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Assessment of geomorphological landforms and features in the Sebkhas region of the Boulhilet Plain, north-eastern Algeria

Abstract: Bousba H., Marmi R., Chabour N., La Licata M., De Amicis M., Bosino A., *Assessment of geomorphological landforms and features in the Sebkhas region of the Boulhilet Plain, north-eastern Algeria.* (IT ISSN 0391-9838, 2024). This paper aims to enhance the knowledge of the geomorphological landforms and features in the Algerian Sebkhas region, (Boulhilet alluvial plain, Constantine High Plains, northeast Algeria), by creating the first geomorphological map of the area at 1:50,000 scale. The methodology adopted in this study is based on an integrated approach which combines the analysis of multi-source data starting from field observations, dedicated GIS and remote sensing data analysis (i.e., DEM and derived maps). The approach consists of accurately mapping the various landforms and features, along with the integration of geological, pedological, climatic, and hydrological data. Moreover, the Sentinel-1 SAR images in Google Earth Engine platform were used to assess areas prone to flooding. Results revealed that the landscape configuration is characterized by complex and active geomorphological processes influenced by tectonic, climatic, and hydrogeological factors. In particular, sebkhas, lunettes, ephemeral wadi channels, gullies, as well as other landforms related to flash flooding were identified, mapped, and illustrated. In addition, the study area is affected by various soil degradation phenomena, including salinization and soil erosion. This novel study lays the foundation for advancing the understanding of the geomorphological complexity of the area and its relationship with the environmental setting, leading to several potential implications and benefits from both scientific and applied perspectives.

Key words: Sebkhas, Boulhilet Plain, geomorphological mapping, soil erosion, GIS, Remote Sensing.

Riassunto: Bousba H., Marmi R., Chabour N., La Licata M., De Amicis M., Bosino A., *Forme del rilievo e caratteristiche geomorfologiche della regione di Sebkhas nella pianura di Boulhilet, Algeria nord-orientale.* (IT ISSN 0391-9838, 2024). Questo lavoro si propone di migliorare le conoscenze geomorfologiche della regione algerina delle Sebkhas, parte della pianura alluvionale di Boulhilet nell'altopiano di Costantine (Algeria nord-orientale), creando la prima carta geomorfologica dell'area alla scala di 1:50.000. La metodologia adottata in questo studio si basa su un approccio integrato che combina l'analisi di dati provenienti da fonti multiple a partire da osservazioni sul campo, analisi GIS dedicate così come analisi di dati telerilevati (DEM e carte derivate). L'approccio consiste nel rappresentare accuratamente le varie forme del rilievo, integrando le informazioni geomorfologiche con dati geologici, pedologici, climatici e idrologici. Inoltre, le immagini SAR Sentinel-1 della piattaforma Google Earth Engine sono state utilizzate per valutare le aree soggette a inondazioni. I risultati hanno rivelato che la configurazione del paesaggio è caratterizzata da processi geomorfologici complessi e attivi, influenzati da fattori tettonici, climatici ed idrogeologici. In particolare, sono state identificate e rappresentate forme quali sebkhas, lunette, canali effimeri di wadi, gullies e altre forme del rilievo legate a eventi di flussi estremi. Inoltre, l'area di studio è interessata da vari fenomeni di degradazione del suolo, tra cui la salinizzazione e l'erosione superficiale. Questo studio fornisce un primo contributo alla comprensione della complessità geomorfologica dell'area e delle relazioni con il contesto ambientale, fornendo nuove potenziali implicazioni d'interesse sia scientifico che applicativo.

Termini chiave: Sebkhas, Pianura di Boulhilet, Cartografia geomorfologica, erosione del suolo, GIS, Telerilevamento.

INTRODUCTION

The fringe between the Tellian Atlas and the Saharan Atlas offers a semi-arid landscape, with an endoreic character, which is very distinctive in the north-eastern part of Algeria. This region is also known as 'the land of salt lakes' or 'sbakhs' (plural of sebkha in the local dialect) (Dresch, 1950), due to the extensive presence of these peculiar features at the bottom of the High Plains of Constantine. By definition, the Arabic

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term ‘sebkha’ (or ‘sabkha’), used in northern Africa and in the Arabian Peninsula, refers to a salt flat that is temporarily flooded (Briere, 2000; Gutiérrez, 2005; Thomas, 2011; Goudie, 2013).

