Annals Geol. Surv. Egypt. V. XXXIX (2022), pp. 1 - 22

AN INTEGRATED APPROACH TO EVALUATE GEOHAZARD POTENTIALITY IN THE DAMT HOT SPRINGS AREA, WESTERN VOLCANIC PLATEAU, YEMEN

BY

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ABSTRACT

The Damt hot springs area has a high vulnerability to geohazards (e.g., earthquake, mass wasting, and flash flood hazards). It is located at the southeastern escarpment of the Western Yemen Volcanic Plateau (WYVP) which is considered as the most volcanic and tectonic active provenience in Yemen. The relatively high risk of integrated factors (e.g., annual rainfall, steep slopes, and potential seismotectonic activities in the study area) has caused it to be an inherently susceptible area. Therefore, this study attempts to assess the geo-environmental conditions and factors and their implication on triggering the geohazards in Damt District.

An integrated approach using field observation, remote sensing analysis, and geospatial data analysis was applied to reveal geohazard prone zones. To better understand the causative factors controlling the geohazards and their environmental impacts, topographical, geological, and hydrological characteristics were mapped and investigated. The common anthropogenic factors including human interference through, excavation of the slopes mainly for house building and mountain terraced cultivation, inconvenient hot spring water utilization, and habitation patterns around the travertine cones area was integrated with the causative factors to increase the risk potentiality of geo-environmental problems.

Based on spatial integration of all contributing factors, most of the scattered hanged villages in the high relief, steep-sloped, highly weathered mountainous volcanic zone is prone to serious geohazards. In this respect, several mitigation measures, including the determination of several dams' localities, are proposed to protect the urban area and enhance the water resources.

Key Words: Damt hot springs, mass wasting, watershed analysis, flash flood, earthquake, potentiality, travertine Cones, Yemen.

INTRODUCTION

The main geohazards comprise phenomena such as earthquakes, mass-wasting, and flash floods (or runoff) causing threats for people and infrastructure. All these hazardous phenomena are usually associated events that may be attributed to similar integrated geo-environmental conditions. Topography (slope gradient), lithology, fracture intensity, soil profile, heavy rainfall, and land use /land cover set are the common geo-environmental parameters controlling the geo-hazard potentiality. Furthermore, each of the above geohazards could be acting as trigger factors for the others, for instance, flash floods and earthquakes are trigger factors for slope instability. Although mass-wasting events occur at a slow rate, the event may cause catastrophic impacts when the area receives sufficient rainfall during rainy storms or is exposed to the earthquake. In this respect, the above-mentioned geo-environmental conditions and causative factors could be regionally applicable and commonly received in the study area which is located within the Western Yemen Volcanic Plateau (WYVP). WYVP is considered the most volcanic and tectonic active provenience in Yemen.

Yemen is located on the southern boundary of the Arabian Plate on top of the Afar hot mantle plume (Coulie et al,2003). During the last decade, several important seismo-volcanic events have occurred in Afar and its surrounding area, confirming the importance of volcanism in this extensional region above an abnormally hot mantle which could be responsible for dynamic processes and earthquakes that usually associated with the geo-thermal system (Rooney et al., 2012, Hansen and Nyblade,2013, Korostelev et al.,2014 and Khanbari,2020). On the other side, the tectonic setting which includes the Arabian Plate motion and the opening of the Red Sea and Gulf of Aden play, an important role to produce earthquakes in Yemen (Khanbri,2020).

The WYVP contains a thick sequence of Oligocene -Miocene alkaline basalt trap series (Fig 1) which are in the Afar mantle plume. It represents the western faulted volcanic margin of Yemen that containing hot springs, geothermal energy sources, and recent volcanic activities. This geological situation is mainly due to its location within the most active rift system in the world where it is bordered by the Red Sea from the west and the Gulf of Aden to the south (Fig, 1).

The Damt area (Fig. 1) has a high vulnerability to geohazards due to its location within the dynamic WYVP area as well as to its geo-environmental characteristic. Recently, Damt was selected to be one of the most promising sites for geothermal energy resource exploration in the WYVP as was discussed in (Minissale et al., 2007, Wagner and Mattash, 2007; and Alnabhani, 2021; and Alkubati et al., 2015). However, published works on the evaluation of geo-environmental hazards in the Damt area are seldom. Among the most remarkable studies in this field are those of (Al-Aydrus, 1997&2010; El-isa, 2015; and khanbari, 2020) who discussed the seismological consideration in Yemen.

Therefore, this study deals with the evaluation of both natural and anthropogenic hazards' potentiality to conserve the study area infrastructures and to save human life. The evaluation depends on the delineation of the hazard zones based on the integration of remote sensing and geographic information system mapping. Accordingly, the present study focuses on delineation of the geoenvironmental characteristics and causative factors controlling the geohazards (e.g., earthquakes, mass-wasting, and flash flooding hazards) in the Damt area. The constructed maps include geological, structural, slope gradient, and watershed.

THE STUDY AREA

The study area is located within the Damt District that belonging to Ad Dalah provenance (Fig.1). It occupies an area of about 1330 Km² and is delimited by latitude 14◦13' and 13◦57' North and 44◦27' and 44◦54' East. The Damt city is connected by asphaltic roads to the surrounding major cities, such as Sana’a, Dhamar, and Ibb (Fig. 1).

The study area occupies part of the northwestern upstream subbasin of the Wadi Bana hydrographic basin which partially occupies the eastern and southeastern escarpment of WYVP (Fig.1a). The WYVP is a high plateau with an average elevation of about 3000m a.s.l and is characterized by a high precipitation rate that reaches over1000mm/year in the Upstream of the Wadi Bana hydrographic basin. Rainfall in the central and western highlands of the WYVP including the study area is influenced mainly by the Red Sea convergence zone. Yemen is a semiarid to arid tropical climate country with a remarkable variation due to topography differences.

