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Remote Sensing and GIS-Based Assessment of Karst Development in Libya: Evidence from the Al-Jabal Al-Akhdar–Benghazi Plain and Tripolitanian Pre-desert

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Abstract

Karst aquifers are unique hydrogeological environments that are characterized by their complex surface and groundwater drainage systems such as dolines, sinkholes, caves, springs, and karst lakes. The present paper aims to investigate the distribution pattern of karst features and analyze their associations with other geomorphological lineaments in two large karst areas of Libya, namely, Al-Jabal Al-Akhdar–Benghazi Plain, which is located in northeastern Libya, and Tripolitanian Pre-desert, which is located in northwestern Libya. The study used Sentinel-2 multispectral satellite imagery, normalized difference water index (NDWI), 12.5-m ALOS PALSAR digital elevation models (DEMs), and Geographic Information System to delineate karst landforms and analyze their relationships with lineament density. The study revealed several karst landforms, including dolines, sinkholes, closed depressions, caves, springs, and karst lakes. These karst landforms were delineated and extracted from the input data by using different thresholds. In addition, lineaments were extracted from the input imagery and analyzed for their density and water-related anomalies. Subsequently, thematic karst density maps were generated and compared to identify karst variability. The study showed that Al-Jabal Al-Akhdar–Benghazi Plain has a more developed karst system, as demonstrated by the presence of well-developed doline fields, larger and deeper closed depressions, higher number of springs and karst lakes, and higher density of large-scale karst features. On the other hand, the Tripolitanian Pre-desert is generally more arid and contains a lower number of closed depressions, dolines, and caves. The study's results also indicate that dolines are distributed according to the pattern of lineaments, suggesting that these features were formed as a result of carbonate rock dissolution through infiltration groundwater flow and enhanced by structural discontinuities. In addition, karst density analysis revealed local areas with high concentrations of karst features that may be prospective for groundwater exploration and sinkhole hazard assessment. Finally, the creation of an integrated

preliminary karst-susceptibility map revealed that the areas in northern Libya, particularly in Al-Jabal Al-Akhdar–Benghazi Plain and Tripolitanian Pre-desert, have higher levels of karst susceptibility due to the presence of carbonate rocks, lineaments, associated groundwater features, and karst landforms. Overall, the present study demonstrated that the analysis of satellite imagery, combined with 12.5-m ALOS PALSAR DEDMs, NDWI, and GIS analysis can be useful in delineating karst-susceptible areas and assessing groundwater potential and sinkhole hazards in Libya.
Keywords: Remote Sensing, GIS, Karst Landforms, Al-Jabal Al-Akhdar–Benghazi Plain, Tripolitanian Pre-desert, Libya.

تقييم تطور التضاريس الكارستية في ليبيا باستخدام الاستشعار عن بُعد ونظم المعلومات الجغرافية: أدلة من منطقة الجبل الأخضر-سهل بنغازي ومنطقة ما قبل الصحراء في طرابلس

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الملخص

تُعد خزانات المياه الجوفية الكارستية بيئات هيدروجيولوجية فريدة تتميز بأنظمة تصريف معقدة للمياه السطحية والجوفية، وتشمل معالم مثل المنخفضات الكارستية، والفجوات الانهدامية، والكهوف، والينابيع، والبحيرات الكارستية. تهدف هذه الورقة البحثية إلى دراسة نمط توزيع المعالم الكارستية وتحليل ارتباطاتها بالسمات الخطية الجيومورفولوجية الأخرى في منطقتين كارستيتين كبيرتين في ليبيا: منطقة الجبل الأخضر وسهل بنغازي (شمال شرق ليبيا)، ومنطقة ما قبل الصحراء في طرابلس (شمال غرب ليبيا). استخدمت الدراسة صور الأقمار الصناعية متعددة الأطياف، ومؤشر الفرق المعياري للمياه، ونماذج الارتفاع الرقمية بدقة 12.5، ونظم المعلومات الجغرافية لتحديد أشكال التضاريس الكارستية وتحليل علاقتها بكثافة السمات الخطية. كشفت الدراسة عن وجود عدة أشكال تضاريسية كارستية، شملت المنخفضات الكارستية، والفجوات الانهدامية، والمنخفضات المغلقة، والكهوف، والينابيع، والبحيرات الكارستية؛ حيث تم تحديد هذه المعالم واستخلاصها من البيانات المدخلة باستخدام عتبات تصنيف مختلفة. وبالإضافة إلى ذلك، استُخلصت السمات الخطية من الصور وحُللت من حيث الكثافة والشذوذات المرتبطة بالمياه. وعقب ذلك، أُعدت خرائط موضوعية لكثافة الظواهر الكارستية وقورنت ببعضها لتحديد التباين في الخصائص الكارستية. وأظهرت الدراسة أن منطقة الجبل الأخضر وسهل بنغازي تتمتع بنظام كارستي أكثر تطوراً، وهو ما يتضح من وجود حقول واسعة ومتطورة من المنخفضات الكارستية، ومنخفضات مغلقة أكبر مساحةً وأكثر عمقاً، وعدد أكبر من الينابيع والبحيرات الكارستية، وكثافة أعلى للمعالم الكارستية واسعة النطاق. وفي المقابل، تتسم منطقة ما قبل الصحراء في طرابلس بظروف أكثر جفافاً بشكل عام، وتحتوي على أعداد أقل من المنخفضات المغلقة والمنخفضات الكارستية والكهوف. كما تشير النتائج إلى أن توزيع المنخفضات الكارستية يتبع نمط السمات الخطية، مما يوحي بأن هذه المعالم تشكلت نتيجة ذوبان الصخور الكربونية بفعل تدفق المياه الجوفية المتسربة، وهو ما تعزز بوجود الانقطاعات البنيوية. وعلاوة على ذلك، كشف تحليل كثافة الظواهر الكارستية عن وجود مناطق محلية ذات تركيزات عالية من المعالم الكارستية، والتي قد تكون واعدة لاستكشاف المياه الجوفية وتقييم مخاطر الفجوات الانهدامية. وأخيراً، كشف إعداد خريطة أولية متكاملة لقابلية التضاريس الكارستية للتشكل عن أن المناطق الواقعة في شمال ليبيا - ولا سيما منطقة الجبل الأخضر وسهل بنغازي ومنطقة ما قبل الصحراء في طرابلس - تتمتع بمستويات أعلى من القابلية للتكون الكارستي؛ وذلك نظراً لوجود صخور كربوناتية، وخطوط بنيوية، وسمات مياه جوفية

مرتبطة بها، وتضــاريس كارســتية. وبشـكل عام، أثبتت الدراســة الحالية أن تحليل صــور الأقمار الصــناعية - مقترناً ببيانات نماذج الارتفاع الرقمية بدقة 12.5 متراً المســـتمدة من القمر الصـــناعي، ومؤشـــر المياه ، وتقنيات نظم المعلومات الجغرافية - يُعد أداة مفيدة لتحديد المناطق القابلة للتكون الكارستي، وتقييم إمكانات المياه الجوفية ومخاطر الحفر الانهدامية في ليبيا.