Although most of these depressions are classified under the ‘Ramsar Convention’ due to their biological and ecological importance (https://rsis.ramsar.org/), access to geological data remains very limited to regional stratigraphic and structural analyses, including only geological maps (Savornin, 1920; Dubourdieu, 1956; Voûte, 1967; Guiraud, 1973; Vila, 1980; Chadi, 1991; Coiffait, 1992, Aris, 1994; Addoum, 1995; Benabbas, 2006), sedimentological and geochemical investigations (Marmi, 1995), and pedological surveys (Department of Agropedology and Agricultural Hydraulics). Therefore, a synoptic and detailed geomorphological or cartographic study of the Constantine High Plains is still lacking. This lack of information poses a significant challenge to any in-depth analysis of the distribution of landforms and their relationship with the area’s morphodynamic factors. Several studies have been carried out around the world in arid and semi-arid zones, focusing on geomorphological processes and the associated dynamics, as well as the influence of climate (Cooke et Warren, 1973; Neal, 1975; Cooke *et al.*, 1993; Gutiérrez, 2005; Thomas, 2011; Goudie, 2013). Other works have focused more specifically on closed depressions of the salt lake type (Anadón, 1989; Currey, 1994; Rosen, 1994; Shaw and Thomas, 1997; Brière, 2000). Other more recent studies have concentrated on understanding ecological, chemical, pedological, and hydrogeological aspects to study their evolution (Neffar *et al.*, 2015; Chenchouni, 2016; Smati and Kitouni, 2019; Hachemi *et al.*, 2020; Hafhouf *et al.*, 2022; Benkesmia *et al.*, 2023; Hafhouf and Abbech, 2023; Nas *et al.*, 2021; Pourali *et al.*, 2022; Benrebouh *et al.*, 2025). Moreover, with the recent advances in remote sensing and geographic information systems (GIS) technologies, researchers’ interest in arid and semi-arid regions has been increasing, as demonstrated by the most recent applications in the fields of terrain analysis and high-resolution geomorphological mapping (Klinge et Lehmkuhl, 2013; Zerboni *et al.*, 2014, 2020; Costanzo *et al.*, 2021; Forti *et al.*, 2024).

However, in Algeria geomorphological research on the sebkhas was rarely carried out. Only Benazzouz (1986) explored (with his doctoral thesis) the Tarf Sebkha, in the eastern part of the high plains, while Moussa (2006) mapped the geomorphology of the Oran Sebkha, in western Algeria. The former demonstrated that the dry climatic transition of the recent Quaternary Period is the main cause of the endoreism observed in the region. He also confirmed the dynamic and active nature of the sebkha by explaining the link between morphodynamic changes and aeolian processes that give rise to successive generations of dunes (Benazzouz, 1986). Whereas Moussa (2006) analyzed the dynamics of the Oran Sebkha focusing on geomorphological features and structures.

Considering the above, the Boulhilet plain and its surroundings represent an ideal laboratory for studying the landforms and the relationship between morphological formations associated with sebkhas. The area contains a large number of sebkhas (four out of eleven in the entire Constantine Plains Watershed) and provides an excellent case study. To address the current knowledge gap, this study aims to: (1) produce a geomorphological map at a scale of 1:50,000, paying particular attention to erosion forms and characteristics, by integrating pre-existing geological data, field surveys, and remote sensing data; (2) assess flood-prone areas that are likely to affect the region’s population rapidly due to extreme flood events, using remote sensing data from the Google Earth Engine (GEE) platform. This is relevant from both a scientific and an applied perspective, as the area provides valuable socio-economic and ecological benefits (i.e. it is a source of salt exploited by local people, and an important breeding ground for migratory birds, especially flamingos). The resulting maps will describe landforms and illustrate the processes that contribute to their formation. The maps will also highlight areas vulnerable to flooding, providing essential data for future research into soil salinity and risk scenarios in this area of great social, economic, and ecological importance.