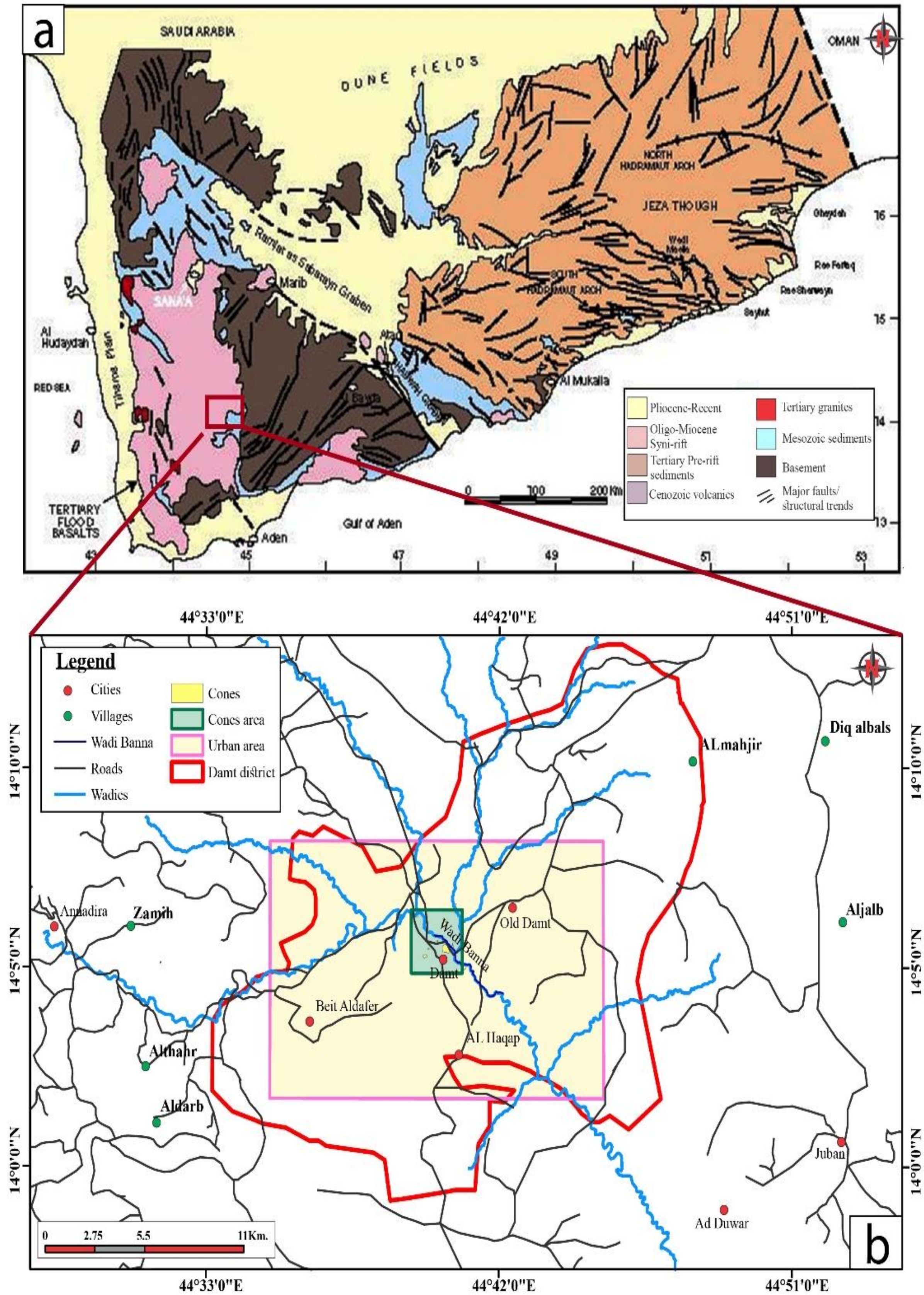

Fig. 1: a: General geological map of Yemen; b: location map of the study area

On the other hand, Damt area is considered an amazing tourist resort in Yemen (Alderwish and Almatary, 2011). It includes hot springs with spectacular travertine conical landscapes around structurally controlled volcanic centers or vents (El-Anbaawy and Fara,1993). Hammam Damt is known for the occurrence of several hot springs and artesian wells over an area of about 25 km². Both springs water and artesian water with an average temperature of 45° C, are used for baths or as swimming pools and hotels, however, this activity needs further development. The local population greatly appreciates the healing effects of thermal water. Which is very effective in the remediation of skin diseases?

DATA AND METHODS

The study Damt area is particularly suspected of several integrated natural and anthropogenic hazards. Remote sensing analysis, geospatial data analysis, and field investigations were integrated to evaluate the impacts of the hazards and hence suggest information on the relation between the hazards and their causative controlling factors.

Our mapping technique is based on the interpretation of the different satellite images, analysis of Digital Elevation Models (DEMs), and detailed field mapping. The used satellite image is L1T (terrain-corrected) Landsat 8 (OLI), and high-resolution Bing maps and Google Earth images.

The geological boundaries had been detected based on the data collected during the field survey of urban and cone areas. The geological boundaries had been extrapolated from urban and cone areas across the whole map supported by interpretations of sharpened Landsat 8 (OLI images. False-color composite (Red Green Blue-RGB 3 2 1 VNIR natural colors and 7 5 3 VNIR/SWIR) were used to characterize the surface texture and lithology identification. The clear identification of the lithological boundaries facilitates the mapping of the main fault traces.

In this work, we used ASTER GDEM (about 30 m spatial resolution and 10–25 m vertical accuracy) to produce topographic contours, slope analysis, and watershed analysis. Topographic contours with 25 m intervals were generated and the false contours and apparent mistakes were manually deleted. The hydrology and surface toolboxes algorithms in ArcGIS 10.6 were used in the present study to analyze watershed behavior, extraction of watersheds, and stream channel networks.

All the previous data and the digital scans of the previously published earthquake, and geological maps were converted into a GIS database that is manipulated to obtain new layers that are used in constructing different maps

RESULTS

Although some geo-environmental hazards of the Damt District were regionally studied as a part of the WYVP, by few authors (e.g., Arya et al., 1985; Dowgiallo, 1986; Al-Sinawi and Al-Aydrus, 1999, Al Dafiry, 2005; Wagner and Mattash,2007, Minissal et al, 2007 and Al Derwish and Al Matary, 2011). none of these studies discussed the integration of those hazards and their interference with human activities impacts. Therefore, the present study discusses the different integrated geohazards (e.g., mass-wasting, earthquakes, and flash flooding) and their causative factors (e.g., climatic, topographic, geological, hydrological, tectonic, and seismic factors).

The results of this study may be useful for the geo-environmental hazards assessment not only in the Damt area but also in similar geothermal fields in the WYVP. Generally, main causative factors for similar geohazards, are divided into preparatory and triggering factors, however, in the present study, the lithological and related causative factors will be investigated as the main preconditional factor for the geohazards.

1 Geological setting of the Damat District

To assess the geohazards' potentiality of the study area, it is important to know the spatial distribution of the lithological units and their structural pattern which is the result of the Red Sea and Gulf of Aden rifting (Fig. 1). Three geological maps of different scales were constructed using remote sensing (RS) and geographic information system (GIS). the resulted maps are called in this investigation as the study area, the urban, and the cone area maps (Figs. 2a, b & c). The first map is the largest and displays the lithological units and the structural elements of the study area. The second includes the house building and cultivated land location. The third geological map includes the volcanic plugs and travertine cones which are usually associated with hot springs.

1.1. Lithological units

The exposed rock succession of the study area is composed of Precambrian metamorphic and igneous complex, Cretaceous Tawilah Group, Neogene and Quaternary volcanic succession, and Quaternary sediments and travertine deposits

The Tawilah Group which is mainly composed of different types of sandstone occupies the moderately elevated and gently sloping hills around the basement exposures at the southeastern corner of the study area (Fig.2a). Two rock units could be recognized in the mapped area, these are lower and upper units which may be stratigraphically equivalent to the two formations of the Tawilah Group after Al-Subbary (1990).

The lower unit is composed of white or yellowish sandstone with occasionally gravel layers and clay thin bed interaction. This unit forms low topographic relief with observed moderate to steep slopes, therefore, it covers relatively narrow stripes overlying the exposed basement rocks (Fig.2a). The upper unit is composed of yellow, cross-bedded, and gravelly sandstone with numerous conglomeratic horizons showing gentle slopes and governing wide areas in the southeastern and northeastern parts of the map (Fig. 2a). Generally, the Tawilah Sandstone beds are dissected by numerous faults, fractures, and dykes of different orientations (Fig. 2C).

The Tawilah Group pinches out towards the eastern part of the area and overlies the subsurface calcareous succession of Amran Group (Middle-Late Jurassic) or non-conformably exposes upon the basement outcrops (El-Anbaawy and Fara, 1993). On the other side, the top beds of the Tawilah Group seem to be eroded and it is immediately below the Tertiary Volcanics (Fig. 2).

The Tertiary Volcanics or Yemen Trap Series in the study area; are identically like those in WYVP. They are divided into two major units; the lower unit is basal basalt and the upper is composed of stratified pyroclastic succession (Fig. 2a).

The basal basalt covers mainly the eroded surface of the Twilah Group. It is occasionally interbedded with continental lake deposits. The upper pyroclastic unit is composed of felsic, Tuffaceous, and ignimbrite volcanic rocks that vary in thickness, fractures intensities, and weathering degrees. Both basal basalt and pyroclastic beds are commonly altered to bentonitic swelling clay materials which may lead to mass wasting at steep slope mountains during heavy rainfalls in the catchment areas of the Wadi Bana basin.

