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Original article

Satellite Detection of Hidden and Ephemeral Water Resources in the Ghat Area, Southwestern Libya

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Abstract
This study investigated the potential hidden and ephemeral water resources in the Ghat area of southwestern Libya using remote sensing, satellite imagery, and GIS. The surface water features, vegetation features and surface moisture variations were identified using the Sentinel-1 radar and Sentinel-2 optical imagery. Water indices, including NDWI, MNDWI, and NDVI, were applied to support the detection of water-related features. DEM analysis was carried out in order to extract information on topography, slope, hydrography, flow accumulation and sinks. Multi-temporal satellite data was also taken into consideration to provide information on seasonal water presence and surface change. Geological, geomorphological, and lineament information was integrated to identify potential groundwater recharge zones and groundwater-potential areas. Generally, this analysis provides an initial understanding of the spatial distribution of areas which may be temporarily wet or have good groundwater potential. The results have demonstrated the importance of integrating radar, optical, and topographic datasets to discriminate between potential active water features, historical drainage, and other landform features. Ground-truthing was required to validate the features identified and determine whether there was available groundwater.
Keywords: Water Resources, Remote Sensing, GIS, Ghat, Libya.

Introduction

The hyper-arid environment is one of the primary sources of scarcity, and water is a rare commodity in desert landscapes. In desert habitats with arid conditions, the amount of precipitation is low and uneven throughout the year. Additionally, the evaporation rate is extremely high, which means that any given water source may only be present for a relatively short time after a rainfall period. Nevertheless, a lake or two, shallow ponds, wadies, and water holes punctuate the desert and are integral parts of the desert ecosystem (Houston, 2006; Box et al., 2008; Free et al., 2013; Kampf et al., 2016; Shaltami et al., 2019, 2021, 2025).

The Libyan Desert forms part of the Sahara Desert, which extends across much of North Africa. The term Libyan Desert is often used more specifically for the eastern Sahara in Libya, Egypt, and Sudan, while the southwestern Libyan region around Ghat is more commonly described as part of the central Sahara and the Fezzan region. The bedrock is generally exposed as the landscape consists of sand and gravel plains, rocky plateaus, dunes, dry valleys and isolated mountains. These environments have developed under long-term arid conditions and contain limited surface water, making groundwater and oases particularly important for human settlement and local ecosystems (Braun et al., 2020).

Previous research has demonstrated that satellite imagery, radar observations, and GIS analysis can reveal paleodrainage systems and paleolakes in Libya, including the Ghat (Nasser, 2023), Kufra (Robinson et al., 2006; Paillou et al., 2009; 2012; Ghoneim et al., 2012; Zamot and Afkareen, 2024), and Jabal Nafusa areas (Al-Haddad, 2026).

Nevertheless, mapping ancient drainage features is different from detecting water that is present today or that recurs periodically. Studies of paleohydrological systems in the Sahara have shown that radar imagery, optical satellite data, and digital elevation models can reveal ancient drainage networks that formed under wetter climatic conditions in the past (Ghoneim et al., 2012).

An important research opportunity is therefore to combine multi-temporal radar and optical observations with terrain analysis to identify contemporary ephemeral water bodies, assess their recurrence, and distinguish them from ancient drainage features and false satellite detections. Multi-temporal satellite observations have been used to map surface-water occurrence and seasonality (Pekel et al., 2016), while research on desert environments has demonstrated the value of integrating optical, radar, and topographic data to distinguish active land-surface processes from older geomorphological features (Abdelkareem et al., 2020). Furthermore, radar-based water mapping can give false positive indications over non-water surfaces; hence, requiring additional information, and needing validation (Santoro et al., 2015).

The use of Sentinel-1 radar imagery is appropriate because of its ability to obtain information from a cloud cover and its sensitivity to the roughness of the surface and to the dielectric constant. Although there is usually little backscatter due to the open water, some desert consistency and a smooth, dry surface may also appear as dark patches. In turn, the multispectral Sentinel 2 can be applied for this purpose effectively, as water can be easily differentiated from the surrounding land by means of visible, near-infrared, and shortwave-infrared wavelengths. It may be possible to benefit from both systems for more effective water detection (Peña-Luque et al., 2021; Jung et al., 2026). Supplementary

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information regarding terrain, drainage paths, slopes, and depressions can be obtained using digital elevation models (DEMs). When combined with satellite observations, they can help determine whether detected water is located in a plausible accumulation zone (Huang et al., 2018).

This is especially relevant in desert environments, where temporary water bodies may be small, short-lived, or difficult to distinguish from other surface features, and where high-resolution remote sensing can improve the mapping of ephemeral drainage networks (Hamada et al., 2016). Accordingly, this study proposes an integrated framework for identifying and monitoring hidden and ephemeral water resources in the Ghat region using Sentinel-1, Sentinel-2, and DEM data. The work emphasizes modern surface-water detecting and attempts to use terrain and geological evidence to recognize additional places for hydrogeological investigations.

Ghat is a region in Libya located in the southwest of the country near the Algerian border in the historical part of Fezzan (Fig. 1). The area is defined by a desert climate, which is determined by mountainous topography, rocky plateaus, and dry ravines typical for the region. The Tadrart Akakus Mountains and the surrounding area of the Wadi Tanezzuft have many rock art, prehistoric remnants, and archaeological finds of different epochs. The local relief with its variability in height is extremely important for the regional hydrology, intercepting the monsoon flows, accumulating them in specific places, and concentrating them.

The Ghat area is characterized by an extremely arid desert climate with high summer temperatures, moderate winter weather, and low annual rainfall. Thus, summer temperatures rarely drop to 40 °C, while rainfall is unpredictable and can be both scarce and torrential. The torrential flows occur in short intervals but can rapidly fill the dry ravines and gullies with water. Vegetation cover is minimal, occurring in clusters of plants in wetlands, oases, and valleys (Passon et al., 2020).

The region has significant variations in rock and sediment types apart from the valley and desert sands which include plateaus of sandstones and rocky areas. The hydrological potential of the region is influenced by the lithology, facilitating the run-off of water, directing it, and temporarily storing it. More significant flows can erode the rocky beds, while some smaller streams and gullies can act as aquifer recharge areas and be the points of groundwater upwelling. As for the topography, it is crucial for water resources in Ghat as the local ravines and depressions can act as dams for larger flows, redirecting them to lower terraces or man-made structures. A qualified assessment of the local water potential requires an in-depth hydrological and geological study of the area to understand the regional flow of water and its movement. The ecological footprint of the region is minimal, while the local climate is limited to a narrow range of temperature variations with high aridity. Vegetation is the critical element influencing the water resources, as it can be found mainly in river valleys, oases, and around water sources. Apart from the natural role, the Ghat area has been a center of human activity and trade as well as an important link in the trans-Saharan trade route due to the presence of water resources. The archaeological findings in the region confirm the ancient oasis and the research of water resources conducted centuries ago (Passon et al., 2020).

The main objective of this study was to identify and assess potential hidden and ephemeral water resources in the Ghat area of southwestern Libya using satellite imagery, remote sensing, and GIS. The objective of this study was to determine temporary water bodies using Sentinel-1 radar observations, Sentinel-2, and water indices, assess vegetation and surface moisture, and analyze landforms, drainage systems, and water bodies through a digital elevation model. The study also sought to identify seasonal variations of water bodies, establish a relationship between rainfall and water bodies, and identify lineaments, groundwater recharge zones, and groundwater potential areas. In addition, the study sought to assess groundwater vulnerability, evaluate the accuracy of satellite-based water detection using reliable reference data, and identify priority locations for future field investigations. Generally, the study aimed to improve understanding of the distribution and characteristics of potential water resources in this arid region and support more effective groundwater exploration and sustainable water-resource management.