الكلمات المفتاحية: الاسـتشـعار عن بُعد، نظم المعلومات الجغرافية، التضــاريس الكارسـتية، الجبل الأخضـر-سـهل بنغازي، منطقة ما قبل الصحراء في طرابلس، ليبيا.

1. Introduction

Karst landscapes are characterized by a variety of unique surface and subsurface features that arise from the breakdown of soluble rocks including gypsum, marble, and limestone. The existence of subterranean drainage systems, where water can flow quickly thru interconnected conduits, is one of the most significant features of karst settings. Karst aquifers can therefore supply significant amounts of water, but their quick groundwater movement also makes them especially prone to contamination (Dussart-Baptista et al., 2003; Einsiedl, 2005; Bonacci and Roje-Bonacci, 2008; Cooper et al., 2011; Zajc et al., 2014; Bin et al., 2017; Zhao et al., 2020; Luo et al., 2023; Jiang et al., 2026). Contrarily, siliceous karst forms in rocks that are often far less soluble than those linked to conventional karst. However, processes like chemical dissolution can create distinctive structures like sinkholes, caves, and leftover rock towers over extended weathering times. The mineral makeup of the bedrock, the presence of acidic organic compounds in precipitation, heavy rainfall, and extended weathering all have an impact on the formation of siliceous karst. When combined, these processes can accelerate the siliceous rocks' ordinarily sluggish breakdown and eventually create landscapes that resemble karst (Piccini, 1995; Vaqueiro-Rodríguez, 2004; Vasconcelos et al., 2013; Hardt et al., 2022).

Fig. 1 represents the karst system as a connected surface and ground water drainage system. The source of the recharge is rainfall which infiltrates the ground and becomes groundwater. This process consists of the dissolution of carbonate rocks by water infiltrating through the ground and dissolving existing fractures and planes, which are later expanded by the same process. The natural formations of the area such as fractures and bedding planes dictate the flow of groundwater, which later can form interconnected passages and caves. The further dissolution can cause sinkholes and cave collapses while the groundwater flows towards the coastal discharge points. Groundwater circulation and karst development are closely related, as Fig. 1 illustrates. The original groundwater circulation paths are governed by the geological structure, and water-rock interactions progressively alter and expand these pathways thru disintegration. The ensuing network of caverns, conduits, and fissures eventually takes over as the primary groundwater flow route. In the end, this ongoing interaction between water and bedrock creates a highly interconnected aquifer system that can supply significant groundwater resources but is still susceptible to contamination and other environmental stresses, especially in areas where groundwater is quickly moved from recharge areas to coastal discharge zones. The Libyan karst has been the subject of numerous investigations (Hunt et al., 1985; El Amawy *et al.,* 2010; Ajazzwe and Ashahomi, 2018; Al Shible, 2019; Abousaif *et al.,* 2022; Zafir *et al.,* 2025; Shaltami et al., 2025; Al Faitouri et al., 2026).

Fig. 2 demonstrates that the Libyan karst is not evenly spread. Where carbonate rocks are exposed or found close to the surface, the primary karst zones are located. There are six main regions: (1) Tripolitanian Pre-desert Karst Region (northwestern Libya); (2) Al-Jabal Al-Akhdar–Benghazi Plain Karst Region (northeastern Libya); (3) Jebel Nafusah Karst Region (northwestern interior); (4) Cyrenaica Interior Karst Province (eastern Libya); (5) Murzuq Basin Karst Region (southwestern Libya); and (6) Kufra Karst Plateau (southeastern Libya). Thus, it can be concluded that the northern part of Libya is dominated by carbonate sediments, which leads to the development of karst processes. Moreover, the recharge of groundwater is higher in this region, resulting in the formation of extensive karst areas. In contrast, carbonate sediments are sparse in the southern part of the country, leading to the development of only a few local karst regions.

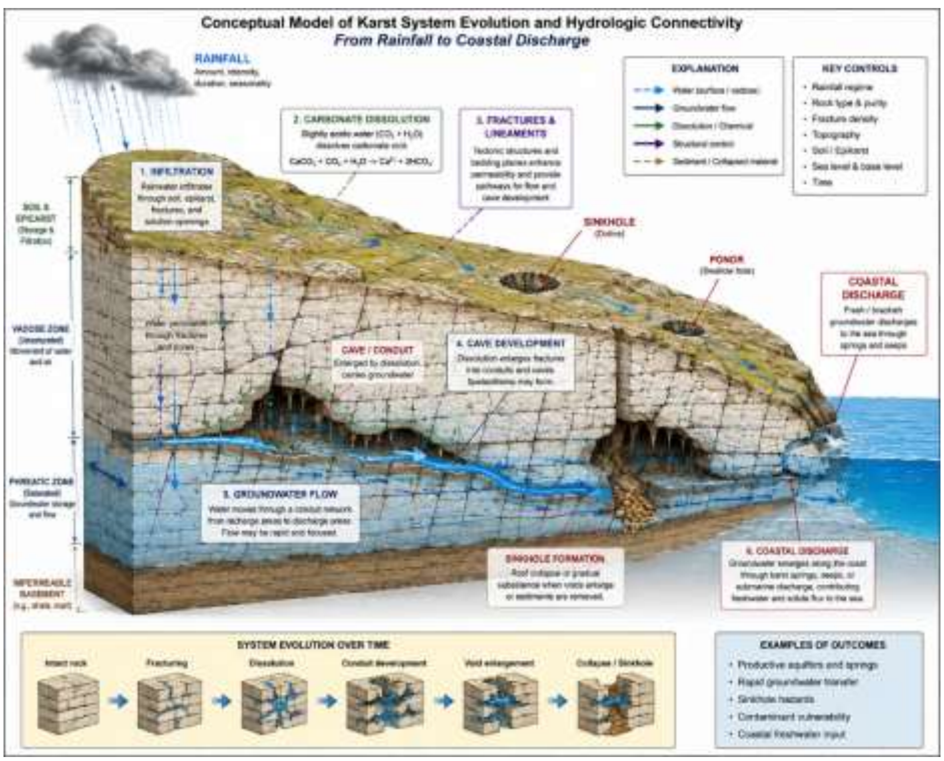

Fig. 1: Conceptual model showing relationships among rainfall, carbonate dissolution, fractures, caves, groundwater flow, sinkholes, and coastal discharge.