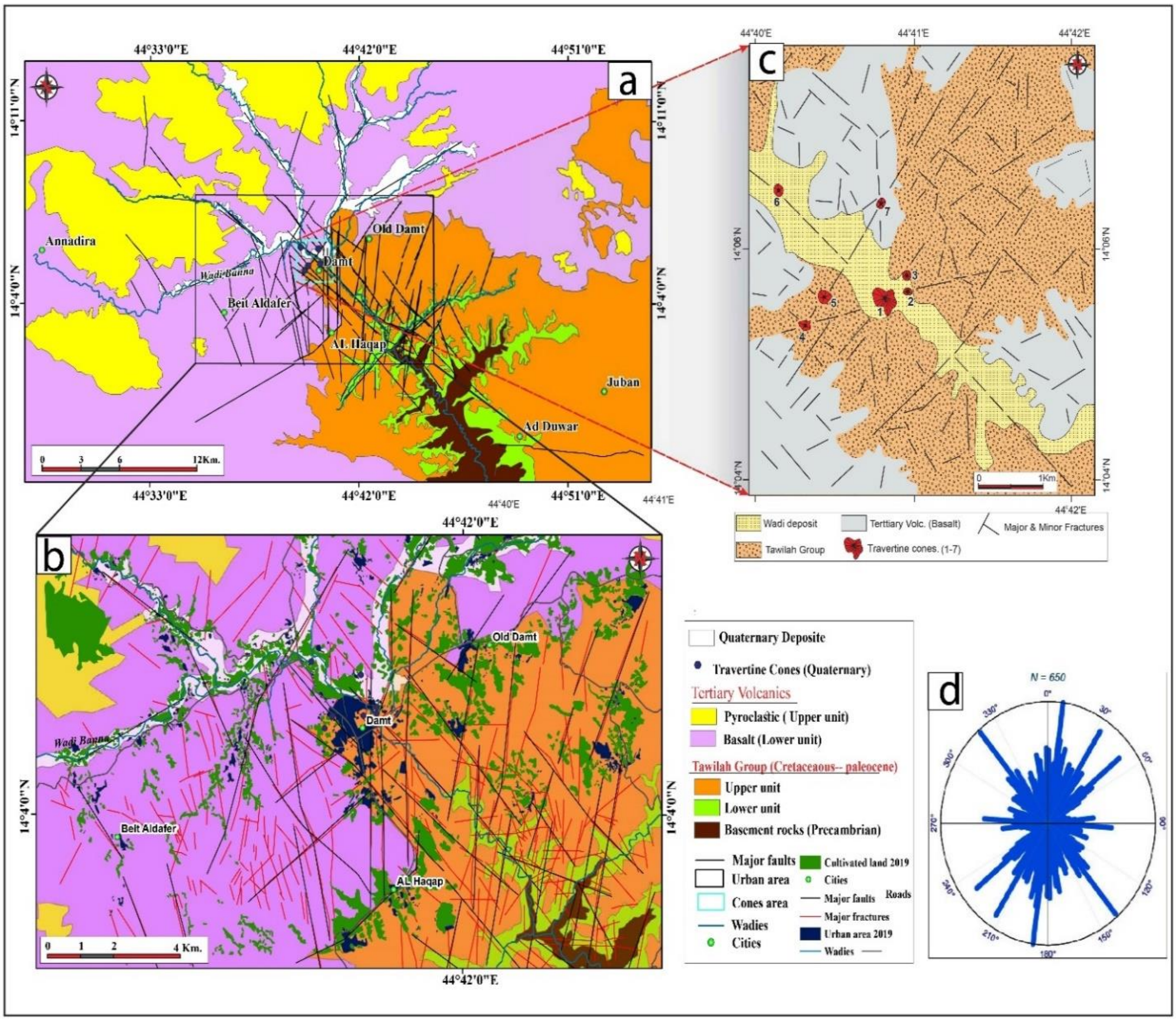

Fig. 2. a: regional geological map of the study area; b: Detailed Geological map of the urban area; c: Detailed geological map of the cone area; and d: Rose diagram of the mapped fault in the Urban area.

The Quaternary Volcanic activities in Yemen continued up to the present time and produced several volcanic fields (i.e cones and sheets) in the WYVP, the most active and the nearest to the area is that of the Dhamar volcanic field. No volcanic fields are detected in the Damt District except some scattered rhyolitic plugs which are completely hidden by letter-formed hot springs deposits in the form of travertine cones. These volcanic plugs may be genetically like the peralkaline rhyolitic cones of the Aden volcanic series which were described by (Cox et al., 1969).

Seven spectacular travertine cones have a number from 1 to 7 in figure 2b, are detected investigated along with two structural trends: the NW-SE (the trend of the main wadi channel of the Nasuq subbasin) and NE-SW (Fig. 2b). The morphological characteristic and land use conditions of these travertine cones are given in Table (1).

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Table 1: Distribution of the travertine Cone characteristics and Land uses in the Cone area, Damt

Table 1: Distribution of the travertine Cone characteristics and Land uses in the Cone area, Damt District for cones locations, see the geological map (Figure 2b)

Cone characteristics & Land uses	Cone No (1)	Cone No (2)	Cone No (3)	Cone No (4)	Cone No (5)	Cone No (6)	Cone No (7)
Cordination	14°05'27.79"N 44°40'21.13"E	14°05'31.50"N 44°40'34.02"E	14°05'35.46"N 44°40'34.32"E	14°05'16.36"N 44°39'41.94"E	14°05'27.48"N 44°39'49.92"E	14°06'16.69"N 44°39'28.74"E	14°06'4.25"N 44°40'18.35"E
Location	West of the wadi Nasuq channel	East of the wadi Nasuq channel	North East of the wadi Nasuq channel	isolated faraway from wadi Nasuq channel	faraway from wadi Nasuq to north east	isolated faraway from wadi Nasuq channel	North East of the wadi Nasuq channel
Base Perimeter	1885 m	309 m	126 m	583 m	678 m	539 m	740 m
Height	75 - 85 m	about 10 m	about 6 m	5 - 10 m	about 12 m	about 13 m	15 - 16 m
Symmetry	assymmetrical	nearly assymmetrical	nearly symmetrical	assymmetrical	assymmetrical	assymmetrical	nearly assymmetrical
Crater Condition	opened with perimeter 122 m	opened with perimeter 83 m	opened with perimeter 45 m	sealed with perimeter 204 m	sealed with perimeter 198 m	opened with perimeter 103m	sealed with perimeter 122 m
Slope of the Cone hill	steep slope to the west & gentle slope to the east	steep slope in all direction particularly to the west	moderately steep slope in all direction	steep slope to the west & gentle slope to the east	gentle slope in all direction	moderately gentle slope	moderately gentle slope
Land use around the Cones (e.g urban and cultivaited lands)	house buildings of Damt city to the west	considerable house buildings to the north west	considerable house buildings to the west	very few house buildings to the west	a lot of house buildings around & on the cone	very few house buildings to the south	few house buildings to the west
	no cultivated lands are observed	scattered cultivated lands to the north east	few cultivated lands to the east	no cultivated lands are detected	no cultivated lands are detected	scattered cultivated lands to the south east & south west	scattered cultivated lands to the north west & south west

travertine deposits have been petrographically studied by (El-Anbaawy and Fara, 1993 and Al-Nabhani, 2021). The present study recognized three types of occurrences around the Harada (cone No.1), these are crater travertine, fissured travertine terraces, and brecciated travertine mounds. These types of travertine deposits could be recognized also in the other cones, particularly those No.2,3 & 6 which have opened craters (Table 1).

Quaternary deposits occupy the main wadi channels, alluvial fans, and wadi terraces through and around the volcanic mountains and Tawilah hills. The wadi channels and downstream areas of the northwest subbasin of wadi Bana receive a great amount of recent eroded materials which resulted from mass wasting at steep slopes of the volcanic mountains.

1.2 Structure Pattern

Damt area as a part of Yemen has a prolonged tectonic history started by Neoproterozoic Pan-African orogeny and, ultimately to the ongoing opening of the Gulf of Aden and the Red Sea (Bosworth et al., 2005; As-Saruri et al 2008, and Khanbari, 2015). Therefore, the Damt area is characterized by superimposed tectonic elements represented by numerous fault and fracture populations.