Although previous studies have demonstrated the usefulness of remote sensing and GIS for flood mapping, hydrological analysis, and groundwater-potential assessment, an opportunity remains to develop an integrated approach specifically focused on hidden and ephemeral water resources in the Ghat region. Although local research has been undertaken to identify flood hazards and drainage routes, multi-temporal Sentinel-1 radar data could be used alongside Sentinel-2 spectral indices, rainfall data, DEM derived drainage attributes and geological information to determine areas where temporary flooding occurs and areas where permanent features are present. In addition, areas where groundwater recharge could occur could be identified. There is also a lack of validation for the satellite data interpretation using field data, well logs or other reliable sources. By addressing these issues a better understanding of the spatial and temporal extent of ephemeral features will be gained which can help to guide future fieldwork priorities. This gap should be presented as a preliminary literature-based research gap, rather than proof that no previous study has addressed these questions.

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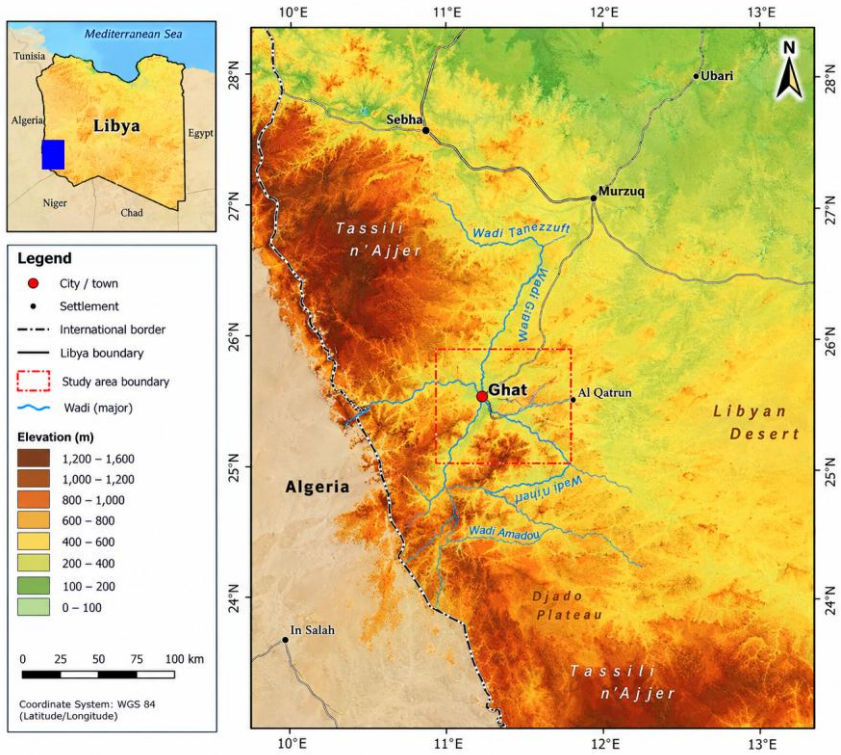


Fig. 1: Location and topographic setting of the Ghat area.

Methodology

The methodology for this study involved using remote sensing methods with satellite imagery, digital elevation models (DEM) and GIS to aid in analyzing surface waters, temporary water bodies and potential groundwater resources within the Ghat area of southwest Libya. Radar images were corrected by performing radiometric correction, speckle reduction and terrain correction on the Sentinel-1 imagery. These aided in identifying potential water bodies and moisture variations on the surface of the earth. Spectral indices were applied to Sentinel-2 and Landsat imagery which included normalized difference water index (NDWI), modified normalized difference water index (MNDWI) and normalized difference vegetation index (NDVI). This helped aid surface water identification and vegetation identification. False color composites and shortwave-infrared (SWIR) band combinations were used to help identify contrasts in land cover, show moisture levels and geological features. Multi-temporal data was used to observe how water is present during different seasons, how long it lasts and changes that have occurred between the images. Rainfall data was analyzed in relation to how much water has been identified across the area to see if there are any links. Elevation, slope, accumulation, drainage patterns and depression from the DEM were used with geological, geomorphological, soil and lineament data to help identify areas of potential runoff concentration, groundwater recharge zones and groundwater potential classes. Using information on aquifers, soil, geology, depth, and possible contaminants, groundwater potential was determined. The water classes were then analyzed using a confusion matrix with accuracy calculations to see how accurate they were when compared to independent data. This included overall accuracy, producers accuracy, users accuracy and F1 score. The maps were then used to identify areas that would be prioritized for further fieldwork, groundwater exploration and protection. However, all interpretations and numerical data must be confirmed using actual satellite data, accurate reference data and fieldwork.

Results and Discussion

Fig. 2 represents how the satellite images and water indices help to identify potential water features in the Ghat region. It provides an overview of the characteristics of the desert area. Using indices such as NDWI and MNDWI, areas that may represent water features can be identified, and dry land, bare soil and rocky areas can be identified. Areas with higher values of the water related indices could indicate areas where some temporary water pooling may have occurred or areas that are moist due to rainfall. However, sometimes areas with high values can also occur over shadowed areas or other surface materials. The figure shows how satellite imagery can be used in conjunction with spectral indices to help identify concealed and ephemeral water resources. Fig. 3 shows the spatial distribution of temporary water sources and drainage features in the Ghat region. This includes shallow depressions, dry riverbeds, and low-lying land that will hold water temporarily. Although the region is mostly arid, there may be areas that will hold water or water in the soil for

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a short time. Identifying these features will help to locate areas that could be investigated further to locate hidden and temporary water sources. To identify these areas, further observations or data would need to be collected.

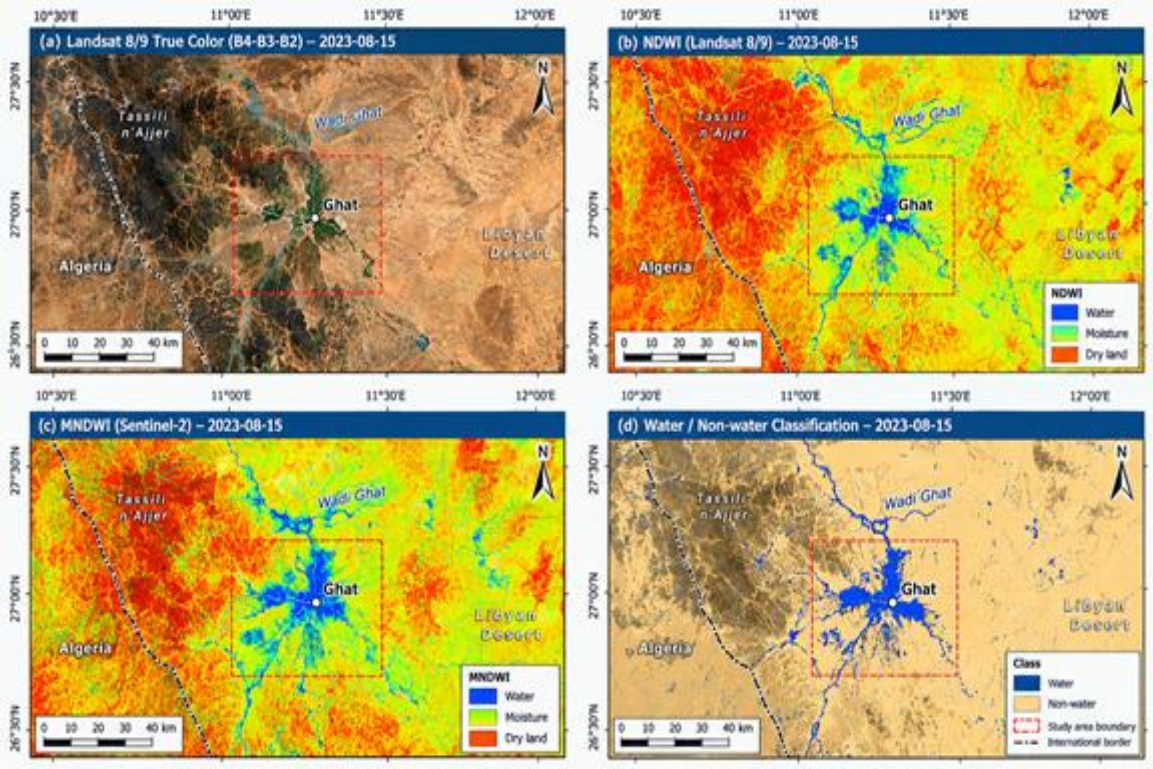


Fig. 2: Satellite imagery and spectral water indices of the Ghat area.