2. Objective

The aim of this study is to detect and characterize karst landforms in the Al-Jabal Al-Akhdar–Benghazi Plain Karst and Tripolitanian Pre-desert Karst regions using satellite images, digital elevation models (DEMs), and GIS-based spatial analysis. The obtained knowledge can be used to delineate karst regions with a high risk of specific hazards related to the development of karst processes. More precisely, the research seeks to: (1) Inventory dolines, sinkholes, closed depressions, karst lakes, springs, and caves; (2) Analyze the relationships between karst forms and the amount of moisture, drainage ways, topography, and geological structures; (3) Identify faults and lineaments that could be the control factors of groundwater movements and karst development; (4) Determine zones with a large number of karst forms; (5) Combine geological, geomorphological, hydrological, structural, and remote sensing data to create a preliminary karst susceptibility map for Libya; and (6) Provide a basis for groundwater exploration, assessing karst hazards, managing ecological systems, and developing infrastructure projects.

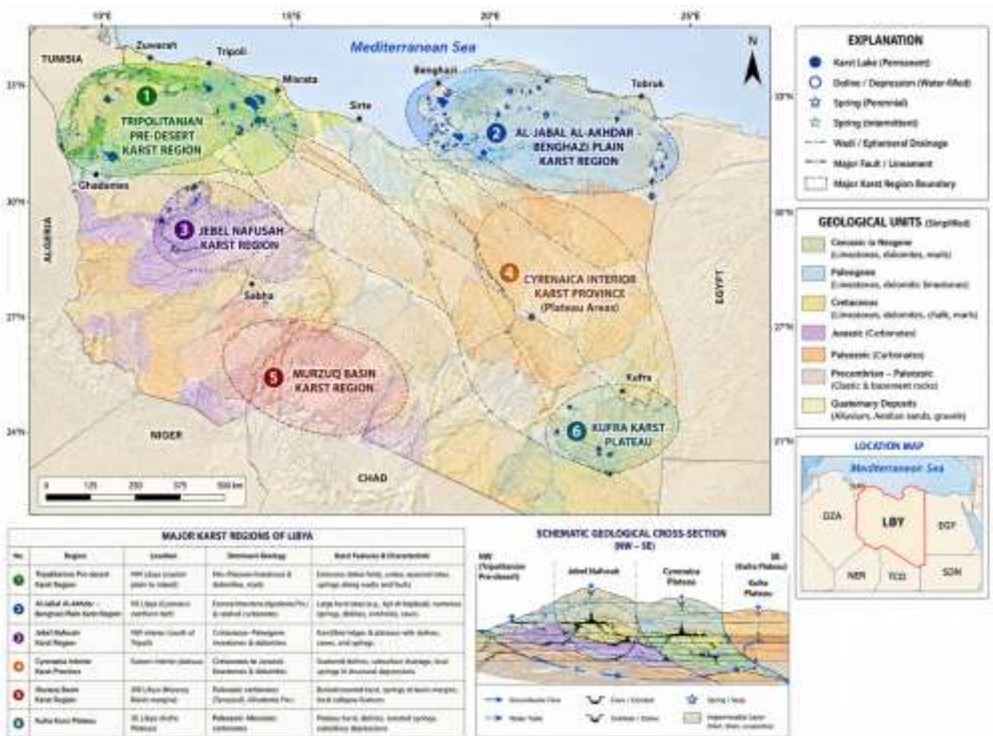

Fig. 2: Location and geological framework of major karst regions in Libya.

3. Methodology

The study analyzed karst landscapes using Sentinel-2 satellite imagery, the normalized difference water index (NDWI), digital elevation models (DEM), and geographical information systems (GIS). Sentinel-2 imagery was utilized to identify dolines, sinkholes, springs, and karst lakes by applying a false-color composite. The NDWI method highlighted water contents and water-related hazards. A 12.5m ALOS PALSAR DEM was employed to examine lineaments and closed depressions using a hillshade model. The identified dolines, sinkholes, caves, springs, and lakes were compiled into a GIS karst-geometry inventory, revealing karst feature hotspots. A tentative karst-susceptibility map was developed by integrating geological, structural, topographical, hydrological, and karst-geomorphological information.

4. Results and Discussions

Fig. 3 shows that the regional pattern of karst development is different in two study areas. In Al-Jabal Al-Akhdar-Benghazi Plain, doline fields, sinkholes, springs, and karst lakes are more numerous, interconnected, and intensive, which indicates a more advanced stage of karst development or better regional infiltration and circulation of groundwater. Meanwhile, the study area of Tripolitanian Pre-desert is featured by an extended occurrence of dolines and sinkholes, yet they are poorly grouped, which is probably related to local dryness. Thus, in both cases, the karst development is manifested in the presence of carbonate rocks and their dissolution; however, the structural pattern of individual dolines and sinkholes is different, and this is associated with differences in the movement and circulation of groundwater. Thus, the analysis using the multi-spectral satellite imagery can provide the necessary information about the potential karst occurrences in Libya, and Sentinel-2 can be used for such identification and mapping purposes successfully.

The Al-Jabal Al-Akhdar–Benghazi Plain is characterized by more prominent and connected doline fields, sinkholes, springs, and karst lakes, compared to the Tripolitanian Pre-desert (Fig. 4). This suggests the existence of a more developed and integrated karst system in the former region. Meanwhile, the latter region exhibits a greater number of isolated dolines and sinkholes, which may be related to the area's arid climate. In both cases, the observed circular depressions suggest the prevalence of carbonate dissolution processes and the influence of groundwater activities on the development of karst topography. Thus, the study concluded that the Sentinel-2 satellite imagery can effectively support regional identification and delineation of karst landforms in Libya.