STUDY AREA

Located about 130 km from the Mediterranean coast, between two contrasting areas, the Tellian Atlas to the north and the Saharan Atlas to the south (fig. 1a), the study region ranges from 800 to 1300 m a.s.l. It contains a vast alluvial plain of 600 km², called Boulhilet. It is part of the sub-basin of Ank Djemel Sebkha (fig. 1b), which in turn belongs to the great watershed of the Constantine High Plains (ABH, 2002; ANRH, 2005). Within this plain, four endoreic saltwater depressions, with flood bottoms, occupy the lowest areas of the plain, such as the Djendli, Ank Djemel, El Merhsel and Boulhilet sebkhas. These depressions represent distinct morphological entities, reflecting specific hydro-geomorphological functioning (e.g., accumulation of water and salts). They are also recognized as Ramsar sites of international importance (fig. 1b) under the Ramsar Convention (https://rsis.ramsar.org/).

The region is subject to a cold to cool lower semi-arid climate (Abdessemed, 1984; Le Houérou, 1995; Côte, 1998), of the «BSk» type (Köppen-Geiger climate classification, 1936). This climate has an impact on vegetation, crops, and water flows. Precipitation is low and characterized by significant seasonal and annual variability. In fact, the average annual rainfall was only 350 mm for the period 1970-2022 (Boulhilet Station, Power Data NASA, https://power.larc.nasa.gov/data-access-viewer/), and climatic conditions have been very restrictive (4 to 5 dry months, many days of frost,

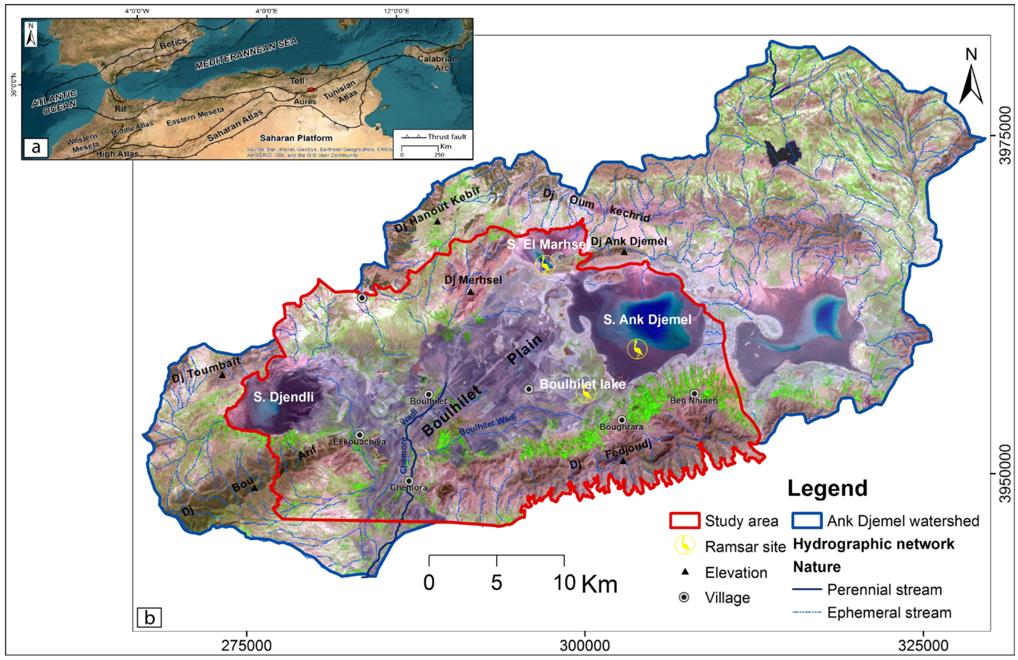

Figure 1 - Location of study area. (a) Structural map of the Western Mediterranean (Roure *et al.*, 2012; Leprêtre *et al.*, 2018) (Data: Esri - World Imagery). (b) Landsat8 image of the Sebkha ank Djemel watershed, dated 05/04/2025 (False color composite, Bands: 6, 5 and 4). The main map area is marked by the red polygon.

Sirocco winds). The production system of the region is primarily based on the cultivation of cereals (*wheat, barley, and maize*) and forage crops (*alfalfa*), combined with sheep farming and grazing. Crops yields are rainfall-dependent, which limits production and makes harvest success uncertain. To address this challenge, irrigation has become essential for all crops. However, this region faces an additional challenge in the form of soil and water salinity, which poses a problem for agriculture.