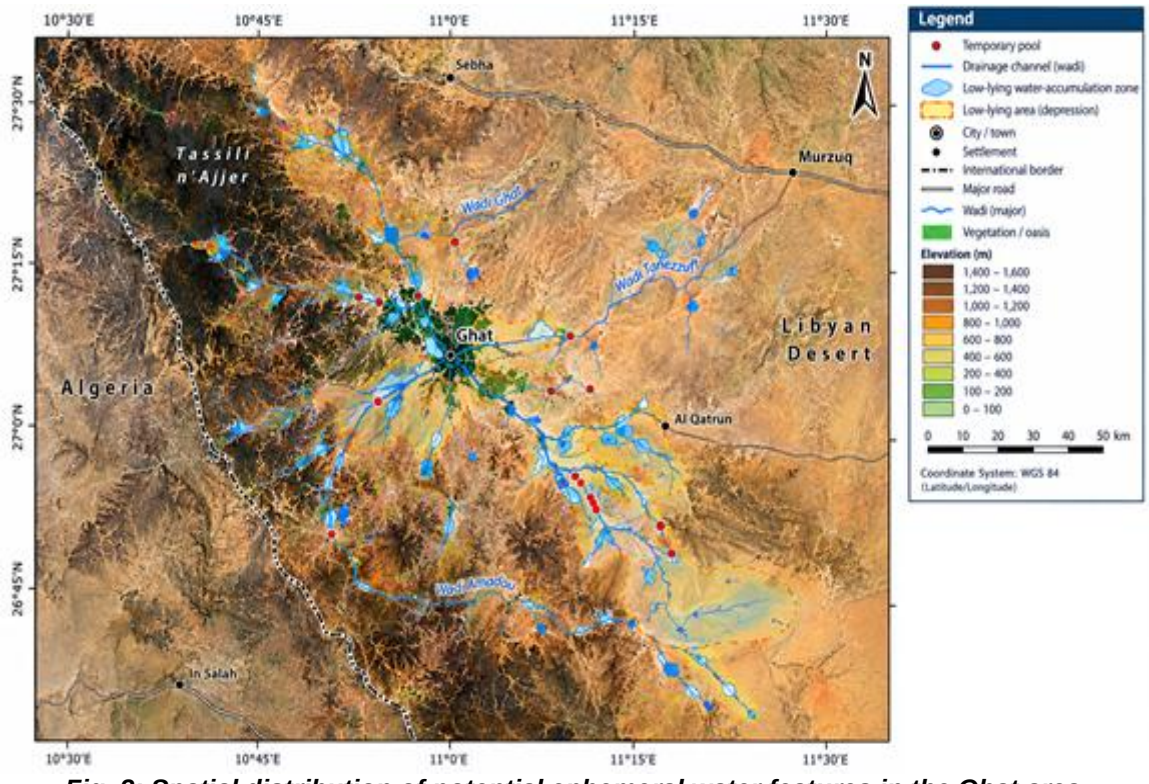


Fig. 3: Spatial distribution of potential ephemeral water features in the Ghat area.

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The Sentinel-1 radar analysis (Fig. 4) shows potential surface water features and changes in moisture levels at Ghat. This variation in radar signal between wet and dry areas could suggest seasonal flooding, soil moisture changes and/or surface roughness changes. Radar can also be useful for areas with high evaporation rates such as this area where rainfall can be unpredictable and optical data can be impacted by cloud. However, these results cannot be confirmed using radar so should be compared to ground observations.

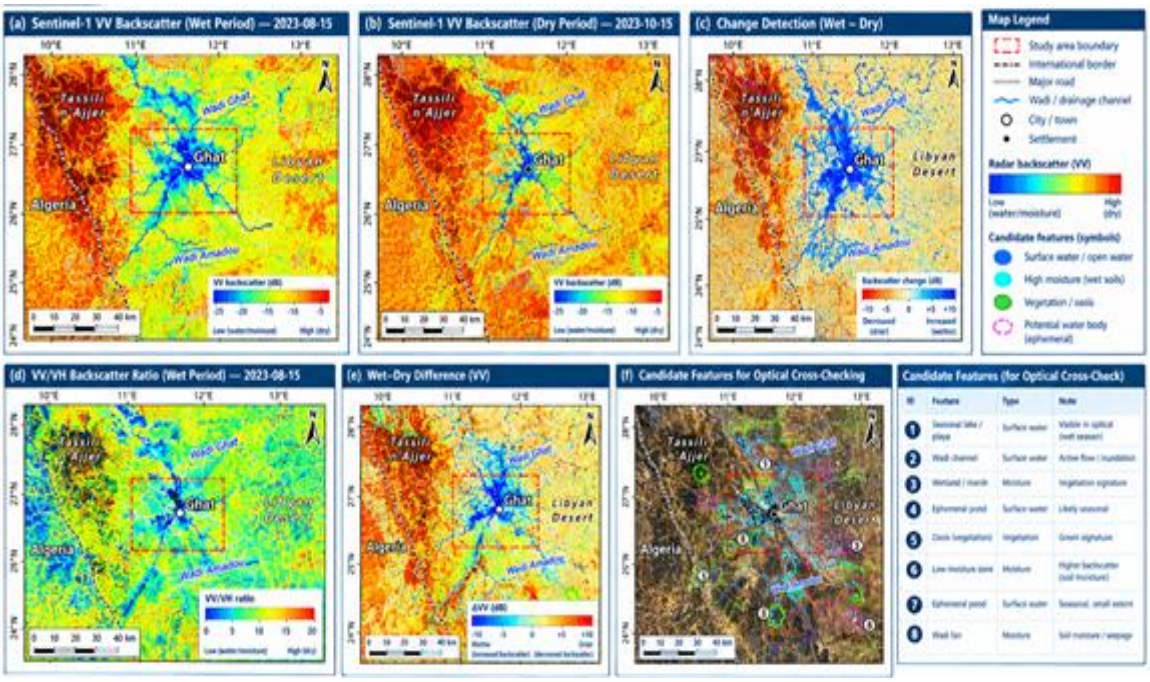


Fig. 4: Sentinel-1 radar analysis of surface-water and moisture indicators of the Ghat area.

The DEM-derived analysis (Fig. 5) illustrates the effect that the elevation and slope have on the flow and pooling of water within the Ghat area. The flow accumulation data helps to understand where the drainage channels are and therefore where water will be pooled from surrounding areas. Depressions and flat areas may also be areas of storage. Flat areas and slopes may aid infiltration if the soils/geology are suitable. For further research on concentrated flows and groundwater recharge, this data can help in identifying locations.