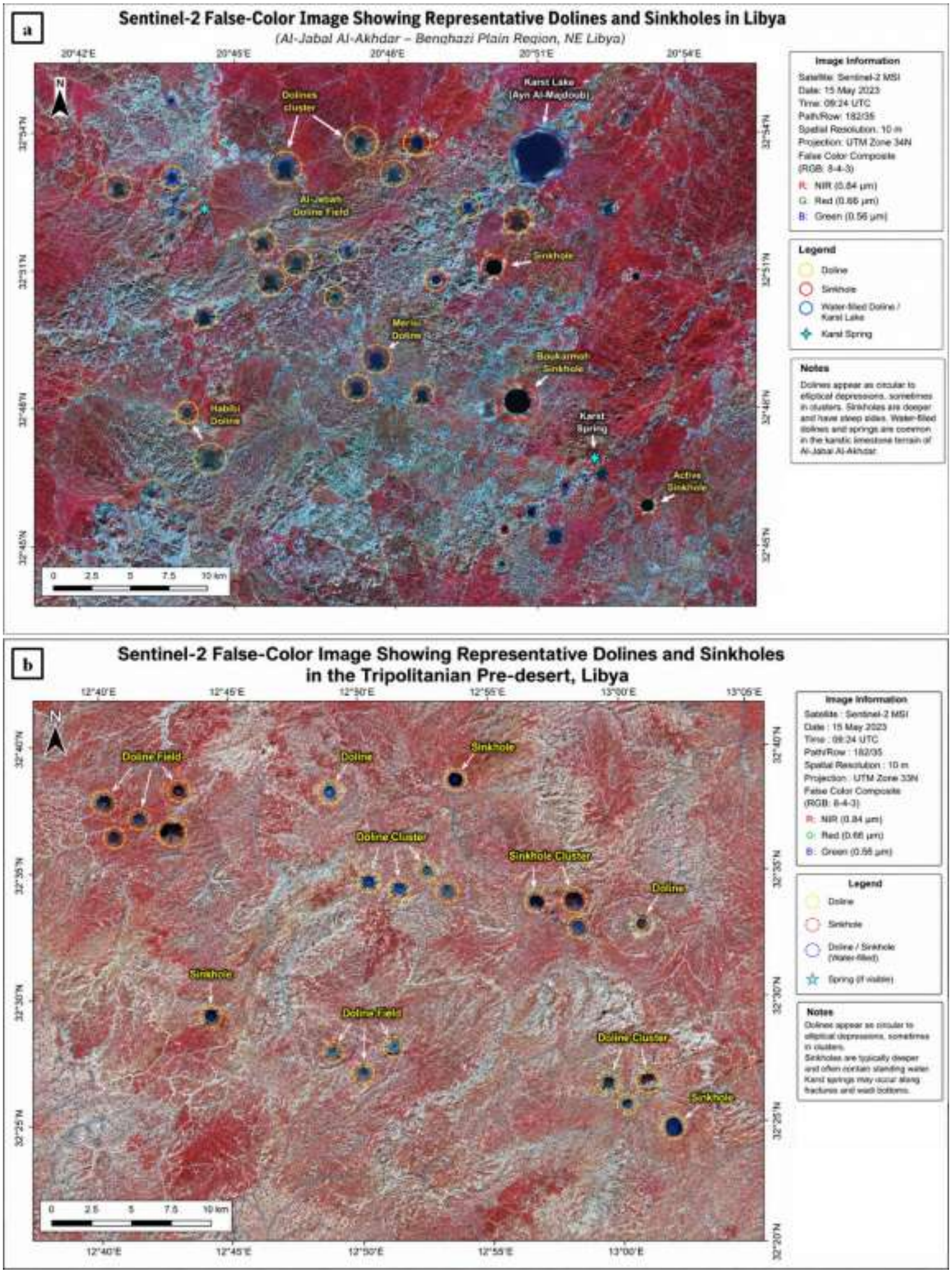

Fig. 3: Sentinel-2 false-color image showing representative dolines and sinkholes in the Al-Jabal Al-Akhdar–Benghazi Plain Region (a); and the Tripolitanian Pre-desert Region (b).

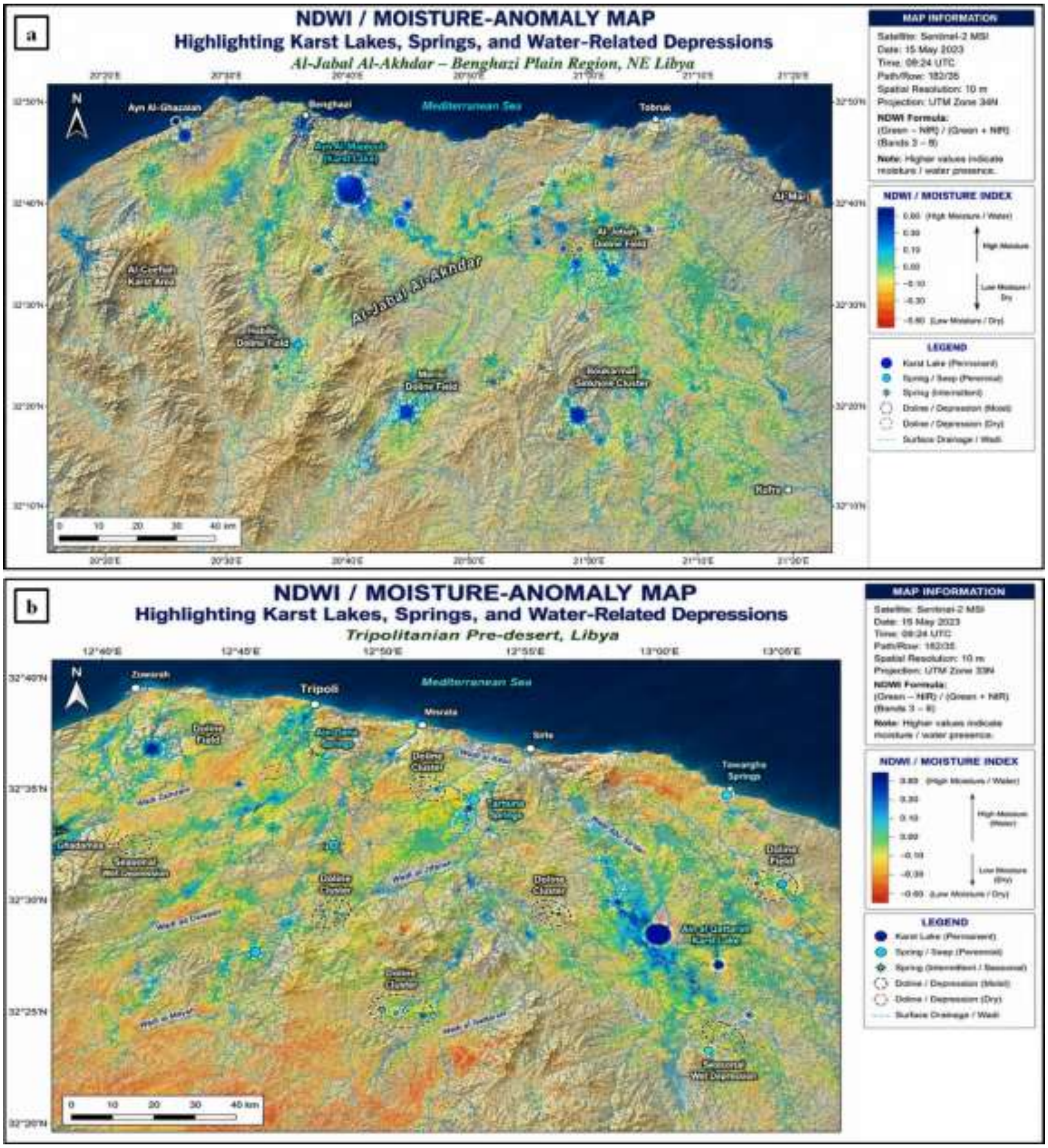

Fig. 4: NDWI/moisture-anomaly map highlighting karst lakes, springs, and water-related depressions in the Al-Jabal Al-Akhdar–Benghazi Plain Region (a); and the Tripolitanian Pre-desert Region (b).