Despite the scarcity of precipitation in this area, it is important to emphasize that intense rainfall episode, although temporary, cause significant soil erosion, such as rill, gully and bank erosion. These erosion processes are frequent in the studied region and affect the alluvial sediments in the plains, as well as the colluvial deposits on the slopes and foothills. Moreover, the lack of vegetation in the area exacerbates soil degradation (Tricart, 1969). Furthermore, these intense rainfall events not only lead to erosion, but also frequently increase runoff and cause flash flooding in the wadis (e.g., recurrent flooding in Chemora Wadi, most recently in 2022). This amplifies the associated risks and damage to crops and property (Algerian press; Technical Department of Chemora Municipality).

Geologically, the study area belongs to the pre-Atlas domain of the foreland of the Maghrebides chain of north Algeria, between the Tellian front to the north and the Atlas front to the south (Guiraud, 1973; Vila, 1980; Maupin, 1982; Coiffait, 1992; Marmi, 1995). It is placed along a subsidence corridor and is bordered by anticlinal folds with a dominant NE-SW Atlasic trend. These folded massifs are affected by major faults and have a main NW-SE orientation as described by Marmi (1995), who also suggested that the directions of the extensive tectonic episodes that led to the formation and evolution of the continental basins are NE-SW and NW-SE. The first is thought to be related to the development of NW-SE troughs. The second episode, more recent, would correspond to the establishment of the current sebkhas (fig. 2a).

The sedimentary formations which crop out in the study area range from the Triassic to the Plio-Quaternary (Vila, 1977a,b,c,d, 1980) (fig. 2b). Marls, limestones and sandstones form all the rock massifs or 'djebels' (in Arabic language). Plains and depressions are filled with thick detrital deposits from the continental Mio-Pliocene and Quaternary alluvium (i.e., conglomerates, sands, silts, marls, clays and gypsum). Saliferous Triassic evaporites have many outcrops and often date back to tectonic accidents.

The soil map produced by Aissoug in 1970 (fig. 2c), based on the French classification system (C.P.C.S, 1967), reveals a mosaic of soils. Revised according to the World Reference Base for Soil Resources (WRB), the terrain is dominated by five soil types: *Calcisols*, *Solonchaks*, *Vertisols*, *Cambisols* and *Regosols* (IUSS Working Group WRB, 2022). The distribution of these soils is heterogeneous, mainly due to the topography, the bedrock and the proximity of the sebkhas. For example, *Calcisols*, which are the most widespread, are generally found on the piedmonts of calcareous mountains. The latter supplies a significant quantity of calcium carbonate to run-off water, thus affecting the development of soils on the lower slopes. On the other hand, *Solonchaks* occupy the areas surrounding the sebkhas and are characterized by a high concentration of soluble salts. In addition, to their proximity to the sebkhas, *Solonchaks* (halomorphic soils) also form in distinct and distant areas of the plain. This can be explained by the influence of hydric processes (e.g., capillary rise, poor drainage) and aeolian processes (i.e., redistribution and displacement of small saline particles from the saline crusts of the sebkhas), which contribute to the accumulation of salts, particularly in distantly exposed areas. *Vertisols*, *Cambisols* and *Regosols*, particularly those affected by waterlogging, are found in the central part of the plain. In some areas, the soils show great diversity, comprising a combination of types, known as diversified soils. Soil texture varies from silty clay to sandy loam, with variable organic matter content (Aissoug, 1970).

The landscape is therefore characterized by: (1) a system of sebkhas encased within the vast alluvial plain of Boulhilet and (2) a discontinuous relief, interrupted by faults or erosional discontinuities, with steep and rugged slopes (escarpments) (figs 3a, 3b). These relief forms consist of the calcareous folds of Djebels Bou Arif and Fedjoudj, with their buttresses in the southern part and the calcareous-sandstone chains of Tombaïte, Hanout Kebir, Merhsel, and Ank Djemel in the northern part (main map).