A group of NW to NNW, NE, and E-W to ENE-oriented fault populations have been mapped in the Damt area. The NW to NNW-oriented faults which are parallel to the main trend of the Red Sea are the main predominant in the study area and have an obvious vertical displacement. Numerous basaltic dikes of the same orientation have been mapped throughout the study area. The E-W to the ENE-oriented faults which are parallel to the main trend of the Gulf of Aden is the second predominant trend in the study area. NE-oriented faults are only mapped in the eastern part of Wadi Bana and affecting the basement and Tawila Group. The three fault trends are intersected formed a dense and complex fault network that is genetically related to different tectonic events and stress regimes. The geo-environmental significance of the mapped fault pattern in the Damt area is obvious and is summarized in the following points

The drainage network is strongly controlled by fault patterns. Generally, streams having linear courses and flowing over the predominant fault trends where the mainstream of Wadi Bana coincides with NW-oriented fault, main streams of Wadi Nasug, Aashri, Hani, and Matalbah coincide with NE-oriented faults. Hot springs and the travertine cones are aligned along the NW and ENE oriented faults and located at the intersection points of the three fault trends Most of the mountain's scarps in the Damt area are fault scarps of the NW and ENE oriented faults

GEOHAZARDS

1. Mass Wasting and slope instability hazards

The Damt area has a high vulnerability to different types of mass wasting hazards which are closely related to geological heterogeneity and variation in slope topography. However, their spatial distribution is further influenced by a weakening of rocks by weathering a long fracture, water content, and other preparatory and triggering factors which will be discussed in section 5. Therefore, the spatial distribution of the hazard-prone areas is preliminarily reported based on slope gradient maps (Figs 3 and 4) with some field observation.

GENERAL CHARACTERISTICS

It is known that the highest susceptibility sites occur in slopes greater than 25° like those predicted to occur in the high volcanic around the urban area (Fig.4) The sites may be exposed to rock falls, land sliding, and debris flows which may be generated by gravitational.

Influence on the steep slope during heavy rainfall. Generally, the mass wasting activities increase with increasing slope angles and water content, depending on the thickness of soil profile and the availability of water content rotational and/or transitional land sliding may occur within the tertiary volcanic mountains. The rotation type needs deeper soil and a long distance from the water divide than the translation one.

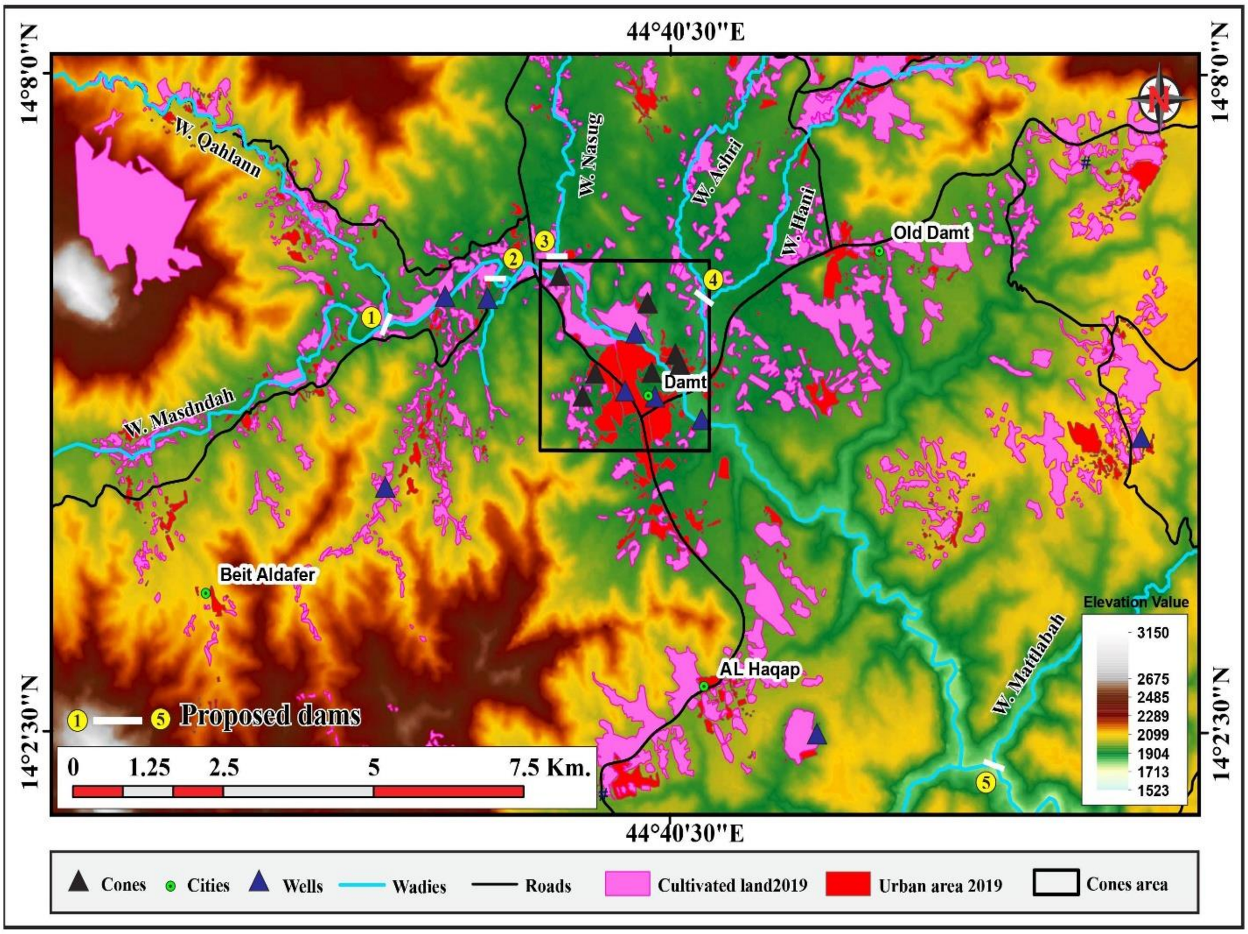

Fig. 3: Digital Elevation Model (ASTER GDEM) of the study area spatial distribution of prone areas

Slope angle is one of the key factors concerning mass wasting susceptibility. Therefore, the study area could be divided into three categories of major prone areas, these are steeply sloped, moderately sloped, and gentle sloped prone areas. This categorization is associated with relative relief situations to further subdividing the prone areas into low, medium, and high relief lands as illustrated in the following paragraphs (Figs. 3 &4).

Steep sloped prone area

Lands with high relative relief

These lands have the highest susceptibility to severe weathering, erosion, land sliding, and debris flow hazards. They occupy the highly weathered and fractured Tertiary volcanic terrains where upstream watersheds with their structurally controlled streams, exist. These lands are concentrated within four blocks (Figure 4) as follows:

- Southwestern block to the South of wadi Masdndah.
- western black within An Nadirah site.
- The northwestern block within Ar Radmh.

- The northeastern block between Wadi Ashari and Wadi Hani.

In these lands all conditions and factors required for the initiation of mass wasting are available. Of these conditions are the widely distributed steep sloping lands which may accelerate the instability, weathering processes, land sliding, and detritus flow.

b) Lands with low relative relief

These lands occupy the southeastern corner of the study area (Fig. 4) within the downstream of wadi Nosuq, one of the main channels of Wadi Bana sub-basins.

They have a high susceptibility to drastic erosion and other factors required for intensive mass wasting activities.

In conclusion, these areas are highly hazardous where they are prone to widespread mass wasting. Most of their slopes are marginally stable that could be rapidly shifted to an activity unstable state by external events (e.g., earthquakes and flash flooding events). On the other side, these areas may be exposed to random construction of unpaved roads by citizen communities to improve accessibility. These human activities which may include excavation contribute to triggering steep slopes leading to further mass wasting hazards.

Moderately gentle sloped prone areas

a) Land with medium relief

These lands occupy the eastern Tawilah hills that extended to the cone and urban area. The hills and their terraces are characterized by moderately steep slopes ranging from 15-25° (Fig. 4). They are moderately susceptible areas and may be exposed to land sliding, particularly along with the clay and mud beds during heavy rain full.

b) lands with low to medium relief

These lands occupy the wadies floors in between the volcanic blocks and the Tawilah hills nearby the urban and cultivated lands. The slope shows low mass wasting susceptibility with about 15° or and mudflow a little more (Fig. 4). Land sliding becomes more active during heavy rainfall.

