subsidence. The value of the area under the curve (AUC) is an indicator for the reliability. If the AUC value was below 0.5, then the susceptibility map is unreliable, and the results are considered inconsistent. However, if the

AUC value was equal to 1, then the susceptibility map is reliable, and the results are considered consistent.

4 Results

4.1 Analysis of subsidence susceptibility criteria affecting the Al-Shamal train pathway

4.1.1 Lithology

The lithology of the study area was digitized from the geological map including deposits of the valleys; deposits of alluvial fans; deposits of mud surfaces; fossil limestone, marl, and flint; limestone, marl, and flint; limestone and sandstone calcareous (Al-Sarhan formation) as shown in Figure 6a. Table 2 presents that the fossil limestone, marl, and flint are the most dominated geologic formations and constitutes about 74.32% of the study area.

4.1.2 Land cover/land use

Land cover types of the study area were derived from the Landsat-8 satellite image acquired in 2020. The extraction of land cover was divided into many steps: (1) band 2 to band 7 were stacked together to generate one image containing six bands; (2) resolution merge of the multi-spectral bands of spatial resolution of 30 m and the pan-chromatic band of spatial resolution of 15 m to improve the visual interpretation of the image; (3) clip the scene to match the boundary of the study area; (4) supervised classification using the maximum likelihood techniques where the training sites (200 sites divided between the classification and the accuracy assessment) required for the classification were collected from the field visits to the study area; (5) the accuracy of the supervised classification was assessed using the training sites collected from field. The extracted land cover types are water, green lands, Wadis, and urban areas. Desert and Wadis occupy 77.45% and 20.83% of the study area, while other land cover types constitute about 1.73% as presented in Table 3. The desert land cover includes the quarries. Land cover and land uses in the study area are shown in Figure 6b. The urban land cover includes multiple uses such as residential, commercial, industrial, retail, and military land uses. The green land cover includes several uses such as the farms, parks, grass, and orchards. The land use was

digitized from topographic maps. The land use is concentrated in the north of the study area, while other parts are desert and wadis.

4.1.3 Elevation

The elevation in the study area ranged from 466 to 1,039 m as shown in Figure 6c. The Al-Shamal train pathway is located at elevation ranges from 466 to 580.6 m. Higher elevations starting from more than 580.6 m are located apart from the train pathway. The elevation criterion was classified into five classes from 466 to 579 m, 580 to 694 m, 695 to 808 m, 809 to 923 m, and 924 to 1,039 m.

4.1.4 Slope

The slope was extracted from the ASTER-GDEM in ArcGIS environment, the slope is ranged from 0° to 46.3° as seen in Figure 6d. The slope criterion was classified into five categories using the statistical distribution from 0° to 8°, 9° to 17°, 18° to 26°, 27° to 36°, and more than 36°. The predominant slope in the study area is less than 9.26°.

4.1.5 Aspect

Aspect was derived from the ASTER-GDEM in ArcGIS environment and classified into nine classes. The north direction from 0° to 22.5° and from 337.5° to 360°, north-east from 22.5° to 67.5°, east from 67.5° to 112.5°, south-east from 112.5° to 157.5°, south from 157.5° to 202.5°, southwest from 202.5° to 247.5°, west from 247.5° to 292.5°, and finally the northwest direction from 292.5° to 337.5° as shown in Figure 6e.

4.1.6 Rainfall

The downloaded mean annual rainfall data ranged from 9.26 to 15.2 mm as shown in Figure 6f. The rainfall criterion was classified into five classes from 9.26 to 9.44 mm, 10.4 to 10.63 mm, 11.63 to 11.82 mm, 12.82 to 13 mm, and finally more than 13 mm. The maximum and minimum rainfall is concentrated in the west and the southeast of the study area.