Fig. 5 clearly shows that lineaments play an essential role in the distribution and development of dolines in Libya's two karst regions. Dolines are distributed either along, near, or at the intersection of major structural trends, probably because of the augmented fracturing that promotes water infiltration, as well as the enhanced flow of ground and fracture waters and carbonate dissolution processes. The higher density of large dolines observed in Al-Jabal Al-Akhdar compared to the Tripolitanian Pre-desert indicates a more intensive development of karst there. Using the DEM-based closed depression analysis is a great way to identify potential doline and sinkhole occurrences (Fig. 6). It can be seen that Al-Jabal Al-Akhdar has more widespread large and deep depressions within the limestone belt compared to the Tripolitanian Pre-desert. This suggests that Al Jabal Al Akhdar possesses more developed karst landscapes. In turn, the latter area contains more chaotic doline clusters occurring in association with seasonal water accumulations. It can be concluded that overall, the topographical properties of the region, along with carbonate dissolution, groundwater circulation, and structural geology, influence closed depression development patterns in the given area. The identified features must be considered sinkholes and dolines that require further field investigation. The two regions are clearly different, as seen by the karst-feature inventory (Fig. 7). Al Jabal Al Akhdar–Benghazi Plain has a well-developed and mature karst system with a large number of dolines, several giant depressions, caves, springs, and karst lakes. In contrast, the karst system in the Tripolitanian Pre-desert is less developed and has more isolated dolines, sinkholes, caves, and seasonal water-related features. In both areas, the spatial association of dolines with caves, springs, and/or depressions suggests the presence of an integrated surface–subsurface karst system. This system is controlled by a network of fractures and solution openings that allow water to infiltrate the bedrock and form caves, springs, and large depressions such as dolines and giant sinkholes.

The density maps (Fig. 8) indicate that the karst development in both study areas was uneven. While Al-Jabal Al-Akhdar–Benghazi Plain shows moderately wide and strongly connected areas of high density, implying a more developed karst, the Tripolitanian Pre-desert appears to be dominated by isolated areas of high density and doline fields. The zones of highest density can be outlined as karst-prone areas where the density of dolines, sinkholes, caves, springs, and closed depressions are presumably the highest. Thus these zones should be prioritized in groundwater potential assessment studies, as well as sinkhole hazard analyses, with consideration of the density distribution, geology, lineament patterns, hydrology, and fieldwork results.

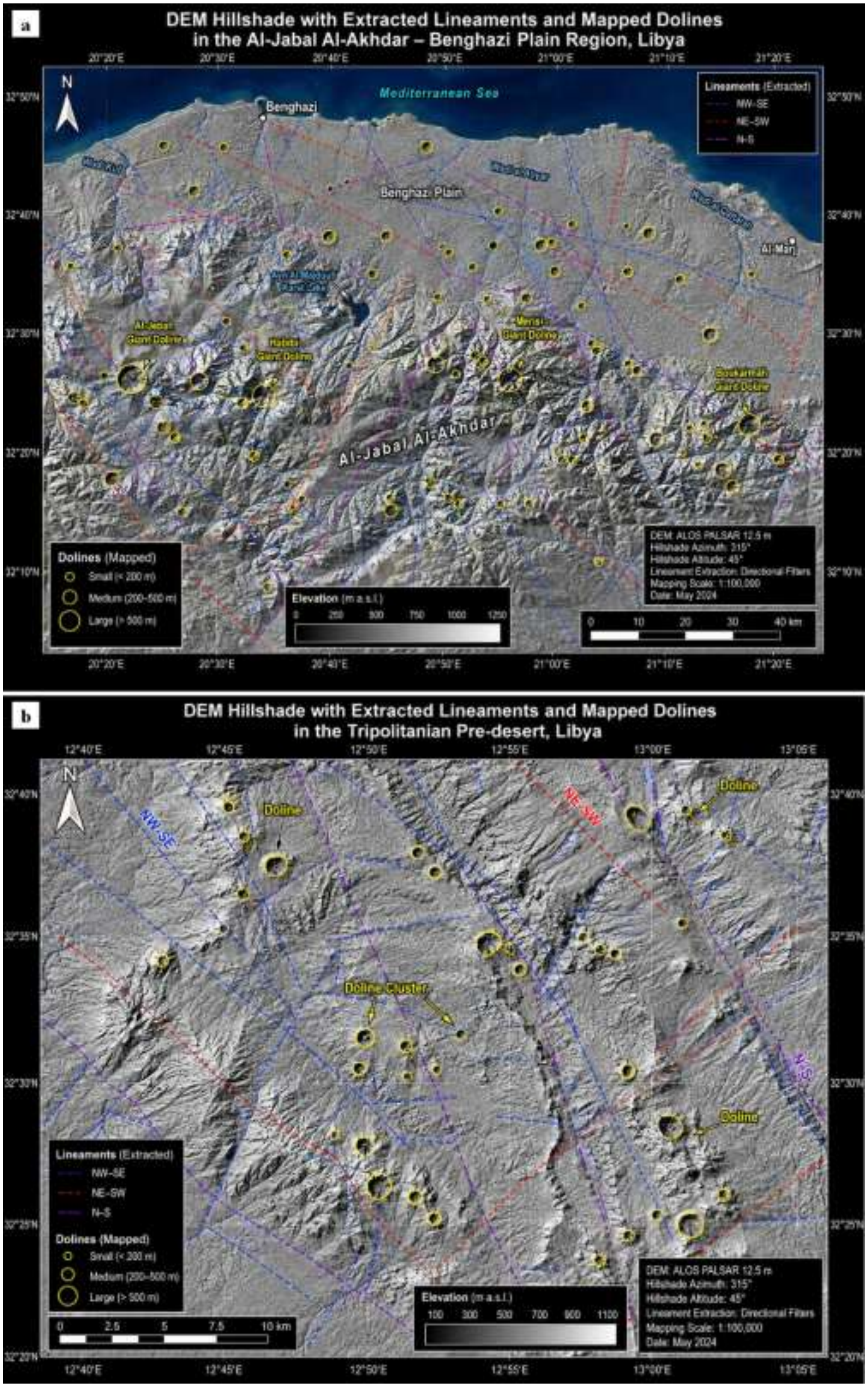

Fig. 5: DEM hillshade with extracted lineaments and mapped dolines in the Al-Jabal Al-Akhdar–Benghazi Plain Region (a); and the Tripolitanian Pre-desert Region (b).