Very gentle sloped prone areas

These areas are characterized (i.e., slope angle less than 15°). They occupy the cones and surrounding urban areas that including houses buildings and cultivated lands. (Figs 3 and 4).

They are occasionally exposed to limited mass wasting activities during heavy rain full. Human activities such as uncontrolled utilization of groundwater for irrigation and construction of randomly unpaved roads may initiate the gently sloped areas to be moderate activity unstable lands.

2. Seismo-tectonic and earthquake hazards

Seismotectonic Setting

General Seismicity that represented by the earthquake epicenters distribution (Fig.5a) seems to correlate well with the major structures (e.g., normal, and strike-slip faults) in Yemen and surrounding areas (Fig.1). The seismic activities of the Red Sea and the Gulf of Aden are corresponding to the mid-oceanic type of seismicity.

These oceanic rifts are characterized by shallow earthquakes which occur mostly as swarms along the ridges and are believed to be volcanically related (El-Isa, 2015). These focal mechanism solutions of the earthquake events along the rift valley of the southern Red Sea suggest a pure normal faulting mechanism with a NNE-SSW extension (Al-Aydrus, 2010), while the focal mechanism solution in the Gulf of Aden shows two types of faulting, normal and strike-slip (Khanbri, 2020).

All earthquakes, geological and structural data are implemented in Geographic Information Systems (GIS) to study the seismotectonic setting of Yemen. Based on the distribution of earthquake epicenters (Fig. 5a). Yemen is divided into six seismotectonic provinces (Khanbri 2020), the western one of them which the present study area is located, is the most active province in Yemen. This province is located near the most active rifting zones of the Red Sea and the Gulf of Aden as well as the Afar plume where the interaction between the tectonic and volcanic activities is the main source of seismicity (Khanbri 2020).

Accordingly, the Damt District is located within the WYVP which occupies the majority of the western seismotectonic province and consequently be considered as the highest seismotectonic part in Yemen. Furthermore, the study area is located near the biggest recent earthquake event in 1982 of Dhamar – Dowran Anes region. This deadliest earthquake in Yemen was felt over a large area including Damt District. It is produced by normal fault of NW –SE orientation, parallel to the Red Sea rift axis due to NE extension which is associated with the rifting (Al-Sinawi and Al-Aydrus 1999).

Earthquake epicenters around Damt District

Based on the recent seismicity investigation (e.g., Huchon and Khambri, 2003; Khambri and Huchon, 2010 and Khambri, 2015 and 2020), and the combination of the regional structural map with earthquake epicenters distribution map of the study area and the surrounding Dhamar, Ibb, and Ad Dhalih provinces (Figure 5 b), the following observations are revealed:

Earthquake epicenter distribution (Fig. 5b) seems to be correlated with the major normal faults that are parallel to the Red Sea and the Gulf of Aden, and Quaternary volcanic fields. However, this is not the situation in the study area where the earthquake epicenters are nearly inside their frame (figure 5 b).

Damt District was affected by mild to weak seismic activity during the Dhamar earthquake 1982 event, despite its occurrence within the most seismotectonic active volcanic province in Yemen.

Dhamar province has an active recent Quaternary volcanic field while this field is not available in Damt area. The absence of the recent volcanic field may result in lowering the seismic activity and consequently lowering the epicenters concentration inside the study area (Fig. 5b).

The seismic situation of the Damt district may, therefore, support the suggestion that the historical seismicity of the region is attributed mainly to the occurrence of Quaternary volcanic fields.

The WYVP could be divided into two seismic zones. The central zone, including Dhamar, Sana'a, and Amran Quaternary volcanic fields, is characterized by high seismic activities and a high concentration of earthquake epicenter distribution.

The other zone of WYVP is the eastern-southeastern zone, including Damt District where Quaternary volcanic fields (i.e., volcanic cones and sheets) are not involved and consequently lesser in seismicity, and concentration of earthquake epicenters (Fig 5b).

Several reasons may be suggested to explain the mild to the weak seismic situation of Damt area

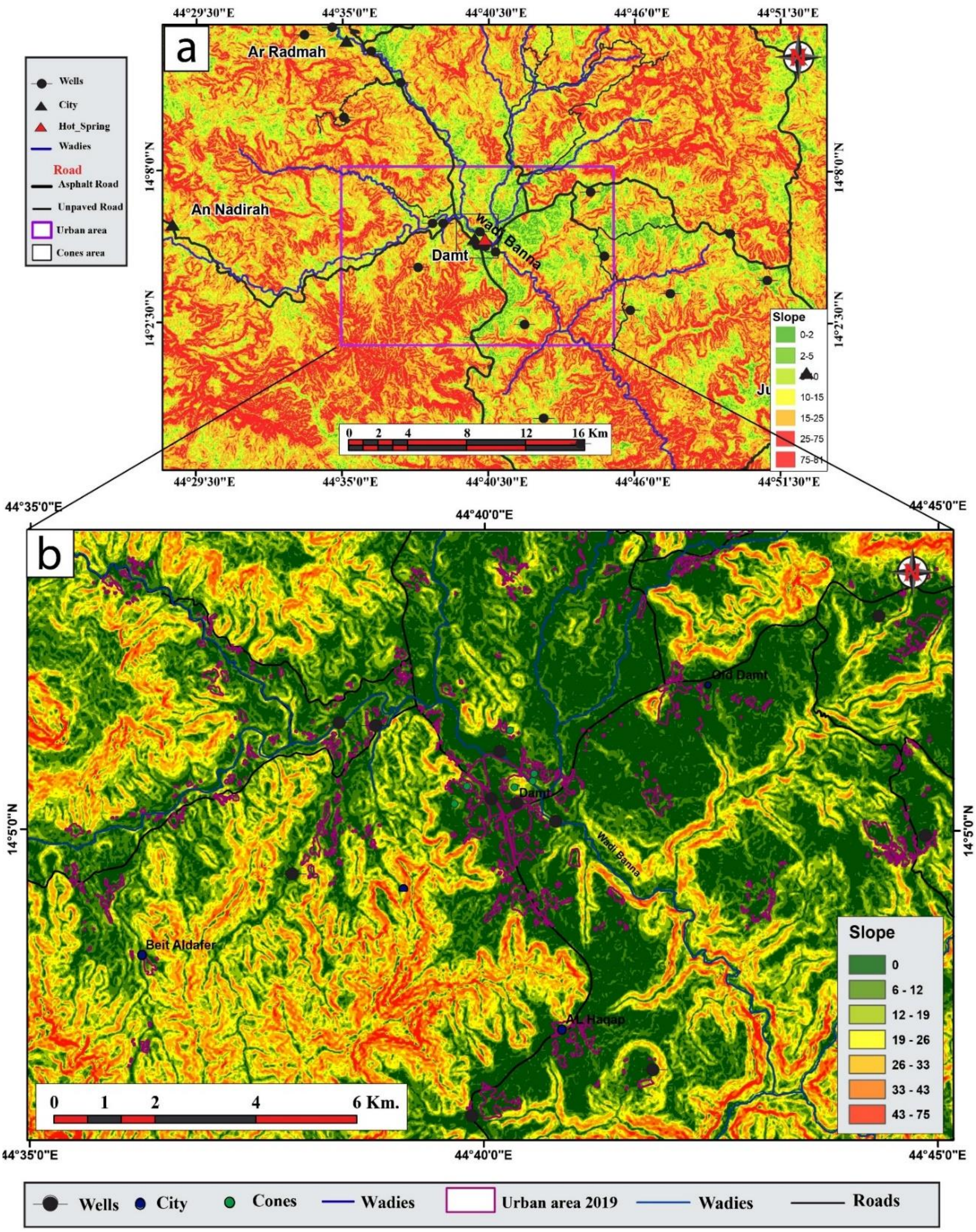

Fig. 4: a. Regional slope gradient map of the study area and it environ; b. slope gradient map of the study area

Close location of the study area to the eastern non-volcanic margin rather than the western one leading to the absence of recent volcanic fields. It is also far from the Afar plume and melting shallow mantle impression.