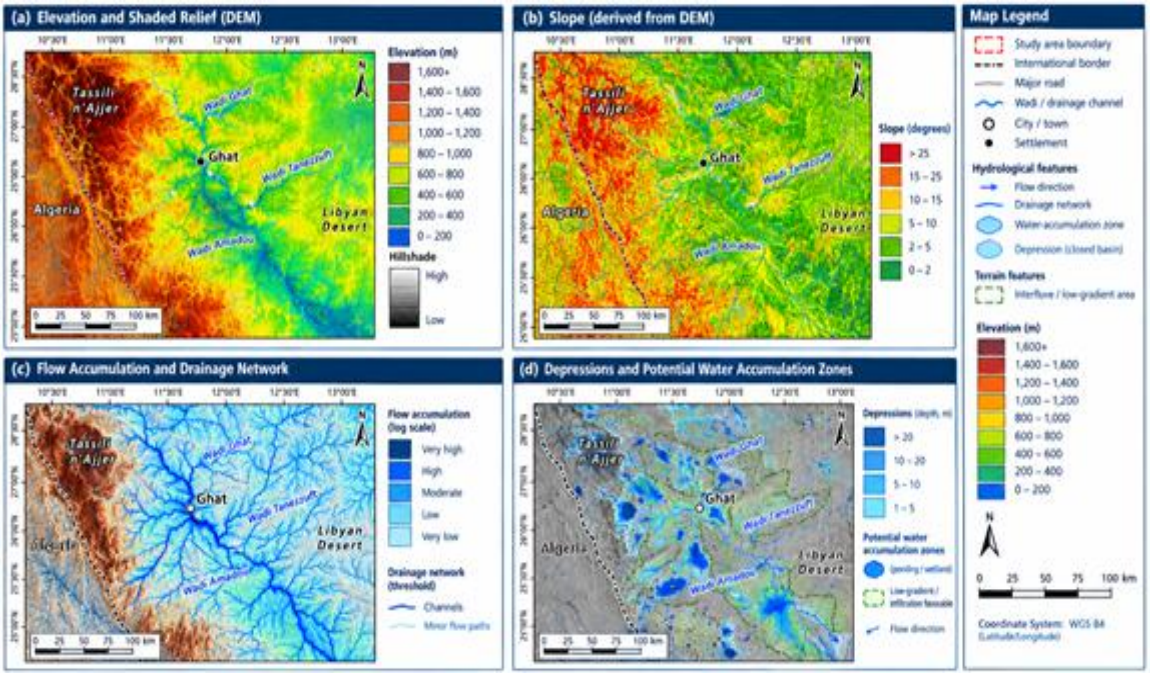


Fig. 5: DEM-derived drainage network and water-accumulation zones in the Ghat area.

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The seasonal water-occurrence analysis (Fig. 6) gives an improved understanding of how surface water is distributed at different points in time. New identified water features can be linked to rainfall driven run-off or temporary pooling. Features that no longer occur are likely to have been lost due to evaporation, percolation or outflow. Recurring features are likely to occur more often. This helps to understand the behavior of the water resources throughout the year within the Ghat area and identify areas that would benefit from further monitoring to determine if they are a temporary feature or a permanent one.

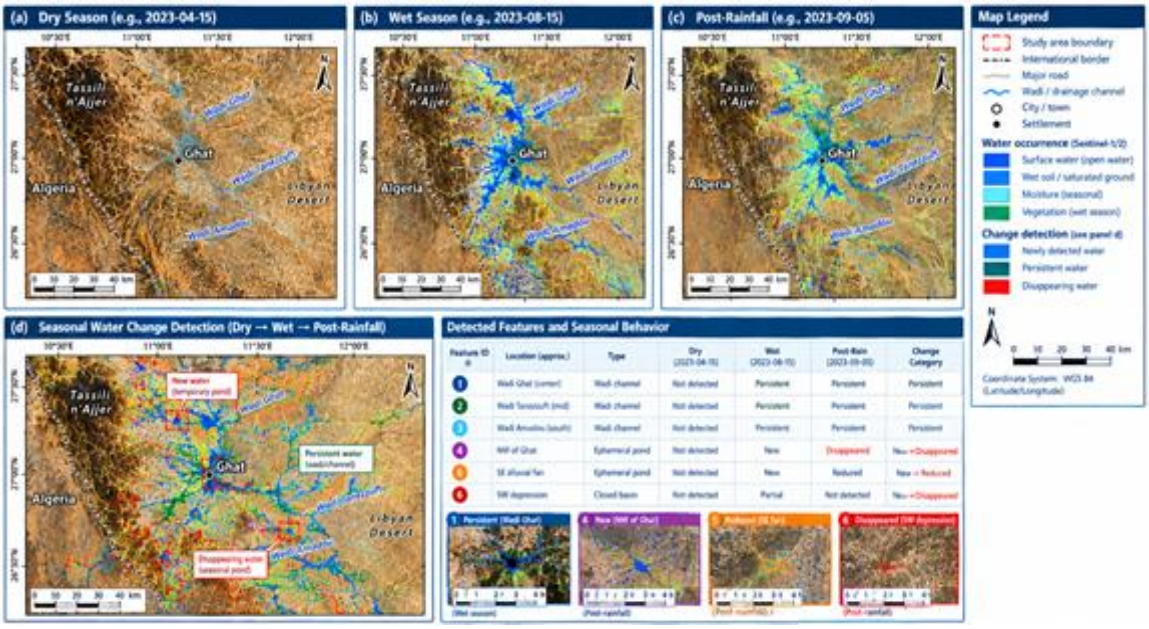


Fig. 6: Seasonal water occurrence and change detection of the Ghat area.

The integrated water resource map (Fig. 7) combines data from the satellite image, radar, drainage characteristics, topography and areas where water could accumulate. This can indicate areas within an area of interest for surface water monitoring, infiltration and groundwater investigations. The areas with high numbers of positive indicator can be targeted for field investigations. The map shows an overview of the water resource distribution, but does not show specific details on groundwater resources or water availability.

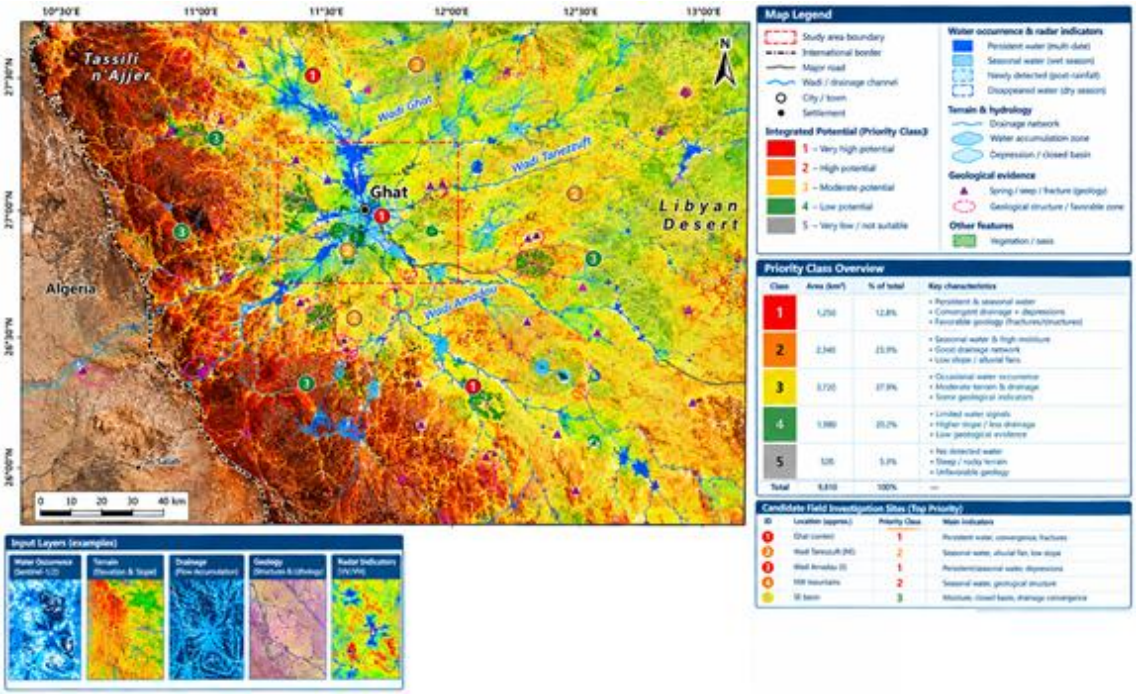


Fig. 7: Integrated potential water-resource map of the Ghat area.

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The Sentinel-2 false-color composite (Fig. 8) uses bands B8, B4 and B3 to allow identification of different landcover types such as vegetation, bare soil, rocky ground, and drainage channels in the area around Ghat. Healthy vegetation will highly reflect near infrared energy and so will often appear bright red or red tones. By looking at differences between drainage channels and the surrounding surfaces it can be possible to identify areas likely to hold onto water following rainfall. A lot of useful information can be gained from these patterns.