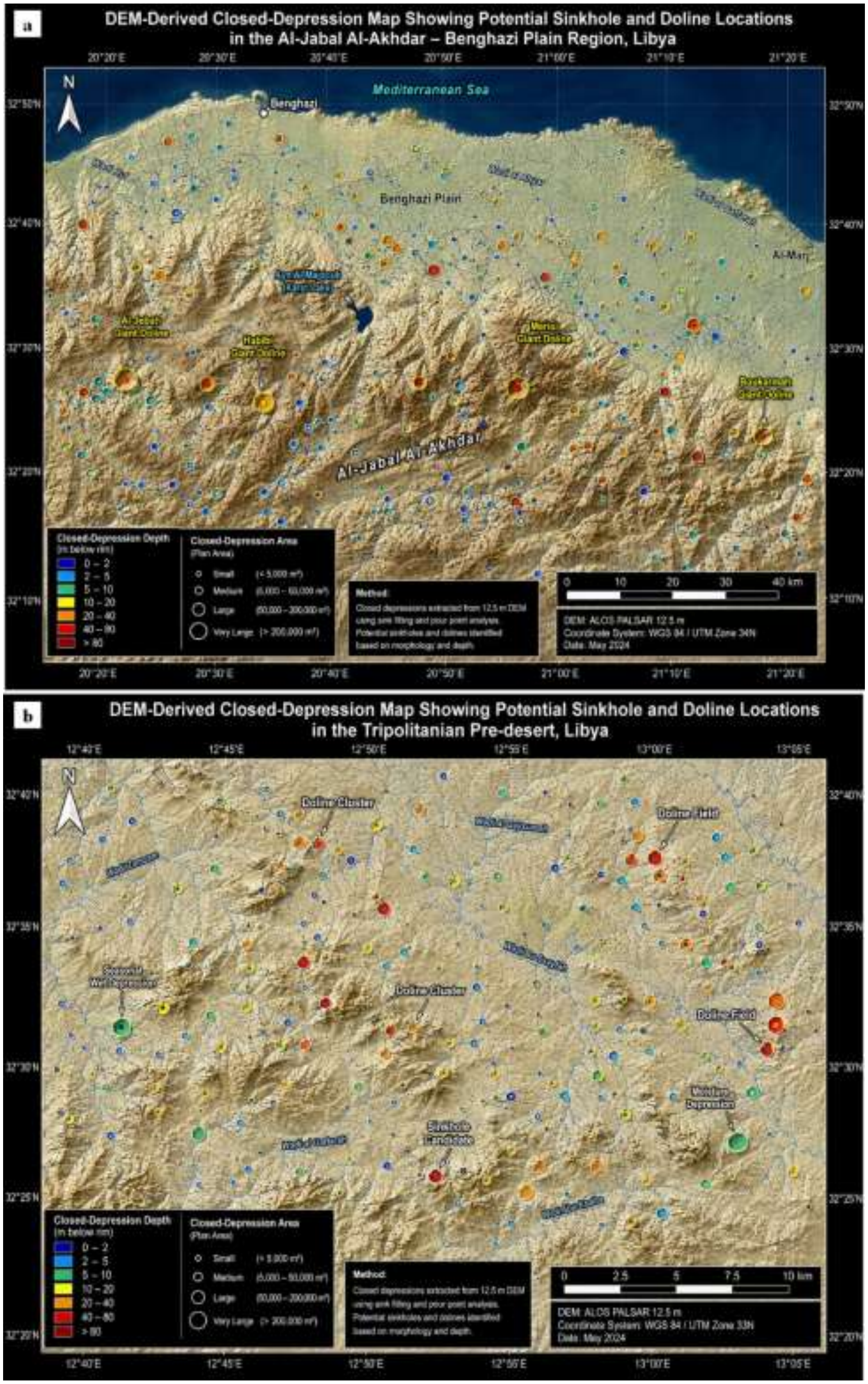

Fig. 6: DEM-derived closed-depression map showing potential sinkhole and doline locations dolines in the Al-Jabal Al-Akhdar–Benghazi Plain Region (a); and the Tripolitanian Pre-desert Region (b).