The hydrographic network (fig. 3c), including the sebkhas, is endorheic, often discontinuous, and subject to significant seasonal and even daily fluctuations in flow and water presence. Chemora Wadi is the only perennial stream (main map). The characteristics of water flows and floods are largely influenced by local topography, vegetation, and irregular precipitation. Severe floods occur suddenly (Guidoum, 2017), sometimes lasting two to three days before rapidly decreasing due to the short and intense nature of rainfall, the steep slopes of the southern basin,

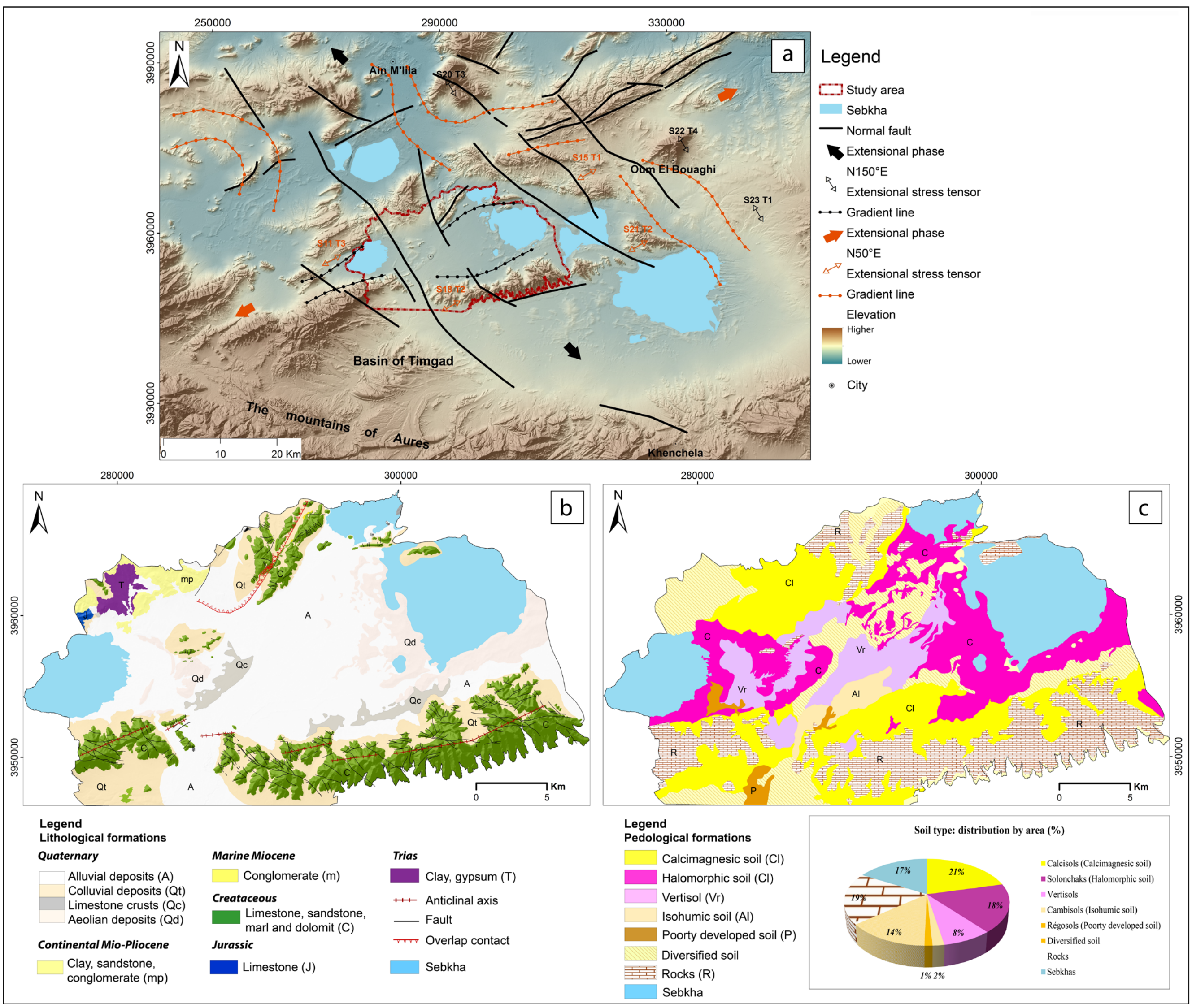

Figure 2 - (a) Relationship of the continental basins (collapse trenches and sebkhas) of north-eastern Algeria with the tectonics (Marmi, 1995). Plio Quaternary extensional phase N50°E (in orange color). Plio-Quaternary extensional phase N150°E (in black color). (b) Simplified geological map (Vila, 1977a,b,c,d). (c) Pedological map (Aissoug, 1970).