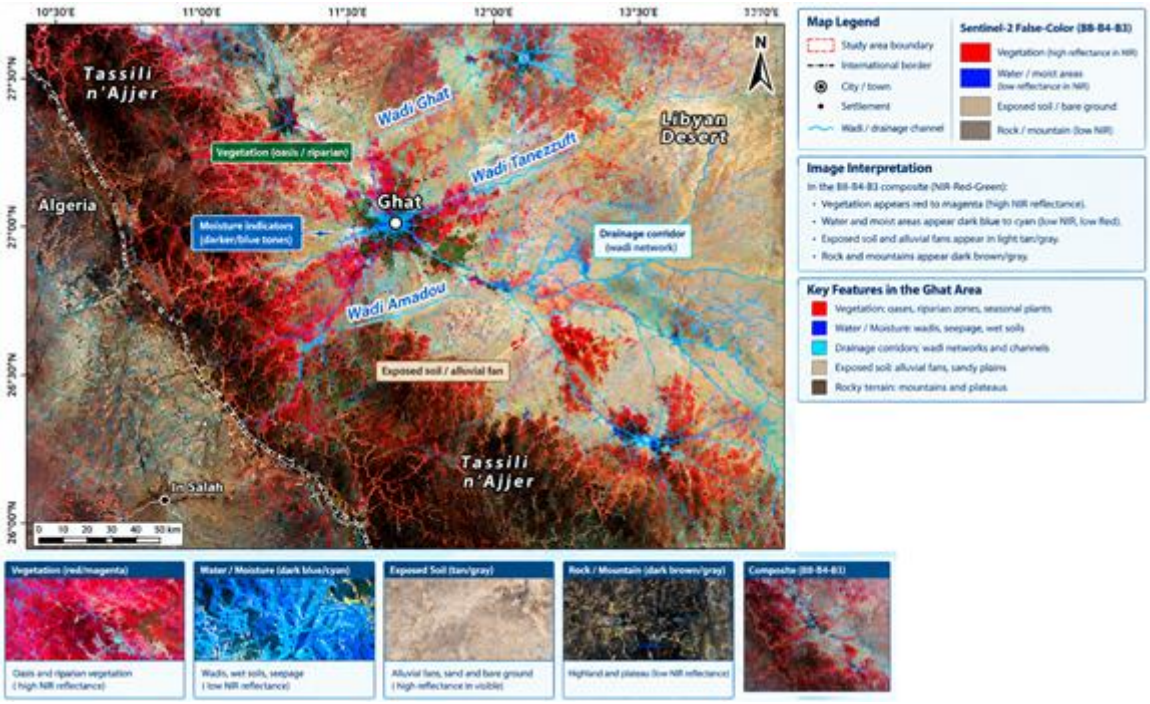


Fig. 8: Sentinel-2 false-color composite for water and vegetation detection of the Ghat area.

The NDVI map (Fig. 9) is used to determine vegetation, based on its reflectance in the near infrared and red bands. Increasing values of NDVI generally indicate more vigorous green vegetation, while lower values usually indicate bare soil or sand and rock, with little vegetation. Vegetation clusters indicate possible oases or areas with more favorable moisture conditions for vegetation in the Ghat area. Comparing NDVI between different dates can help determine if there have been changes in vegetation due to availability of water, irrigation, rainfall and/or land use. Ground based observations are required to determine what factors are causing the vegetation changes.

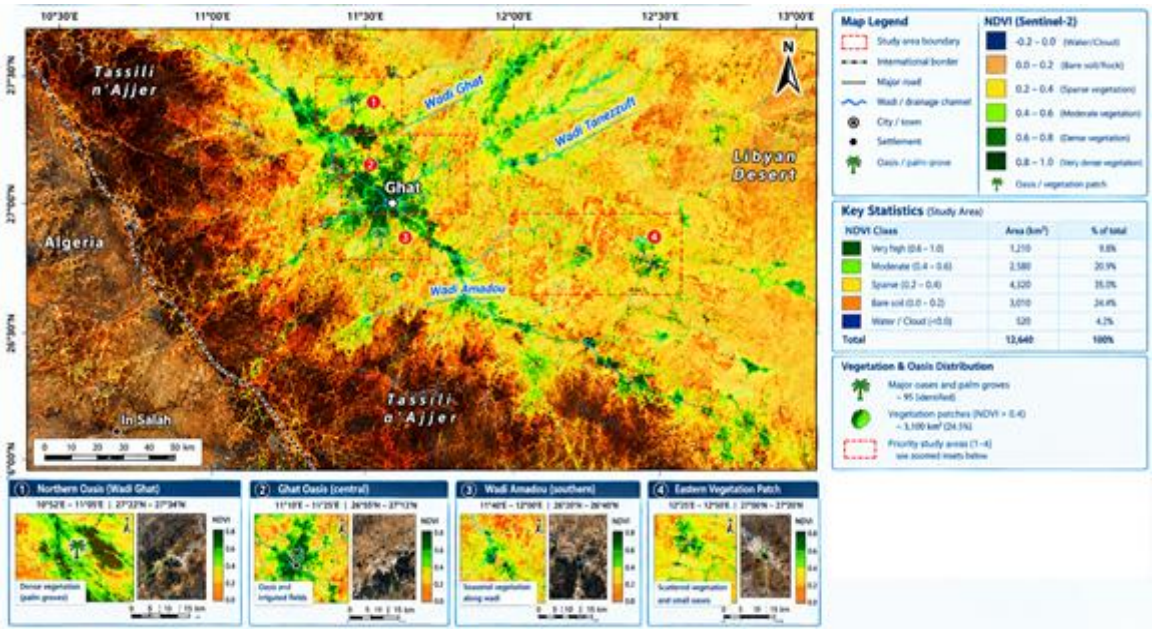


Fig. 9: NDVI map of vegetation and oasis distribution in the Ghat area.

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The SWIR analysis (Fig. 10) can also help to identify variations in surface moisture; outcropping lithology and sediment types in the Ghat area. The variations in spectral reflectance could show differences between rocky areas, sandy areas and alluvial deposits. Alluvial and sediment filled valleys are important as their permeability can affect infiltration and groundwater storage. However, SWIR images provide only basic surface information. Without further geological and hydrogeological information, it would be impossible to define how deep the aquifer was, how thick it was or how much water content it contained.

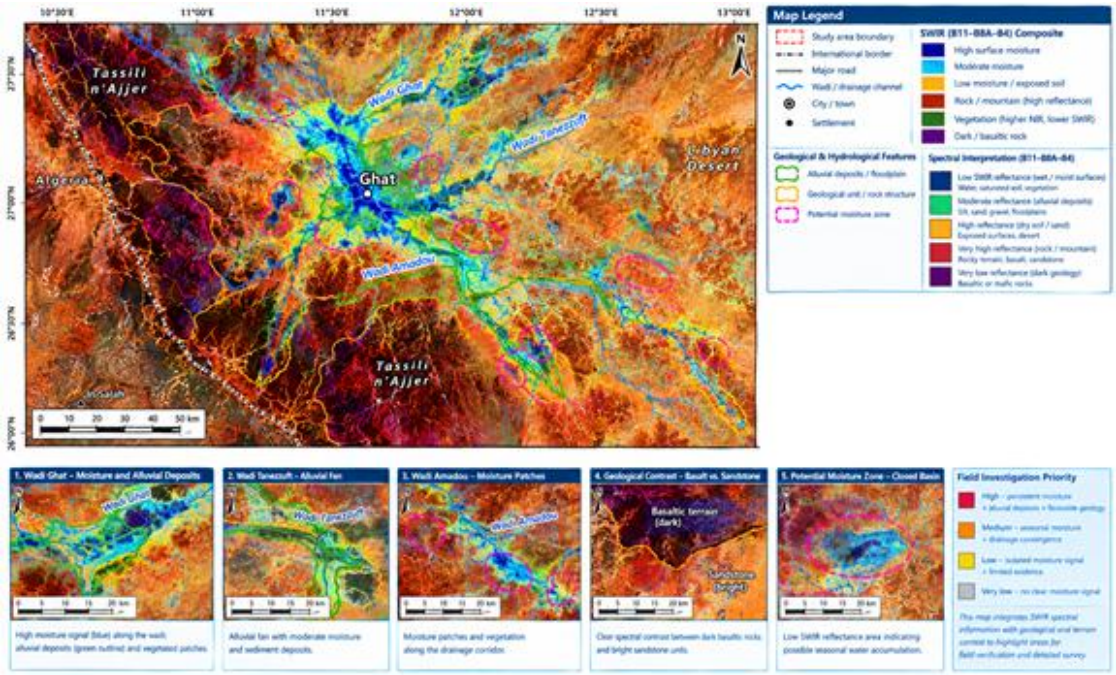


Fig. 10: SWIR-based surface moisture and geological feature map of the Ghat area.