Close location of the study area to the relatively stable eastern basement block (Fig.1). However, some low magnitude earthquake epicenters are potentially scattered to the southeast to the southeast of the study area because of reactivation of the old basement faults during the rifting of the Red Sea and the Gulf of Aden.

In conclusion, the tectonic picture in Damt is complicated by numerous diagonal faults running mainly parallel to the Red Sea and Gulf of Aden rifting trend. It is far from being tectonically calm and it is considered the prone area to earthquake

3. Watershed analysis and flash flood hazard
Hydromorphometric Characteristics

Wadi Bana is one of the main hydrographic basins draining to the Gulf of Aden. It contains several sub-basins, at one of which the study area is located (Fig. 6). The study area occupies a great part of the northwest sub-basin of the Wadi Bana basin (NSWP). Based on the DEM processing through the GIS Spatial Analyst technique and using the ARC hydro module to routinely extract the stream networks. the DEM data are used to characterize the morphometric and geomorphic features of the investigated sub-basin.

Based on the distribution and orders of the stream, the NSWB is further categorized into four additional sub-basins which are called in the present study sub-sub basins (SSB) with numbers 1, 2, 3, &4 (figure 6). The SSBs and belonging to NW Wadi Bana, Wadis Masdinda-Qhlann, Wadi Nasuq, and Wadis Ashri-Hami respectively (Fig. 6). The upstream catchment area of SSB 2, 3, 4 is located outside the area of the study, while that of SSB a is located within the southeastern corner of the study area. The SSB 1,2 & 3 downstream are prone to flash hazards to the northern zones of the study area where the main urban cities are located (Fig. 6) it is observed that most artesian wells and hot springs are accumulated around or near this downstream area where the groundwater aquifers may be recharged. The downstream of SBB 1 is located outside the study area where it relates to the main channel of the Wadi Bana basin while its upstream tributaries are cutting through the Tawilah |sandstone and highly weathered basement rocks (Figs. 2 and 6).

The values of morphometric parameters of the SSB 1, SSB 2, SSB 3, and SSB 4 were calculated according to the symbol and formula of the traditional references given in table 2. The drainage network analysis shows dendritic type dominating the stratified volcanic rocks and the Tawilah sandstone in the NSWB. Most of the streams associated with the basement rocks are of a straight line that intersected at a right angle revealing structural controls (Fig. 6).

Generally, the distribution of the morphologic parameters (table 2) illustrates that the study watersheds are well-drained basins showing different shapes and dimensions due to their lithological, topographical, and structural characteristics. As revealed from the watershed analysis (table 2), the smallest basin area is that of SSB 4 the largest one is that of SSB 1 and the other two watersheds (SSB 2 and SSB 3) have intermediate values. This phenomenon of the light value of SSB 1 and the contrasting low values of SSB 4, is observed not only in the basin area but also in many other parameters, basin order, basin relief, basin length, basin width, ruggedness number, and texture ratio (table 2). These may indicate that the smallest watershed (SSB4) which has the lowest values (table 2) would be expected to have sharply peaked flood discharge. Contrary to that situation, the largest watershed (SSB 1) which has the highest values (table 2) would be expected to have attenuated flood discharge periods.

The values of the steam frequency, drainage density, and infiltration ratio are found to be slightly variable or nearly equal in the study watersheds (Table 2). These parameter values depend on the lithology, structures, infiltration power, and relief and consequently control flash flooding potentiality in the study area. The drainage density, for instance, is a vital factor that controls the runoff potentially, where the highest values can accelerate the runoff and water accumulation. On the other side, the infiltration ratio is used as an indicator for infiltration rate evaluation and acquired by multiplying drainage density and stream frequency (Faniran, 1968). However, in this study, the trends of these parameter values are not clear and consequently could not be used directly to predict the flash flood potentiality due to their influence by hill slope and fracture intensity distribution. Furthermore, the relief ratio is used as a degree of the general steepness of the main wadi channels, and it is a marker for the degree of erosion development operating on the slope of the basin (Schumn, 1958). The relatively high value of relief (gradient) ratio in SSB 4 (51.2) if compared with that in SSB 1 (234) as given in table 1 may support the conclusion that the SSB 4 watershed would be expected to have higher potentiality for the flash flood than the SSB 1 watershed.

Spatial distribution of prone regions.

The flash flood hazard potentiality in the study area is influenced by the impact of the amount of rainfall, steepness factors, rate of soil or bedrock infiltration, and land use. The average rainfall during the whole year in Damt District which is related to semiarid climate is 370mm. its pattern is sparse and erratic in frequency, duration, and distribution where the monsoonal season occurs from March to May and the second season between July and September (Alderwish and Almatary, 2011). The rainfall pattern represents one of the critical factors contributing mainly to the amounts of water flow, slope intensity, surface erosion, and soil transportation which occasionally cause inland sliding on the volcanic terrains.

The steepness factor affects mostly water flow direction, water velocity, and runoff susceptibility. The surface runoff depends on the rates of infiltration where the higher rates are associated with lesser runoff susceptibility. Therefore, the increasing soil permeability leads to decreasing the runoff hazards and simultaneously allows aquifers to recharge. In addition, an urban area that including house buildings and paved roads is characterized by smaller infiltration and thus produces greater runoff. Great habitation and utilization of main wadi channels for agriculture purposes enhance the flash flood risks.