4.1.7 Faults

Faults were digitized using the geological map, the lengths of the faults ranged between 5.02 and 84.87 km

Figure 6: The criteria of ground subsidence susceptibility affecting Al-Shamal train pathway. (a) Lithology, (b) land cover/land use, (c) elevation, (d) slope, (e) aspect, (f) rainfall, (g) distance from faults and earthquake epicenter and (h) distance from stream orders.

as shown in Figure 6g. The length of the nearest fault to the Al-Shamal train pathway is 13.57 km with distance apart from the train pathway equal to approximately 11 km.

4.1.8 Earthquakes

The earthquake epicenter was digitized from the geological map of the study area as illustrated in Figure 6g. The

Table 2: Area of geological formations

Geology	Area (km ²)	%
Deposits of the valleys	1994.40	18.11
Deposits of alluvial fans	2926.24	26.57
Deposits of mud and silt	189.03	1.72
Fossil limestone, marl, and flint	5385.04	48.90
Limestone and sandstone calcareous	516.74	4.69
Total	11011.45	100

Table 3: Area of land cover types of the study area in 2020

Land cover	Area (km ²)	%
Green lands	91.23	0.83
Desert	8528.19	77.45
Wadis	2293.47	20.83
Urban areas	98.57	0.90
Total	11011.46	100

earthquake epicenter is about 53 km from Al-Shamal train pathway.

4.1.9 Streams

The stream network was obtained according to Strahler using the hydrological toolset in ArcGIS software, and three orders were obtained: first stream orders, second stream orders, and third stream orders as shown in Figure 6j. The length of the first stream order represents 3047.34 km, and lengths of second stream and third stream order have lengths of 1523.63 and 1803.68 km, respectively.

5 Discussion

The analysis of causative ground subsidence susceptibility maps in Figures 7 and 8 showed that about 18.55 and 81.45% of lithology criterion in the study area had moderate and very high susceptibility, respectively. The very high susceptibility is concentrated in deposits of the valleys, deposits of alluvial fans, and deposits of mud surfaces. The moderate susceptibility is in fossil limestone, marl, and flint, limestone and sandstone calcareous. Very low, moderate, high, and very high susceptibility hazards in land cover/land use criterion in the study area represented 0.853, 77.45, 20.83, and 0.90%, respectively. The very low susceptibility is in all types of

green areas including farms, parks, grass, and orchards. The moderate susceptibility hazard is situated in retail land uses, and very high hazard was in urban and built-up areas including the residential, commercial, industrial, and military land uses.

The most susceptible elevation class is from 466 to 579 m as the susceptibility is low for high elevated areas due to the existence of bedrocks, which are considered resistant to weathering. High slope areas are the most susceptible to hazard. Nearly, 77.54 and 17.90% of slope in the study area has very low and low susceptibility hazards, respectively; however, the moderate, high, and very high susceptibility hazards represent about 3.18, 0.82, and 0.56%, respectively, of the study area. Aspect criterion of 23.24 and 28.15% in the study area has very low and low susceptibilities, respectively, in the south-west, west and southeast, south directions. The rainfall with very high and high susceptibility occupies 12.24 and 33.08%, respectively, of the study area corresponding to areas more than 13 mm. The moderate susceptibility is dominant in the study area with about 45.53% at annual average rainfall from 11.63 to 11.82 mm, while the very low and low susceptibilities of 0.01 and 9.14%, respectively, have annual average rainfall of less than 11.63 mm. Areas with high rainfall intensity are the most susceptible. Rainfall can make a synergistic effect as it has the ability to increase the water content in clay areas and increase the sliding.

The faults, earthquake epicenter, and stream networks vector layers are converted to raster format with a 30 × 30 m spatial resolution to match the pixel size of the other raster layers. Then, all raster layers are classified into five categories using the Euclidean distance tool in spatial analyst tools of ArcGIS 10.4.1. The most susceptible areas of the distance to faults criterion are those regions of distance less than 9,238 m from the Al-Shamal train pathway, which constitutes 4.44% of the total study area susceptibility. The faults at distance from 9,239 to <18,478 m corresponding to 17.13% of the total faults have high susceptibility. The low susceptibility is located at distance from faults ranging from 27,719 to 36,958 m, and the least susceptible areas are of distance more than 36,958 m corresponding to 43.54% of the total susceptibility. The very low susceptibility is common with respect to the distance from faults criterion. The earthquakes are the most triggering factor after rainfall. The earthquake epicenter in the study area is about 53,538 m far from Al-Shamal train pathway. The shorter distance between the epicenter and the train pathway is the most susceptible and vice versa. Distances less than 17,361 m from the epicenter are the most hazardous and