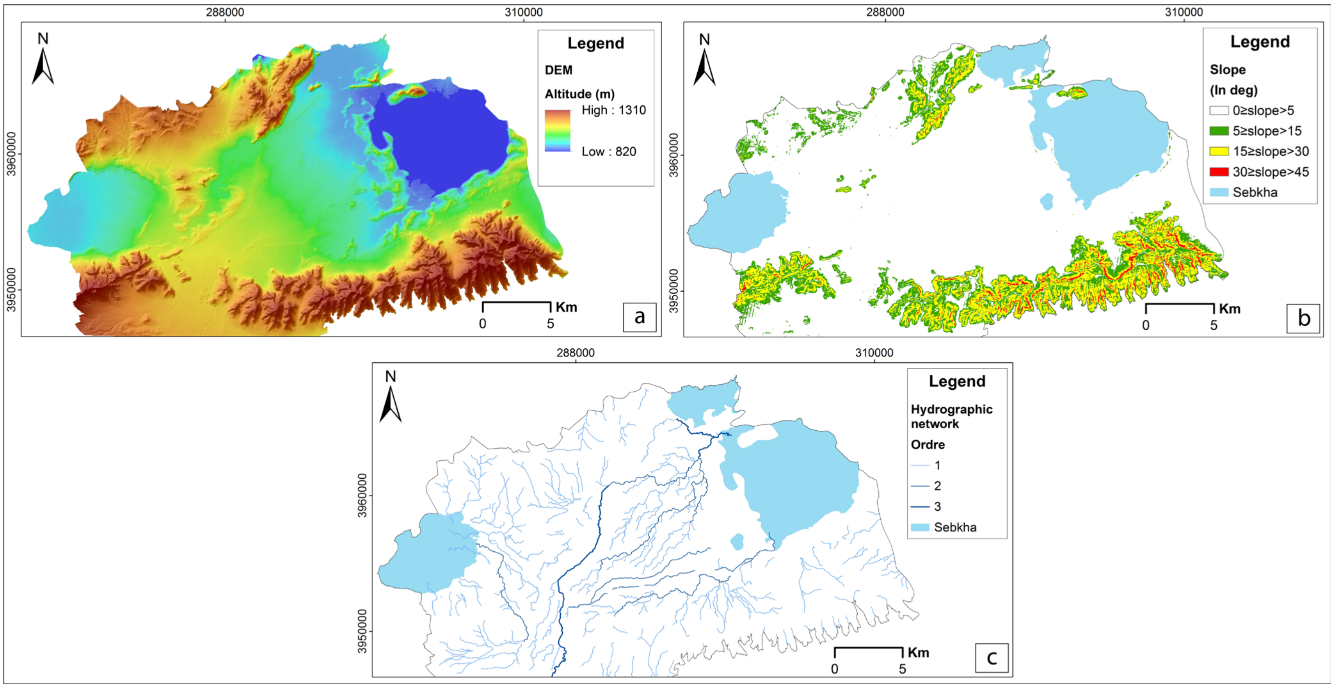

Figure 3 - (a) DEM illustrating the relief. (b) Slope map. (c) Hydrography map of study area.

and the high evaporation rate. These floods have a significant impact downstream, contributing to the recharge of aquifers (Guiraud, 1973) as well as the sebkhas. The latter are not permanently submerged and receive water inputs only during periods of significant flooding (Bousba *et al.*, 2023). During dry periods, the water flow of the main wadi decreases, evaporation increase, and the wadi and its tributaries dry up upon entering the plain.

METHODOLOGY

The methodology adopted is based on two complementary approaches: i) the Geomorphological survey and mapping; and ii) the assessment of flood-prone areas.

Geomorphological survey and mapping

When it comes to geomorphological mapping in arid and semi-arid regions, many researchers tend to rely on terrain analysis techniques and field observations (e.g., Klinge and Lehmkuhl, 2013; Zerboni *et al.*, 2014, 2020; Costanzo *et al.*, 2021; Forti *et al.*, 2024).