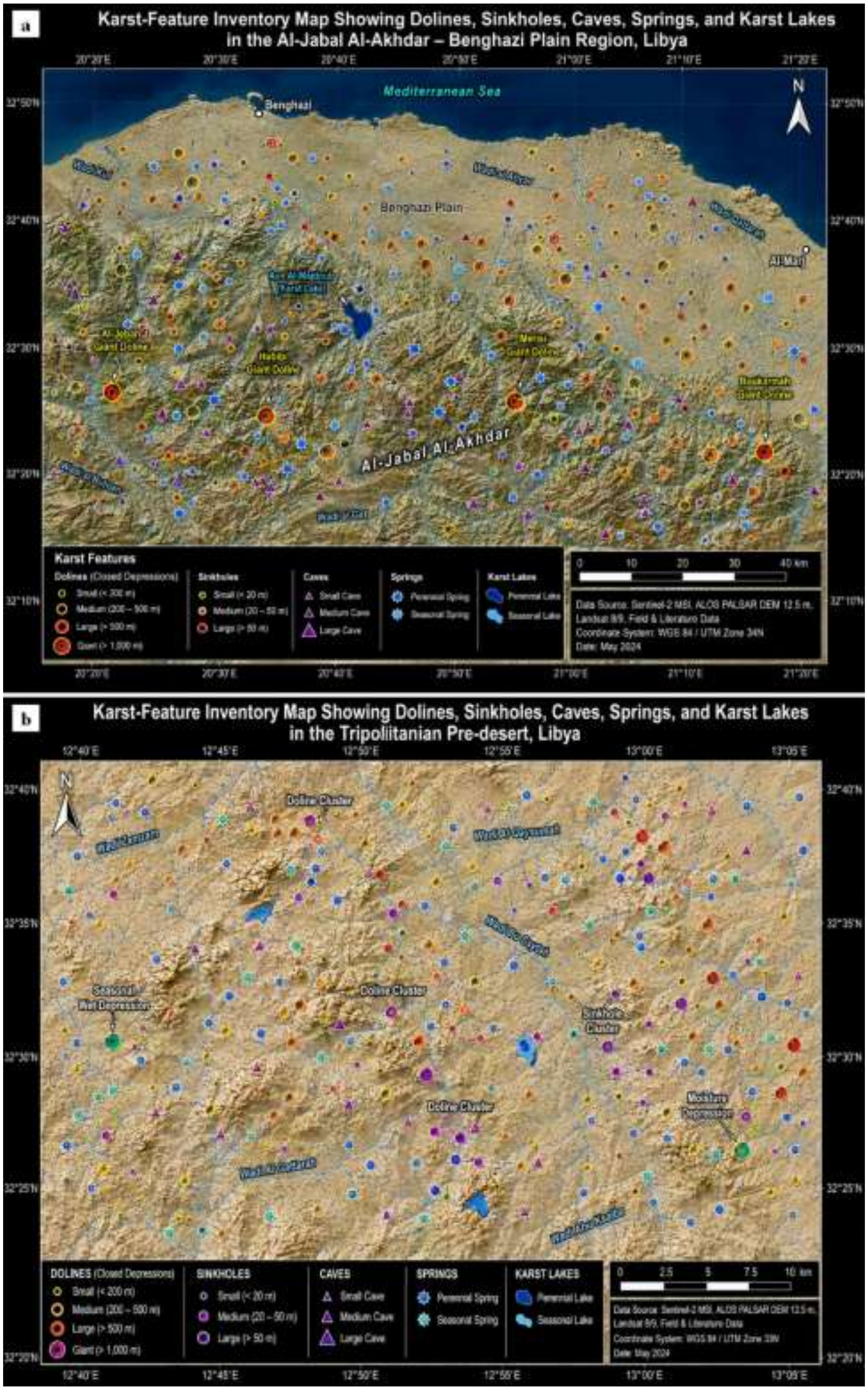

Fig. 7: Karst-feature inventory map showing dolines, sinkholes, caves, springs, and karst lakes in the Al-Jabal Al-Akhdar–Benghazi Plain Region (a); and the Tripolitanian Pre-desert Region (b).

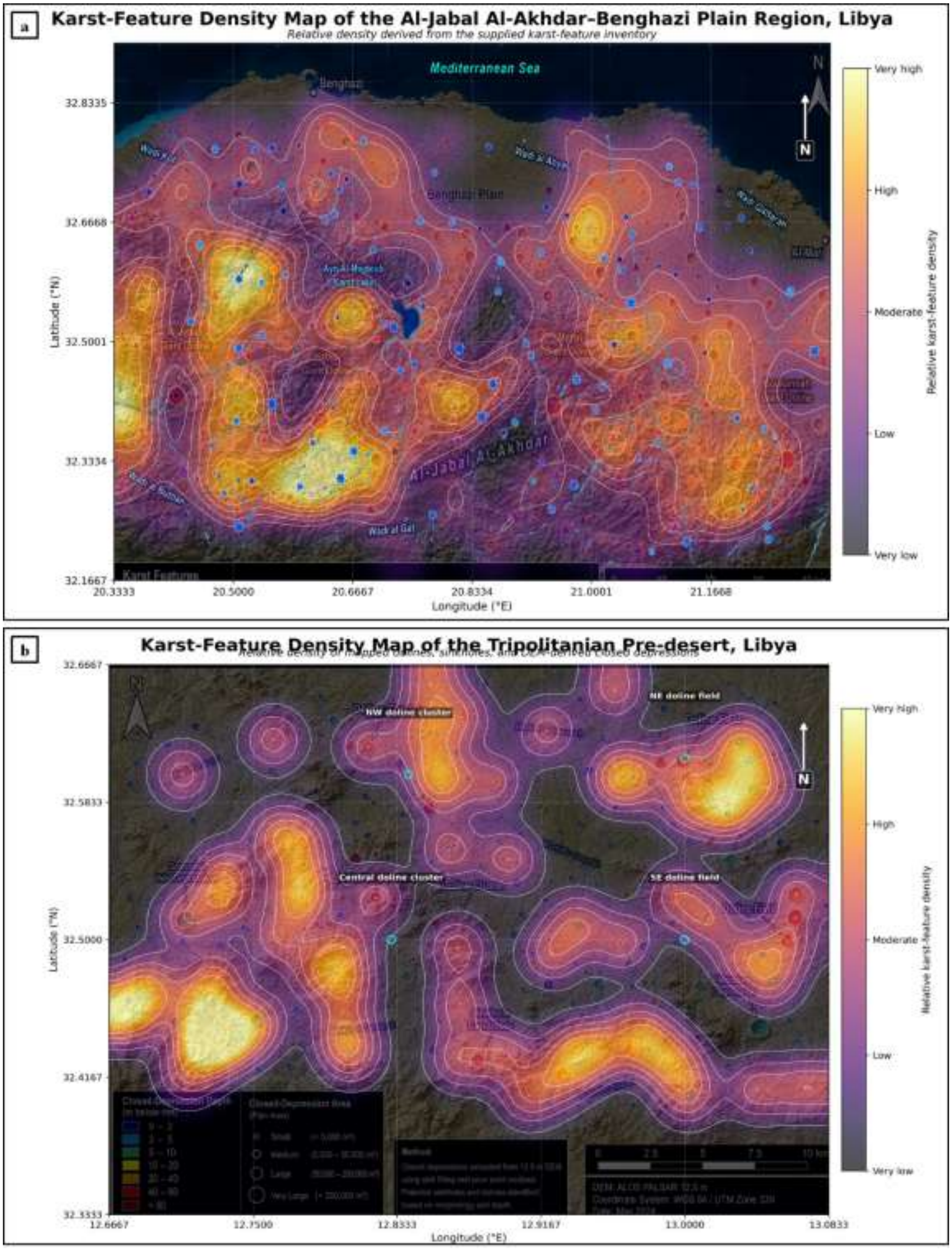

Fig. 8: Karst-feature density map of the Al-Jabal Al-Akhdar–Benghazi Plain Region (a); and the Tripolitanian Pre-desert Region (b).

The tentative karst-susceptibility map (Fig. 9) reveals a substantial variation in the potential for developing carbonate rocks across Libya. Localities with very high, high, moderate, low, and very low susceptibility account for most of the country. The highest karst susceptibility values (red, orange, and yellow colors) are observed mainly in northwestern Libya, in the Al Jabal al Akhdar-Benghazi Plain, and the Tripolitanian Pre-desert, with the presence of carbonate rocks, lineaments, geomorphological depressions, groundwaters, dolines, and sinkholes. Thus, this area has the highest potential for developing dolines, sinkholes, caves, springs, grottoes, underground drainage, and karst lakes. The central, southern parts of Libya, the Sahara Plateau, and the Libyan Desert are characterized by moderate, low, and very low karst susceptibility. Only several localities in the southern and southwestern parts of the country have high, very high, and extreme karst susceptibility. Although the Sahara plateau and the Libyan Desert are poorly suited for carbonate rocks development, karst may appear there due to the presence of carbonate rocks, groundwater, and specific structural discontinuities. It may lead to the formation of caves, grottoes, sinkholes, and dolines.