Figure 7: The classification of criteria of ground subsidence susceptibility hazard affecting Al-Shamal train pathway. (a) Lithology, (b) land cover/land use, (c) elevation, (d) slope, (e) aspect, (f) rainfall, (g) faults, (h) Earthquake epicenter and (i) streams.

constituted about (8.6%) of the total susceptibility. Distance from 17,362 to less than 34,723 m has high susceptibility with about 23.9% of the total susceptibility. The distance from 34,724 to 52,086 m has moderate susceptibility (26.9%), the distance from 52,086 to 69,447 m has low susceptibility (2.23%), and finally, distance above 69,447 m has the lowest susceptibility with about 15.01%. The stream orders are considered one of the most causative criteria to

subsidence susceptibility. The distance from streams network less than 749 m has very high susceptibility with 19.86%. Distance from 750 m to less than 1,499 m has high susceptibility with 19.9%. However, distance from 1,500 to 2,249 m has moderate susceptibility with 20.1%. The very low and low susceptibilities at distance more than 2,250 m represent 40.15% of the total susceptibility. Lithology, rainfall, distance from faults, aspect, and

Figure 8: The criteria of ground subsidence susceptibility affecting Al-Shamal train pathway. (a) Lithology, (b) land cover/land use, (c) elevation, (d) slope, (e) aspect, (f) rainfall, (g) distance from faults, (h) distance from earthquakes epicenter, and (i) distance from streams.

distance from earthquake epicenter are the most causative subsidence and subsidence susceptibility criteria, followed by distance from streams, land cover/land use, elevation, and slope. The GSS map shown in Figure 9a was calculated using equation (4), where the AHP pairwise comparison matrix was applied to assign the priority weights for the causative ground subsidence susceptibility through the distribution of an online questionnaire to eight experts in different expertise. The questionnaire aims to get the experts' judgments on the weights of ground subsidence susceptibility causative parameters in the study area. The questionnaire was designed as online Google forms and sent via e-mail to the experts. More than one expert was chosen to eliminate any biases in weights' judgments. The obtained weights of the pairwise comparison matrices were aggregated

using the geometric mean illustrated in equation (1). As a subsequent step, each criteria layer was multiplied with the weights as shown in equation (5):

$$\begin{aligned}
 GSS_{AHP} = & \text{Lithology} * 22.52 + \text{Rainfall} * 15.82 \\
 & + \text{Distance from faults} * 14.06 \\
 & + \text{Aspect} * 12.58 \\
 & + \text{Distance from earthquake epicenter} * 11.65 \\
 & + \text{Distance from streams} * 8.62 \\
 & + \text{Land use/land cover} * 7.64 \\
 & + \text{Elevation} * 3.98 + \text{Slope} * 3.13.
 \end{aligned} \quad (5)$$

The analysis of GSS in Figure 9b shows that the study area is subjected to moderate susceptibility with about 32.56%. The very low and low susceptibilities represent nearly 29.8

Figure 9: Ground subsidence susceptibility (GSS).

and 11.52%, respectively. The very high and high susceptibilities constitute about 8.44 and 17.68% from the total study area. The obtained results manifested that:

- (1) Lithology of the study area is composed of six geological formations, the very high susceptibility is in deposits of the valleys (77.28%) and the high susceptibility is in the fossil limestone, marl, and flint with about 46.13%.

Figure 10: ROC curve between the ground subsidence collected from Saudi Geological Survey and the ground subsidence extracted from the ground subsidence susceptibility map.