Following the same approach, we first collected existing geological and topographic data to establish a solid data basis. Preliminary data assessment in our study area was conducted on the Digital Elevation Model (DEM) (European Space Agency) at a resolution of 30 m and derived maps (hillshade, slope, hydrographic maps) were also used.

The integration of a mosaic of topographic and geological maps at a scale of 1:50,000 – namely sheets n° 146, 147, 173 and 174 provided by the *Algerian Geological Survey Agency* (https://bndg.asga.dz/bndg/) (Vila, 1977a, b, c, d, 1980) allow to characterize the topography and analyse the structure of the bedrock formations. In addition, pedological map of the plain at a scale of 1:50,000 (*Department of Agropedology and Agricultural Hydraulics*) (Aissoug, 1970) was assessed to evaluate the spatial distribution of soils and their extent. In particular, aerial photographs from 1972 and 1973, at a scale of 1:20,000, and recent Google Earth Images were examined to identify local morphological features and landscape changes over time. All data were processed using the WGS 1984 UTM Zone 32N coordinate system in a Geographic Information System (GIS) through QGIS (version 3.8) and ArcGIS (version 10.6) software.

The geomorphological map was realized during several field surveys carried out in 2023, 2024, and early 2025 following the Italian guidelines for geomorphological mapping (Campobasso *et al.*, 2018, 2021). These geomorphological guidelines cover a wide range of landforms and deposits associated with various morphogenetic systems (litho-structural, aeolian, etc.). According to Bosino *et al.* (2024), the Italian official geomorphological cartographic approach has been successfully applied in a several international studies, although it may require landform additions for certain morphoclimatic conditions, such as in the present study. Therefore, missing morphotypes can be integrated by introducing newly coded landforms within one of the existing morphogenetic systems. For example, we have slightly adapted the symbol of the classic 'alluvial fan' cited in the Italian guide, changing only the color of the third arrow and naming it 'deltaic fan', to take account of its relationship with the sebkha. This adaptation remains consistent with the general symbolism and is not intended to create a new morphological category, but to refine the representation of a known type according to the local context.

Our field observations focused on the visual and descriptive analysis of various landforms, particularly ravines near sebkhas, which are indicators of erosion and sediment transport towards these depressions. Moreover, we performed dedicated soil profiles analyses in representative gullies that cut the sedimentary sequence of the sebkhas, in order to link detailed soil observations with pre-existing observations on stratification and grain size of the sebkha deposits described by (Marmi, 1995; see the map in Supplementary Material). The symbology and associated colors were adapted to precisely and coherently illustrate the landforms based on the main morphogenetic process.

The distribution of the different geomorphological units – including sebkhas, litho-structural and gravitational landforms (e.g., scree slopes), aeolian landforms (e.g., lunette), fluvial and runoff associated landforms (e.g., gullies) – were assessed and mapped. In addition, the bedrock lithologies and tectonic elements were reported on the map.

Finally, the geomorphological map (see supplementary materials) is presented at the scale of 1:50,000. The map key does not distinguish between active and inactive forms, because all the mapped landforms selected the ISPRA methodology (Campobasso *et al.*, 2018, 2021) are only active or reactivable under current morphoclimatic conditions. The final design of the map was processed using Adobe Illustrator software.