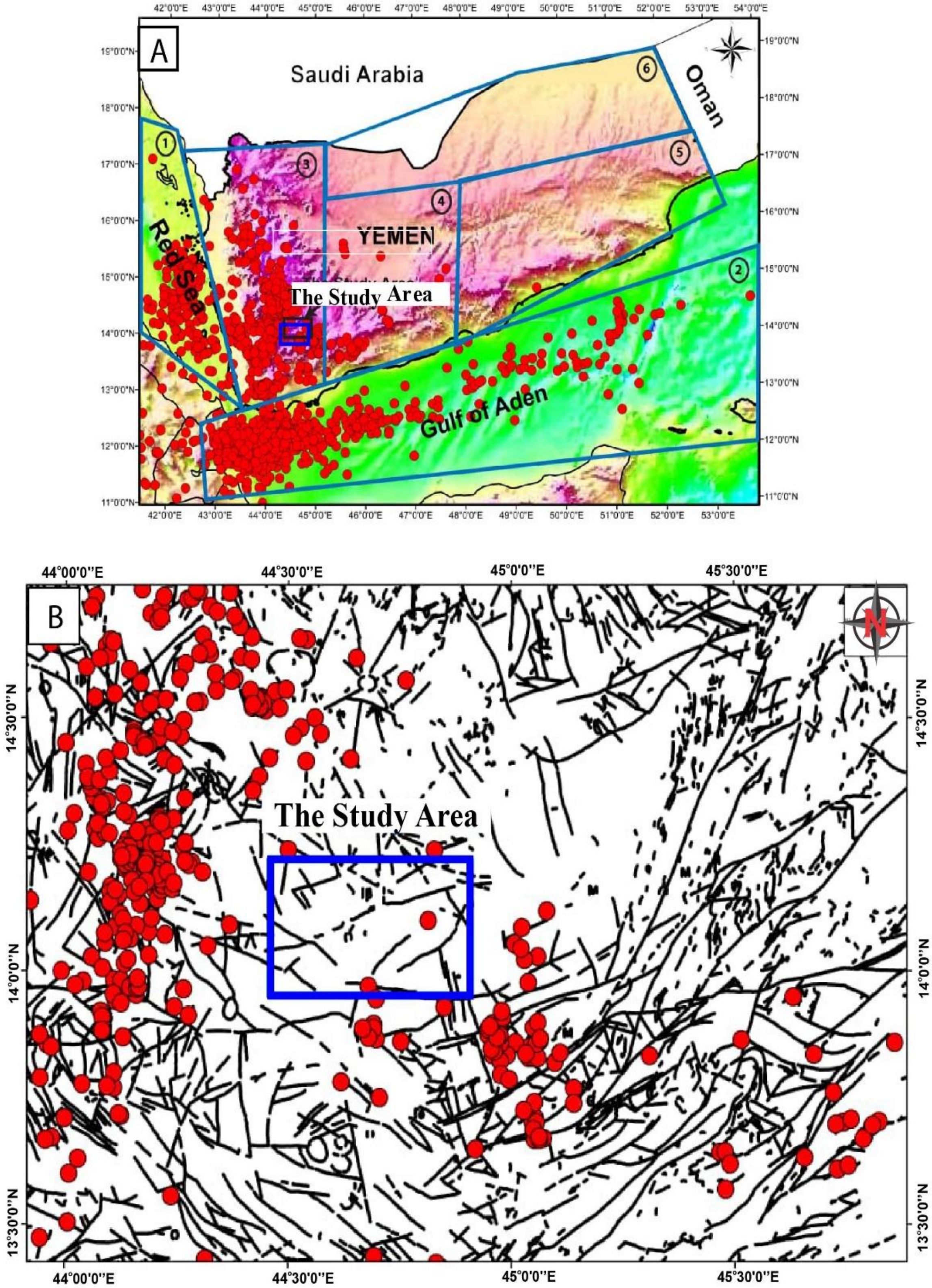

Fig. 5: a. Siesmogenic zone of Yemen (Khanbari 2020); b.Fault map and distribution of the earthquakes' epicenters in the study area and its environ.

Table 2: Results of calculated morphometric parameters in Sub- Sub Basins No. 1, 2, 3 & 4 (for location see figure 6)

Morphometric parameteres and its formula				Calculated Values			
				Sub - Sub Basin No.			
Serial	**Parameter**	**Reference**	**Symbol/Formula**	**No. 4**	**No. 3**	**No. 2**	**No. 1**
1	Area (Km)	Schumn (1956)	A	239.2	638.2	820.7	2542
2	Perimeter (Km)	Schumn (1956)	P	79.6	134.4	157.3	284
3	Basin order	Strahler (1957, 1964)	u	4	5	5	6
4	Drainage density (Km/Km^2)	Horton (1932, 1945)	$D_d = \sum L_u/A$	0.67	0.37	0.71	0.73
5	Stream frequency	Horton (1932, 1945)	$F_s = \sum N_u/A$	0.58	0.54	0.53	0.57
6	Infiltration number	Faniran (1968)	$I_f = D_d \times F_s$	0.39	0.2	0.37	0.42
7	Length of overland flow (Km)	Horton (1945)	$L_g = 1/(2D_d)$	0.75	1.35	0.7	0.68
8	Z_x (m)		Maximum elevation of the basin	3097	3072	3232	3239
9	Z_m (m)		Minimum elevation of the basin	1865	1881	1881	1006
10	Basin relief (Km)	Strahler (1952, 1957)	$B_h = Z_x - Z_m$	1232	1191	1358	2233
11	Basin Length (Km)	Gregory and Walling (1973)	L_b = Largest horizontal distance between 2 points parallel to	24.064	39.073	47.9	96.5
12	Basin Width (Km)		W_b = Largest horizontal distance between 2 points nearly	19.343	25.559	29.7	49.1
13	Relief (gradient) ratio (Km)	Schumn (1956)	$R_h = B_h/L_b$	51.2	30.48	28.4	23.1
14	Ruggedness number	Schumn (1956), Melton (1957), Strahler (1964)	$R_n = B_h \times D_d$	825.44	440.67	964.2	1630
15	Texture ratio	Schumn (1956)	$R_t = N/P$	0.88	1.27	1.39	2.6
16	Form factor	Horton (1932)	$R_f = A/(L_b)^2$	0.41	0.41	0.36	0.27
17	Circulatory ratio	Schumn (1956)	$R_c = 4\pi A/P^2$	0.47	0.44	0.41	0.4
18	Elongation ratio	Schumn (1956)	$R_e = 2\sqrt{(A/\pi)} / L_b$	0.72	0.73	0.67	0.59
20	Constant channel maintenance (C)	Schumn (1956)	$C = 1/D_d$	1.49	1.47	1.4	1.37

According to the data integration, three prone regions of flash flood hazards are delineated. The highest hazardous region occupies the high elevated steep-sloped volcanic upstream middle stream areas (Fig. 4). The volcanic rocks in these areas are characterized by low infiltration degrees with high stream density. The occupation of this region by some scattered (hanging) villages (Fig. 3) may enhance the flash flood hazard potentiality.

The second region is in the northeast and northwest and central parts of the urban area which represents the down-streams of SSB 2, SSB 3, and SSB 4 (Fig.6). These parts of the watersheds are considered highly risky areas; however, their hydrological characteristics may attenuate the risk degree. This region is partially covered by Tawilah sandstone outcrops, highly fractured basaltic bedrocks, and Quaternary deposits where all these types of lithology could be worked recharging water sources for the underneath aquifers in this downstream area, especially after the heavy rainfall. Furthermore, the urban area of Damt city is almost founded upon Tawilah sandstone's gentle sloped hill and therefore is naturally protected from runoff water accumulation which flows or runs through the lower leveled wadi channels around the major hill outlines.

The third region is located within the SSB 1 watershed where the highest weathered basement rocks and fractured Tawilah sandstone dominate the region (Fig.6). The histomorphometric characteristics of the region may reduce the risk of flooding and facilitate the aquifers recharging.

DISCUSSIONS AND CONCLUSION

1 Integrated controlling factors

Geohazards can seldom be attributed to a single causative factor but should rather be seen and a result of preconditions, preparatory and triggering causative factors. However, in the Damt case study, it is difficult to separate preconditions from preparatory factors, so we discuss the integrated controlling factors under two topics:

Preconditions – preparatory factors including topographic, lithological soil profile, structure, and hydromorphologic factors.

Triggering factors including heavy rainfall, seismicity, and land use (e.g., population pressure and aggressive human interference).

It is worth mentioning that mass-wasting and flash flood hazards are mostly influenced by similar integrated controlling factors. This study indicates that seismicity cannot be the main triggering factor in Damt area. The following is a brief discussion on examples of integrated impacts of these causative factors.

1.1. preconditions and preparatory factors.

The main factor controlling the magnitude and severity of mass-wasting and flash flooding in the study area is the topographic slope (i.e., slope angles) where the slope influences the extent and rate of surface runoff: the steeper the terrain the more readily water runs off over the surface and less it tends to sink into the soil. Also, the steep slope topography (with a slope angle greater than 25 degrees) triggers surface erosion and insolubility hazards, even with a slight rainfall amount.

Because no sharp contact between the shadow soil and the parent bedrock is observed in the Damt area, both are discussed as lithological factors. The rate of surface runoff is influenced by the extent of infiltration, which in turn is controlled by the soil type and how much soil is exposed. The study area is covered by highly weathered volcanic and basement rocks as well as sandstones and wadi deposits. It is clear that the lithological condition which includes small clay contents, degree of weathering, and infiltration rate, plays an important role in the extent of mass-wasting and earthquake hazardous impacts on houses building and cultivated terraces. The presence of these types of rock may cause significant amplification of seismic shock waves.

During and after heavy rainfall, most fractured volcanic rocks are altered to swelled clay minerals and become land sliding prone bedrocks. It was found that high clay and silt content in soil increases the erosional susceptibility.

Structural factors influence mass-wasting and earthquake hazards. Fault and major locations act as the primary tracker for mass-wasting susceptible zones. Most of the volcanic and basement lithological units in Damt area were exposed to a long period of weathering process resulting in very susceptible lithology for cracking, fracturing, and sliding. Furthermore, the structural setting in the Damt area creates different deformation grades causing several weak zones in the weathered rocks, particularly along the main channels of the northwest sub-basin of the Wadi Bana greater basin (NSWB). The disintegrated rocks, due to weathering and fracturing, may increase water flow along steep channels during heavy rains.