The multi-date water-occurrence map (Fig. 11) identifies where water has been repeatedly identified throughout the satellite time series. Water that has been frequently identified may be permanent or recurrent. However, water with a low occurrence may be temporary, such as temporary pools after rainfall. Low water occurrence may also show how insensitive the satellite data can be. This helped identify where there was a high area of water and therefore where seasonal monitoring and validation should take place.

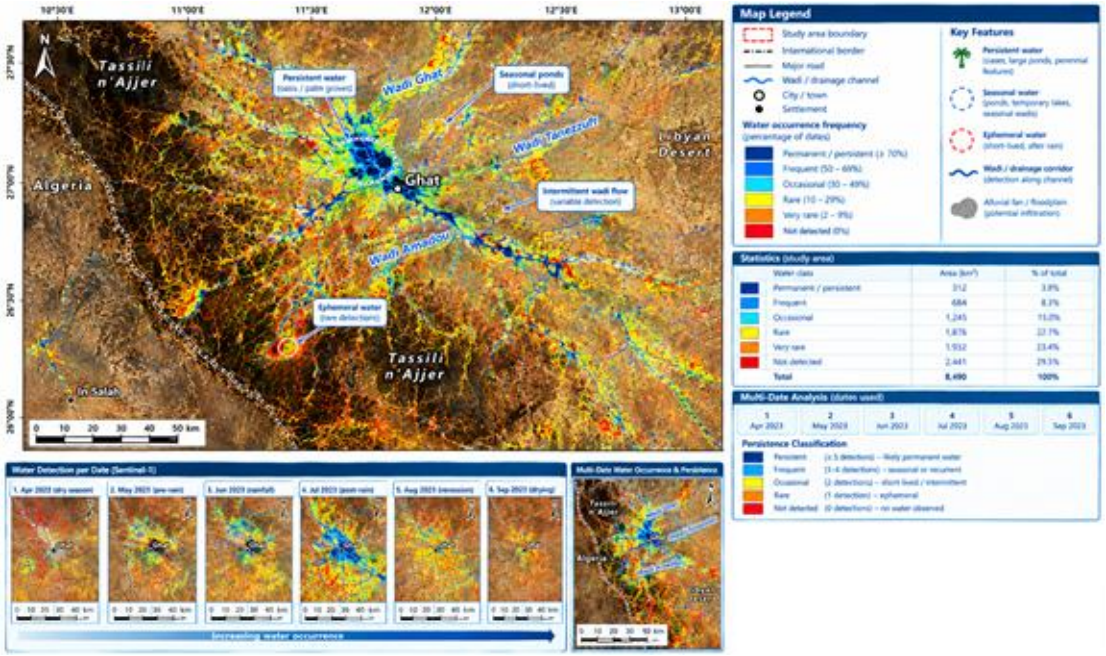


Fig. 11: Multi-date water occurrence and persistence map of the Ghat area.

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The potential groundwater recharge map (Fig.12) takes different factors into account such as gradient, drainage density, rainfall, geology, soils/surface materials and lineament density to determine areas with potential for infiltration. Areas with low gradients, permeable sediments and convergent drainage systems will provide good infiltration conditions if there is a source of runoff/rainfall. A well connected faulting network will create good infiltration conditions. High slope and low permeability surfaces can create high runoff. These areas show where there may be recharge opportunities but no specific values can be given. They should be backed up by geological surveys and monitoring of the groundwater.

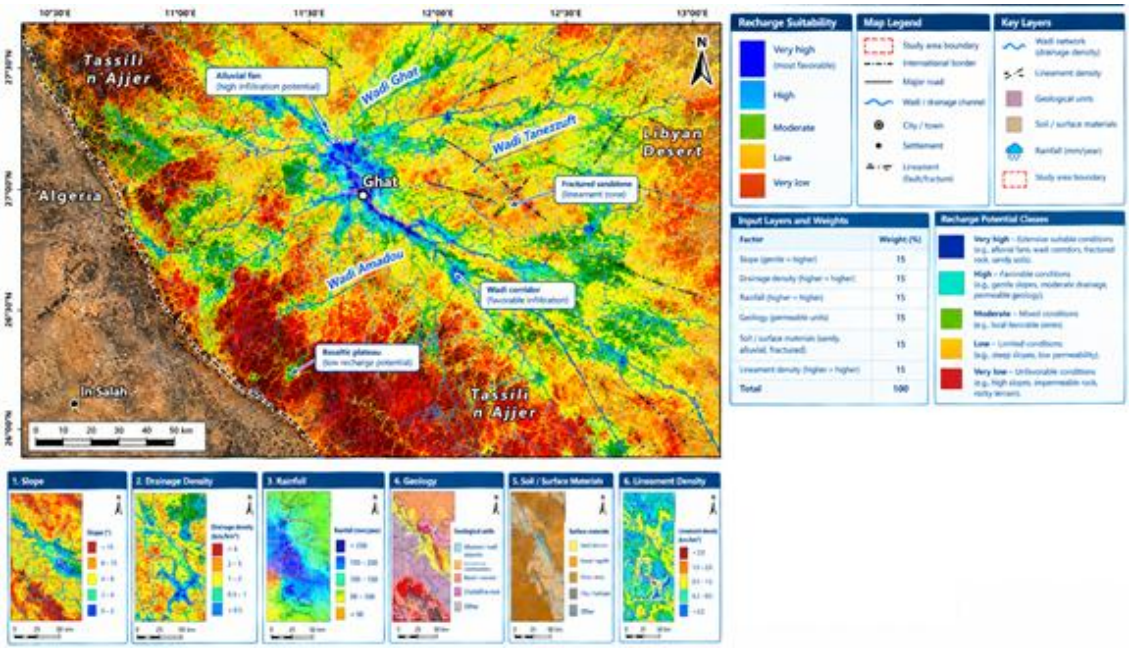


Fig. 12: Potential groundwater recharge zones in the Ghat area.

The geological-lineament map (Fig. 13) shows linear features which have been interpreted from the satellite image and DEM. These may represent faults, fractures and geological contacts. Some of these may affect groundwater flow by forming flow paths through fractured rock but some may be impermeable and unrelated. Correlating lineaments with mapped wadi locations, patches of vegetation and areas of potential water accumulation can show areas where there could be structural influences on groundwater distribution. Ground survey and geophysical surveys would be required to confirm the geological nature of these features and their importance to groundwater.



Fig. 13: Geological lineaments and potential groundwater pathways of the Ghat area.

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The geomorphological map (Fig. 14) displays the primary geomorphological features that are found within the study area. This includes wadis, alluvial fans, terraces, depressions, rock uplands, dunes and infilled valleys. The presence of these features will have an impact on the hydrology of the area. Wadis and alluvial fans can create areas of concentration and deposition of sediment. The permeable material can be used to provide zones of infiltration and groundwater storage. Areas farther down may receive more runoff from rocky uplands. The map provides a good basis for understanding how the geomorphological features relate to the surface water and potential groundwater resources.



Fig. 14: Geomorphological map of the Ghat area.