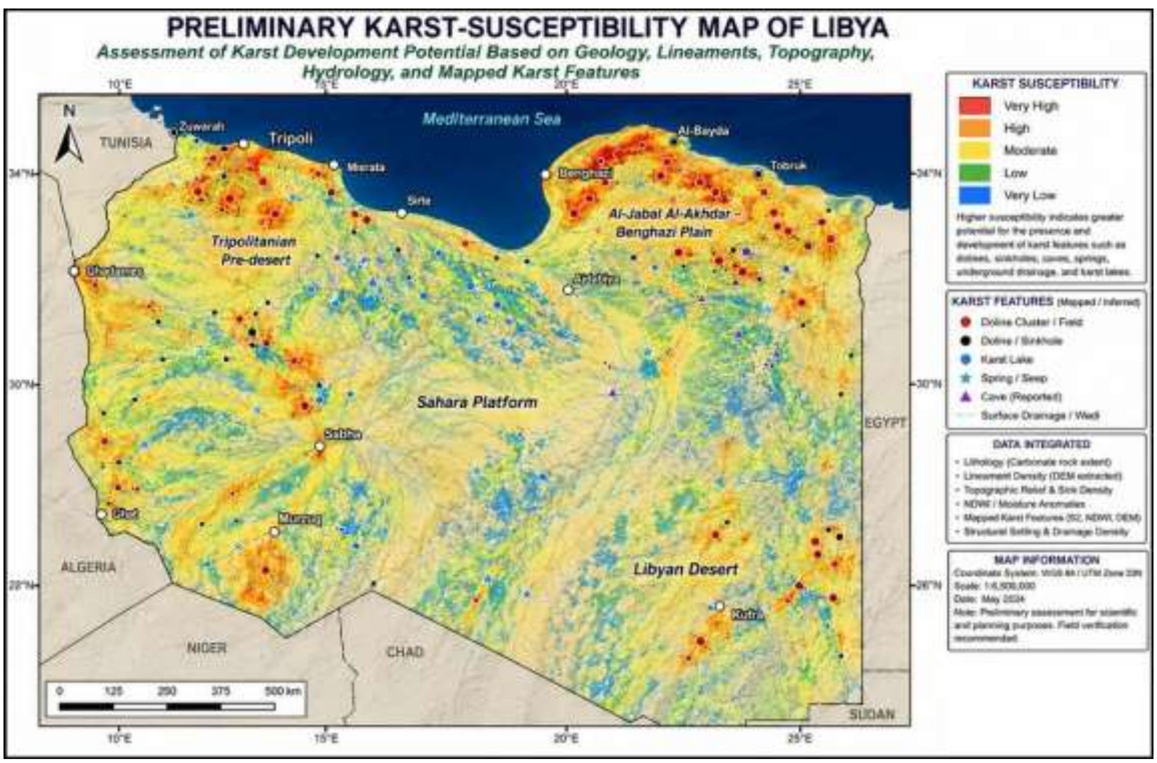

Fig. 9: Preliminary karst-susceptibility map of Libya.

5. Conclusions and Recommendations

This study proves that remote sensing, DEM, and GIS are accurate and effective tools for identifying and analyzing karst landforms in Libya. Using Sentinel-2, NDWI, ALOS PALSAR, DEM data, lineaments, and existing information about geological and karst features enabled us to estimate the areal distribution of dolines, sinkholes, closed depressions, caves, springs, and karst lakes. In particular, the two regions differ significantly in several aspects. The Al-Jabal Al-Akhdar–Benghazi Plain has a more developed and complex karst system than the Tripolitanian Pre-desert because it has more numerous and interconnected doline fields, large closed depressions, caves, springs, and karst lakes. This complexity and interrelation imply a more substantial groundwater system and carbonate dissolution in this region. On the other hand, the Tripolitanian Pre-desert has a significant number of dolines, sinkholes, closed depressions, caves, springs, and karst lakes that are poorly interconnected and sometimes grouped in larger clusters. Seasonal water accumulation and moisture are also typical for this area. This difference can be explained by the fact that the Tripolitanian Pre-desert is a drier region, so its karst features are more isolated and local. The association of karst features with lineaments is also crucial: many doline fields are related to one or more of these structural disturbances. It can be explained by the fact that they control the pattern of fracturing and, thus, the flow of groundwaters and water circulation processes that lead to carbonate rock dissolution. This hypothesis is supported by the closed-depression analysis that also highlights the importance of local topography, carbonate rock dissolution, groundwater flow, and structural geology in doline and sinkhole development. All the identified areas with closed depressions should be considered potential karst features that require further ground survey and analysis. The karst-feature density is another crucial indicator of the regional analysis. It implies that the Al-Jabal Al-Akhdar–Benghazi Plain has larger karst areas that are more complex and interconnected, while the Tripolitanian Pre-desert has some highly dense, isolated regions. Such sites are also valuable and should be explored in detail. Using the developed density analysis, it is possible to identify prospective areas with complex groundwater systems, caves, dolines, sinkholes, closed depressions, and springs. On the country scale, most of the karst susceptibility areas are located in the north of the country, while the central and southern parts have only a few isolated karst features. Local accumulations of potential dolines, sinkholes, caves, and springs in the center and south of the country are also possible, but they are not as significant as in the north. In general, this study proved that remote sensing and GIS methods can contribute to the accurate identification and analysis of karst features in Libya.

Here are some of the recommendations based on the performed research:

(1) It is recommended to make field checks of identified positive holes and depressions found in the DEM to differentiate sinkholes from other types of depressions.

(2) It is necessary to perform geological and structural investigations in high-density and high-susceptibility zones to identify the relationships between carbonate rocks, faults, fractures, lineaments, and karst development.

(3) Groundwater investigations should be focused on high-density karst zones. It is recommended to start with the areas where dolines, springs, karst lakes, closed depressions, and lineaments are associated.

(4) Sinkhole-hazard assessments should be considered in the development of infrastructure, land-use planning, and management in large dolines, deep closed depressions, sinkhole clusters, and highly susceptible regions with significant karst cover. This factor should be taken into account for the sustainable use of this ecosystem.
(5) There is a need to consider seasonal variations for mapping water-related features in the karst landscape of the Tripolitanian Pre-desert. Such information will help understand the hydrological regime of the area by monitoring the dynamic changes in spring outcrops, seasonal lakes, and seasonal depressions.
(6) It is recommended to use higher-resolution remote sensing data for future studies focused on the detailed inventory of small dolines, sinkholes, fractures, and other geomorphological features.
(7) It is necessary to expand hydrogeological investigations in major karst areas and study fractured and karstified carbonate rocks to understand the groundwater recharge mechanisms and flow regimes in these regions.
(8) The identified national-scale susceptibility map should be considered a screening-level assessment tool only and should not be used as a primary hazard assessment guide at the national level. Different karst areas require more detailed geological, hydrological, geotechnical, and field investigations to evaluate their potential for detailed hazard assessments related to sinkholes. Thus, the susceptibility map should be used as a regional-level guide to prioritize areas for further detailed analysis.
(9) The karst areas identified as highly susceptible to sinkholes should be considered when developing sustainable water resources management plans, environmental protection strategies, infrastructure construction, and sinkhole hazard assessments, especially in northern Libya.

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