The study hydromorphologic parameter is an essential factor controlling the flash flood hazard potentiality. The most important of these integrated controlling are stream frequency and drainage density as well as the infiltration ratio. However, these parameters are found to be slightly variable without clear trends and consequently, could not be used directly to predict the flash flood potentiality due to their influence by other integrated factors such as hill slope and fracture intensity factors. Instead, the shape and dimensions parameters are indicated to be more applicable controlling factors than the others. Contrary to that of SSB1, it is indicated that the smallest watershed SSB4 which has the lowest parameters values would be expected to have sharply peaked flood discharge. It is indicated that the downstream of the watersheds SSB1, 2, 3, and 4 are more vulnerable to flood hazards than their upstream, however, the northeastern watershed SBB4 is relatively more vulnerable to flood hazards than other ones.

1.2. Triggering factors

Rainfall, particularly extreme rainfall events or thunderstorms, is believed to be one of the serious factors producing flash floods or initiating mass wasting in the study area. During flash floods, a tremendous volume of water is running in a short time. During this short time, shallow landslides/debris flows may occur in the volcanic mountainous zone around the urban Damt city.

Generally, earthquake events represent the triggering processes that cause mass wasting activities. it is predicted to detect landslides, for instance along major fault zones associated with the extension of the epicenter trends. Distance to epicenters was considered as an important factor indicating land mass-wasting susceptibility. However, the Damt area is surrounded by earthquake epicenters which may result in the formation of mild to a weak seismic situation of the area. Therefore, seismicity cannot be a main triggering factor in the study area, contrasting with the surrounding regions in the WYVP. In these regions, the weaknesses of the traditional Yemeni houses are the main factor for damages rather than the magnitude of the earthquake.

Land use factor is the key factor triggering mass-wasting hazards and increasing the negative impacts of flash flood activities. For examples of human interference (e.g., excavation, construction of buildings and roads as well as cultivation of reclaimed lands), will be briefly discussed herein. Excavation for different purposes such as house building, unpaved roads, and agriculture terraces, was the direct trigging cause for slope failure and creep phenomena. The unpaved roads which are very common in study mountainous regions, contribute as another crucial reason in triggering steep slopes to erosion which leading to severe mass wasting hazards. The urban area either within the Damt city block or within the mountainous villages is surrounded by or adjacent to dense cultivation which represents another threat to the stability of the building foundation. The soil of the foundation is highly affected by drained water seepage around the cultivated farms.

2 Mitigation Measures and Recommendations

2.1 Mitigation measures for mass-wasting hazard

Some important actions are recommended to reduce the slope instability hazard and protection the infrastructures in the prone area, of them:

- Reducing the slope angle and decreasing the slope length by the building of contour walls, bench terraces, check dams in gullies to break the slope.
- Maintaining roads and other infrastructure in the hazard-prone areas to avoid soil erosion and land sliding.
- Designing effective site management plan including slope and runoff velocity controlling measures.

2.2. Mitigation measures for earthquake hazard

To avoid damage resulted from predicted earthquake events certain design cautions and monitoring systems must be taken into consideration. Of these measures are the careful choice of foundation sites, using suitable materials for foundation, building construction, and careful choice of engineering design to avoid the negative impact of earthquake hazard.

2.3. Mitigation measures for flash flood hazard

It is important to erect several dams or barriers along the main channels of the sub-sub-basins SSB2, 3, and 4 near their downstream inside the study urban area (Figures 3 and 6). These suggested dams are important, not only for reduce or prevent flash flooding hazards and protect the Dame city but also for saving huge quantities of waters which play an effective role in increasing infiltration opportunities to recharge the underneath shallow aquifers in the study area.

The water is temporarily accumulated in low areas (Fig. 3) acting as ponds and lakes. Storing flood water in man-made closed lakes (reservoirs) during the rainy season is another important action to increase water harvest for agriculture development. The proposed locations for these dams (Fig. 3) are the intersection points between Wadi Masdnda and Wadi Kahlan (Dam No. 1 in figure 3), between Wadi Ashri and Wadi Hani (Dam No. 4), and between Wadi Nasuq and Wadi Mattalahah (Dam No. 5) as well as at Wadi Nasuq and Wadi Masdnda near the outer border of the con area (Dam No. 3 and Dam No. 2 respectively.

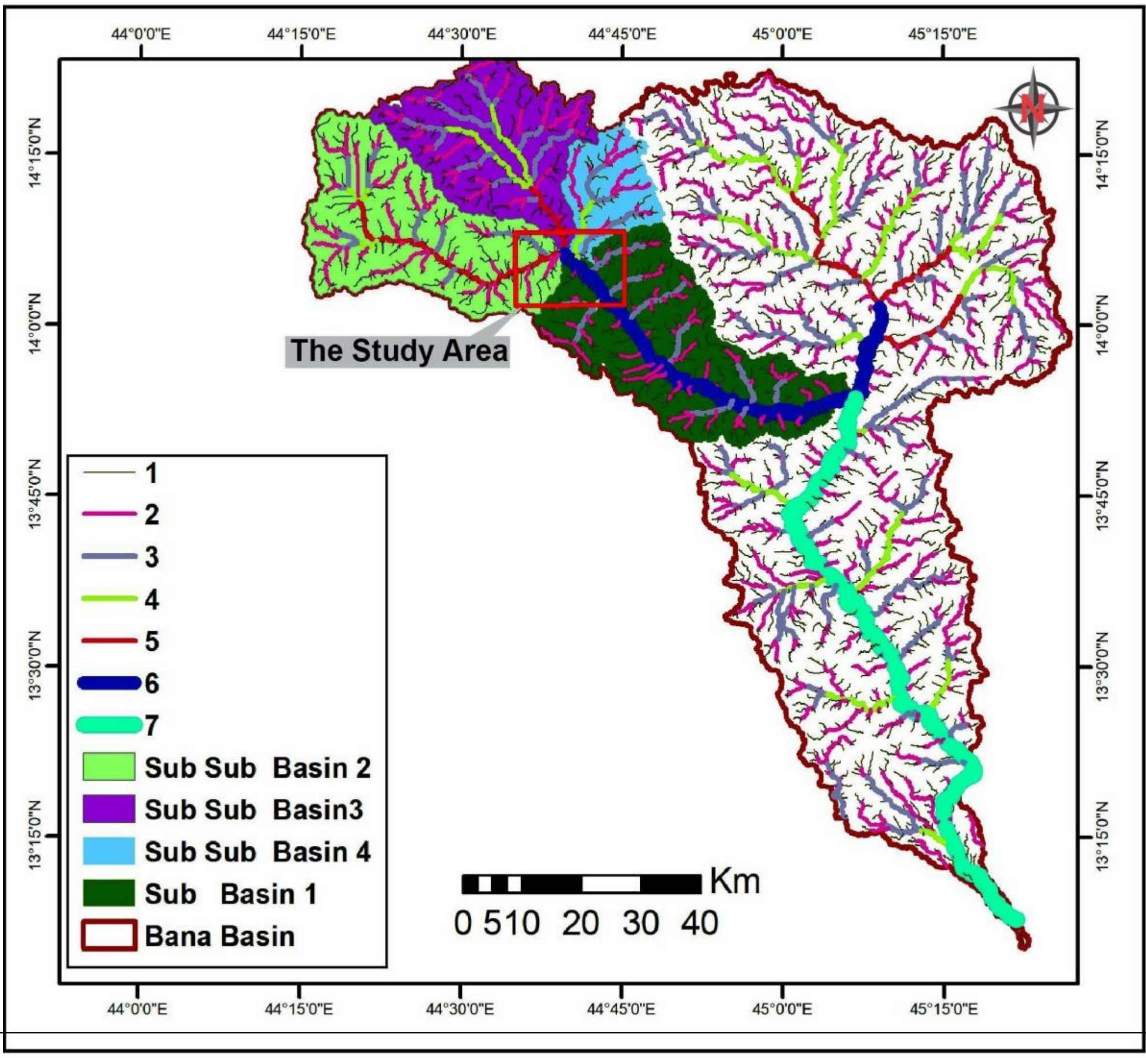

Fig. 6: Stream order network of Wadi Bana hydrographic basin and its sub-basin

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