The integrated groundwater-potential map (Fig. 15) has been prepared using various factors like geology, geomorphology, drainage pattern, slope, lineaments and rainfall by using GIS based multi-criteria decision analysis. Those areas which have favorable combination of multiple favorable factors are assigned higher potential, whereas areas with unfavorable combination have been assigned lower potential. These zones will be prioritized for borehole investigations, geophysical studies and hydrogeological field investigations in Ghat area.

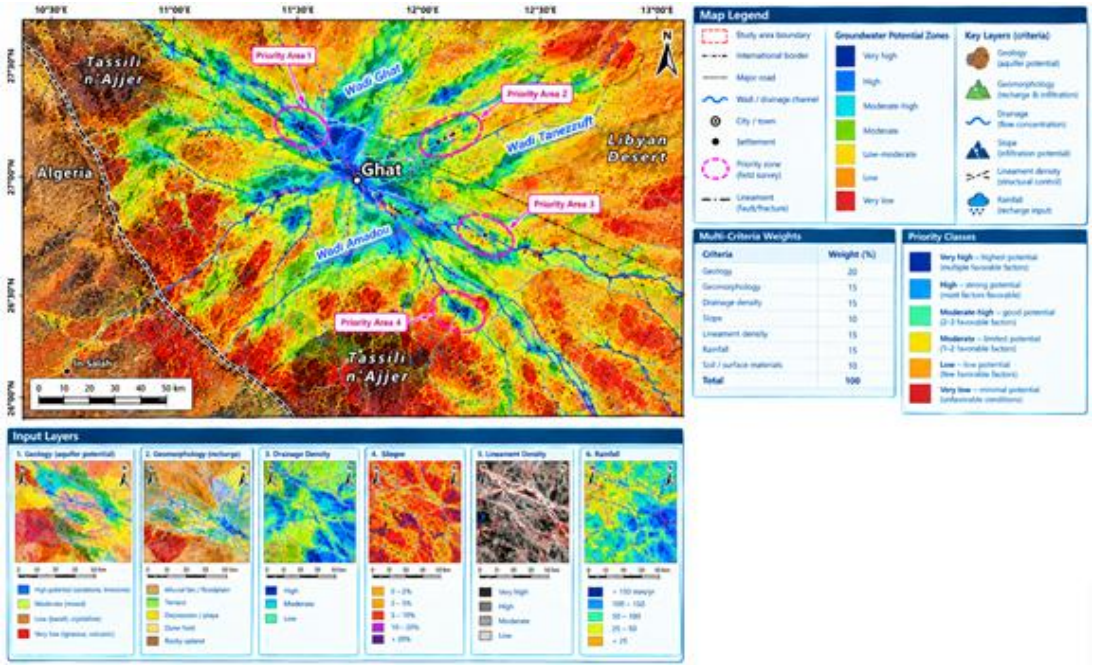


Fig. 15: Integrated groundwater potential zones of the Ghat area.

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The rainfall–water-extent analysis (Fig. 16) looks at how rainfall effects the amount or size of water features picked up by satellite imagery. An increase in water features may indicate runoff into wadis and depressions or ephemeral water bodies. A lag analysis can be carried out to see if a lag occurs between rainfall and appearance of water. This can help identify the impact of climate variability on temporary water resources.

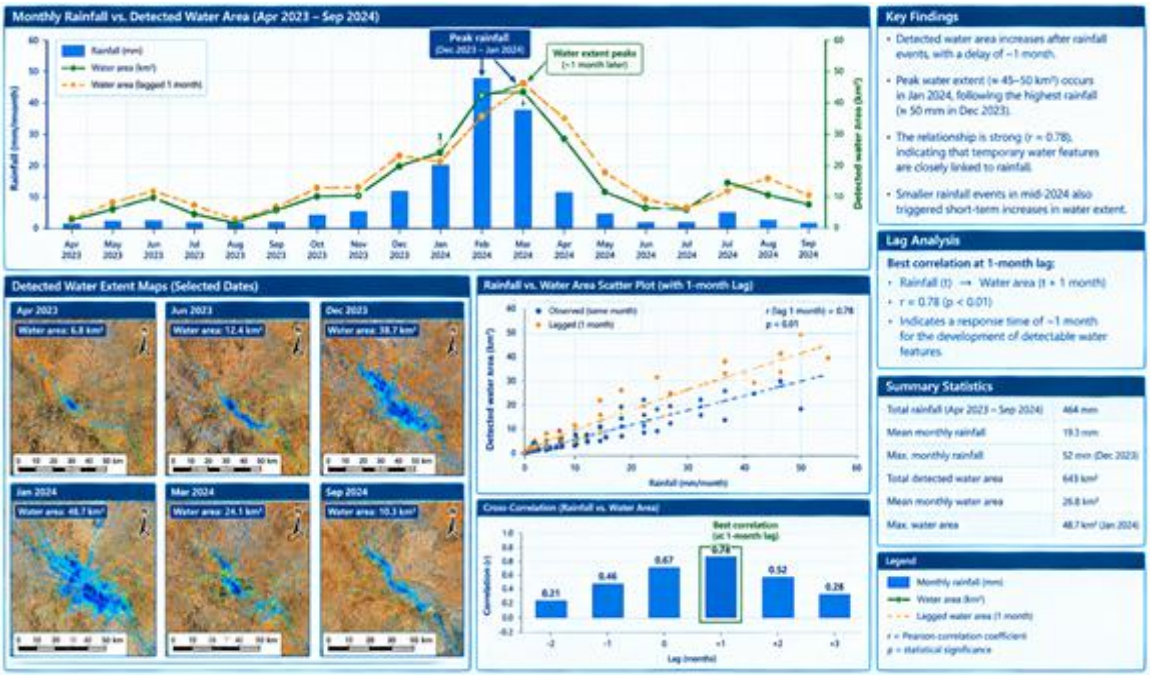


Fig. 16: Relationship between rainfall and detected water extent in the Ghat area.

The before-and-after rainfall radar analysis (Fig. 17) was undertaken to compare the Sentinel-1 data before and after the rainfall event. This can show differences in surface conditions between the two times due to a change in backscatter. Changes in backscatter can indicate areas of potential flooding, increased surface moisture or changes in the roughness and vegetation in drainage corridors. This is particularly useful for the Ghat area as radar can be collected during cloudy conditions and at night. However, changes in backscatter may not always be an indicator of water as it will depend on the surface characteristics and radar geometry. Field observations can be used to help give a more reliable analysis.

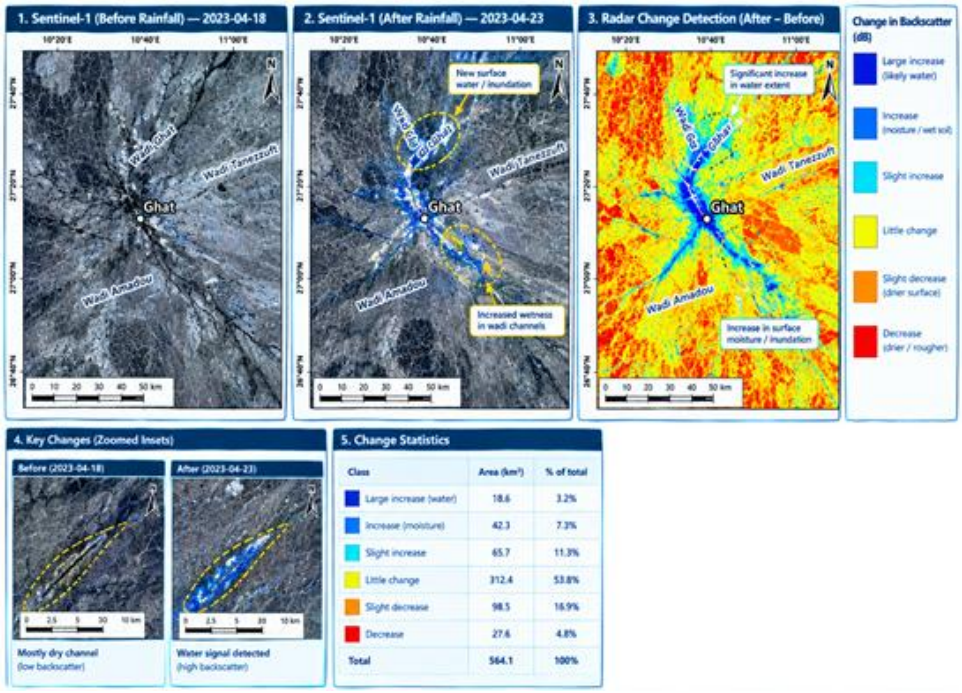


Fig. 17: Before-and-after rainfall radar change detection of the Ghat area.