- (2) Land cover/land use have very high, high, moderate, low, and very low susceptibilities in the desert areas with 62.73, 70.27, 79.14, 83.44, and 81.88%, respectively.
- (3) The highest susceptibility with respect to elevation criterion is in areas with elevation from >923 m (28.96%), and the lowest susceptibility is in areas with elevation located from 809 m to less than 923 m with about 0.96%.
- (4) Slope criterion has very high susceptibility with 78.93% in areas with a slope from 0° to 8° . Very low susceptibility with nearly 0% in areas of slope between more than 36° .
- (5) Aspect has the highest susceptibility in the southeast direction (34.16%) followed by susceptibility of 20.28% in the northeast direction.
- (6) Rainfall criterion had 33.96% highest susceptibility in areas with rainfall intensity from 11.63 to 11.82 mm. The rainfall intensity with high susceptibility (37.44%) is in the areas of the annual average of 12.82 to less than 13 mm.
- (7) Distance from faults has the highest susceptibility for distances less than 9,238 m with nearly 59.2% and lowest susceptibility for distances greater than 36,958 m with 0%.
- (8) The very high, high, and very low susceptibilities with respect to distance from earthquake epicenter are 28.41, 31.61, and 9.04% with distances less than 17,361 m, 34,723 m, and more than 69,447 m, respectively.
- (9) The highest susceptibility with respect to the distance from stream network is 29.7% with distances more

than 2,999 m. The lowest susceptibility is 25.7% for the distance less than 749 m.

The ground subsidence susceptibility map obtained from the integration of AHP and GIS-MCDA was validated using 50 locations subdivided into two datasets. The first set included 35 locations with prior ground subsidence and the second set included 15 locations with no prior ground subsidence susceptibility. The training locations included 100 locations distributed over the whole study area. The AUC value was 0.971%, which is equivalent to 97.1%, % that indicated high reliability of the results. Figure 10 shows the ROC curve drawn between the ground subsidence values collected from the Saudi Geological Survey (SGS) and the ground subsidence values extracted from the susceptibility map.

6 Conclusions and recommendations

In the past few decades, Saudi Arabia is exposed to natural geohazards hazards including the earthquakes, subsidence, sinkholes, and landslides, which caused losses to life, property, and infrastructures. The human intervention has worsened the severity of these hazards. The study area of this research is located in the north western of Saudi Arabia, which exposed to more than 30,000 earthquakes during 2009 in Harrat Lunayyir with fault length reached 8 km. Moreover, the north western part of Saudi Arabia for more than 1,400 years ago experienced volcanic eruptions. The Al-Shamal train pathway with about 2,750 km length is constructed starting adjacent to the international border of Jordan then to Qarrayat city and finally in Riyadh. Subsidence mapping are essential in the study areas as it is earthquake and faults struck region.

An innovative AHP methodology was applied in the present study. The AHP priority weights were obtained by designing an online Google form questionnaire and sending it to multiple experts with different expertise in the study area. The weights obtained from different experts helped to avoid biases in weights' values. Moreover, the AHP questionnaire permitted obtaining accurate weights of causative ground subsidence through the experts' judgments. The different obtained weights were aggregated using the geometric mean, which considered the most applicable method to aggregate the different experts' responses.

The integration of the AHP and GIS-MCDA presented precious technique to shed light on the areas prone to

ground subsidence in the study area. In this study, a GSS was developed using nine factors, namely, lithology, land cover/land use, elevation, slope, aspect, rainfall, distance to faults, earthquake epicenter, and distance from streams. The results of the study revealed that (1) the lithology, rainfall, distance from faults, and earthquake epicenter are the most important and highly weighted ground subsidence causative factors. (2) Along Al-Shamal train pathway, the ground subsidence susceptibility is ranged from very low to moderate due to the formations of alluvial fans and the existence of green areas as the roots stabilize the land and make them less susceptible to subsidence. (3) The very high and high susceptibilities are concentrated in the south, south western, and eastern areas because of the existence of faults, epicenter, and fossil limestone formations.

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Supplemental data: Link of the online Google form questionnaire: <https://forms.gle/ErwtNg64RL76t8zL7>.

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