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The groundwater-vulnerability map (Fig. 18) shows how vulnerable areas of groundwater are to contamination based on different factors such as aquifer properties, soil porosity, geology and proximity to potential sources. Areas that have shallower groundwater levels, more porous materials or lack natural protection will be more vulnerable due to increased chance of pollutants entering the aquifers. This can assist in identifying important locations for groundwater monitoring, pollution prevention, and careful land use planning. However, just because an area is vulnerable it does not mean that it will be contaminated. Water samples must be taken from the groundwater and sent to a lab to ensure if the water is indeed of poor quality.

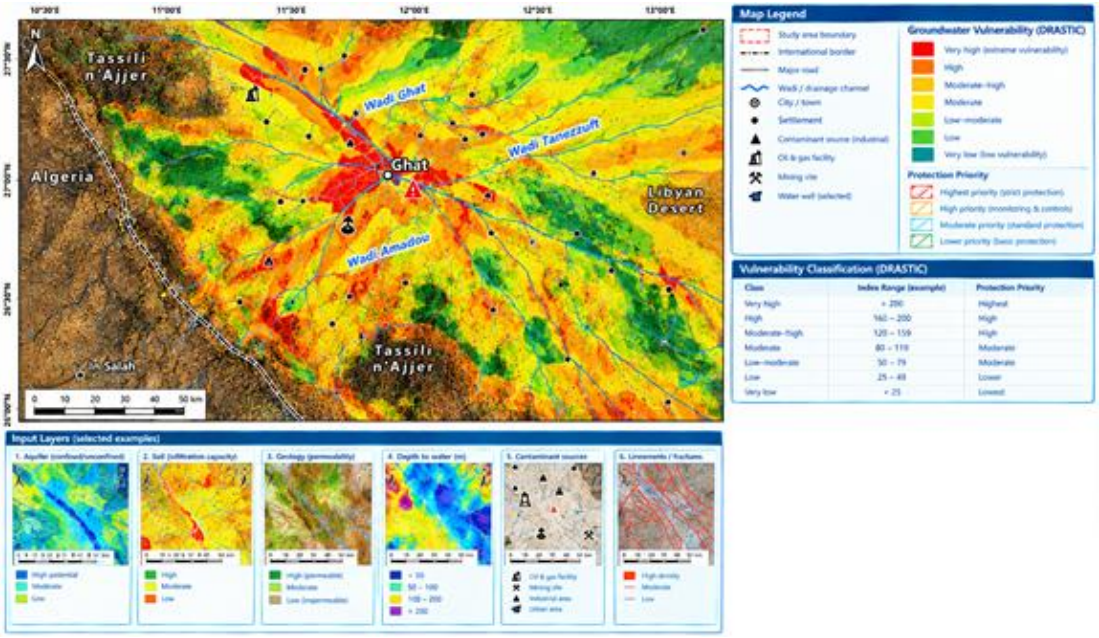


Fig. 18: Groundwater vulnerability and protection priority map of the Ghat area.

The reliability of detecting water using satellite data in the Ghat region has been evaluated by comparing the water classified from Sentinel-1 radar satellite images to independent reference data and/or carefully interpreted satellite images (Fig. 19). A confusion matrix can be used to give a summary of classification agreement. Other metrics which have been calculated include overall accuracy, producer's accuracy, user's accuracy, F1-Score and Cohen's Kappa. From the example results given it can be seen that the overall accuracy is 93.6% which shows that there is good agreement between the classified satellite imagery and the reference data.

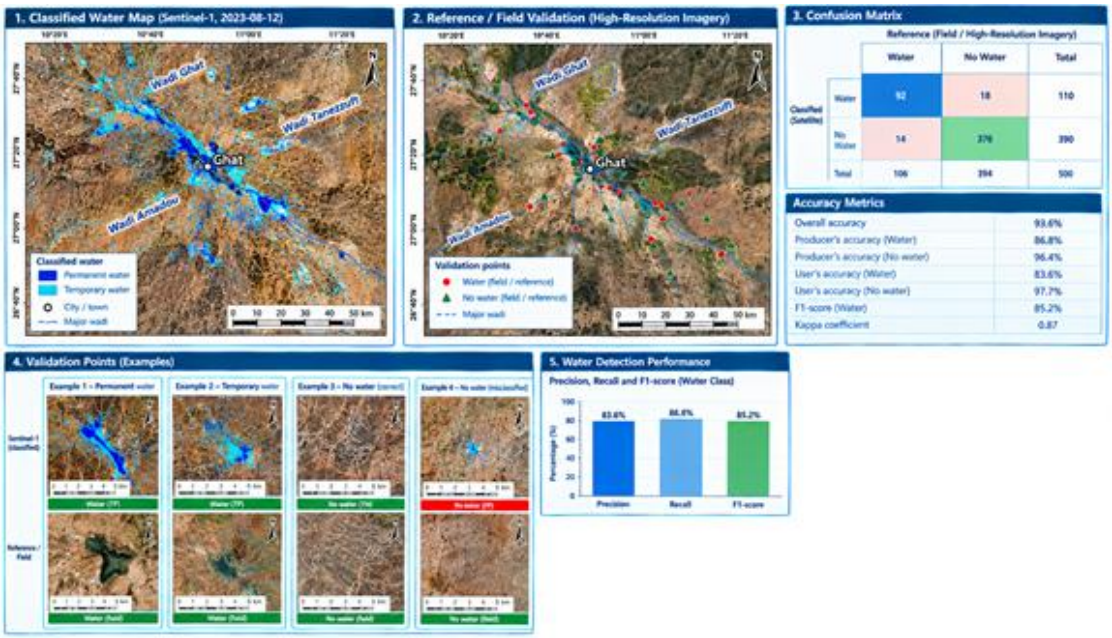


Fig. 19: Accuracy assessment of satellite-based water detection of the Ghat area.

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Conclusions and Recommendation

This study demonstrated the usefulness of integrating satellite imagery, remote sensing, and GIS for identifying potential hidden and ephemeral water resources in the Ghat area of southwestern Libya. Additional information was provided by the various data sources (Sentinel-1 radar, Sentinel-2 optical, and spectral water indices) to identify possible water bodies, vegetation, and changes in surface moisture. Drainage patterns, depressions and potential areas for runoff to collect were identified using the DEM. The multi-temporal data allowed a seasonal analysis of potential surface water features, identifying potential ephemeral water features. In addition to this, geological, geomorphological and lineament analysis were used to identify areas which may have favorable infiltration conditions and potential groundwater occurrences. This produced initial areas of interest for further investigation into potential water resources. However, there was no confirmation possible using remotely sensed indicators alone that groundwater would be present, how much, what quality and how deep it would be. Therefore, it is necessary to conduct field surveys, geophysical studies, groundwater level measurements, and water quality analysis.

Future research should include fieldwork in areas with high potential for transitory water and groundwater. Geophysics, borehole data, geology and groundwater levels can help with groundwater exploration. Regular monitoring can be done using Sentinel-1 and 2 imagery, which will show how the surface water, vegetation and moisture content changes throughout the seasons. Rainfall data can also be used alongside the satellite imagery to understand the relationship between rainfall and temporary water sources. Groundwater samples should also be taken and analyzed.

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