Assessment of flood-prone areas

Remote sensing data is a valuable resource for assessing flood vulnerability (e.g., Cian *et al.*, 2018; Liu *et al.*, 2021; Xue *et al.*, 2022; Ramadhan *et al.*, 2023; Shinde *et al.*, 2023; Singh and Rawat, 2024; Sudaryatno *et al.*, 2024; Loukili *et al.*, 2025). This study used multi-temporal analysis to identify potentially flooded areas (Twele *et al.*, 2016). A script was run on the Google Earth Engine (GEE) platform on Sentinel-1, C-band Synthetic Aperture Radar (SAR) images in dual polarisation 'VV and VH' (i.e., 'Vertical transmit – Horizontal receive' are the polarisation modes of Sentinel-1's radar signals), which have a spatial resolution of 10 m. The use of these images for flood detection is well documented in the literature, particularly in the guidelines published by the ESA (ESA Flood Mapping Guidelines). These images were acquired during the wet (January-March) and dry (June-August) seasons each year from 2016 to 2024. In total, 16 periods were analysed (two season's per nine years) by filtering images containing both polarisations (VV and VH). However, only the VV band was exploited as it offers better sensitivity to flooded surfaces. A composite of the 10^{th} percentiles is generated for each period, enabling noise and speckle effects to be minimised, thanks in particular to spatial filtering (focalMean). This technique captures pixels with low values typical of flooded regions (where reflectivity is low in the VV channel). A water mask detected by applying a threshold of -15 dB to the VV image, enabling wet or waterlogged areas to be identified. Thereafter, two binary masks are generated: one for the dry season ('water_dry') and one for the wet season ('water_wet'). The flood prone zone is then determined by identifying wet pixels that are only present during the wet season and absent during the dry season. This makes it easier to differentiate between temporary water (such as flooding) and permanent water.

The results final are visualized in GEE using maps and graphs and subsequently exported as raster (GeoTIFF), vector (SHP) files and statistical information (e.g., graph of flooding area in km^2 from the period 2016-2024). To enhance interpretation, legends and the boundaries of the study area are included. Finally, the flood frequency map was validated though a geomorphological approach, comparing the model output with evidence of floods detected using Google Earth and in the field.

RESULTS AND DISCUSSION

The main result is a 1:50,000 geomorphological map (main map, supplementary materials), which shows a variety of landforms and features influenced by a wide set of natural processes often interacting with anthropogenic elements. The landforms were identified, grouped and described as follows: (1) Development of sebkhas and their sedimentological features, (2) Litho-structural and gravitational landforms, (3) Aeolian landforms, (4) Fluvial and runoff associated landforms. Furthermore, the study region's flood-prone areas were assessed, with the aim of determining the potential hazard and vulnerabilities in these areas.

Development of sebkhas and their sedimentological features

The sebkhas (fig. 4) are temporary salt wetlands with a flat topography (Goudie, 2013). They lie at an elevation of roughly 830 m (lower than the rest of the plain) and are bordered scattered halophytic vegetation known locally as 'chott' (e.g., *Sarcocornia fruticosa*, *Suaeda fruticosa* and *Atriplex halimus*) (Chenchouni, 2016).

According to Marmi (1995), the sebkhas basins are undergoing a process of distension, accompanied by a subsidence and their evolution is not influenced by the characteristics of pre-existing geological structures such as synclinal or anticlinal massifs formed during previous tectonic phases (Atlas tertiary phase). However, they are influenced by more recent tectonics (whose chronology is still uncertain), characterized by the reactivation of NE-SW-oriented normal faults. The sebkhas in the study area are only sporadically flooded. They are fed after rainfall by inflows of runoff or by artesian aquifers (Guiraud, 1973), which are often rich in salt due to their flow through Triassic or Miocene formations (Benkartoussa and Côte, 1974). This results in the formation of a shallow water table that can persist for several weeks or even months (see main map, landscape 3). During the dry season, these depressions provide an ideal surface for evaporation, causing the water to disappear and leaving a whitish crust of sodium chloride on the surface (main map, soil 2). Meanwhile, wind blows away recently deposited sediments through deflation process (main map, landscape 2). Their boundaries typically have irregular shapes, as their surface area varies depending on climatic conditions and the volume of water supplied by water flows from the wadis.

As with many different studies around the world on the sedimentary filling of salt lakes (Eugster and Hardie, 1975; Anadón, 1989; Marmi, 1995; Last 2002; Chairi and Abdeljaouad, 2019; Renaut and Owen, 2023), these morphotypes present a very distinct sedimentary stratification. In both the middle and bottom of the sebkhas, the dominance of fine sediment fraction (e.g., clay, silt and fine sand) in the sedimentary infill is notable (see main map). This evidence can be attributed to two main factors: (1) the flat topography and the absence of strong currents facilitate the decantation of fine particles, resulting in their gradual sedimentation; and (2) the presence of salt which promotes flocculation, thereby enhancing the deposition of clay particles. High salinity is evident from salt accumulations on the surface and at depth (as observed in the field). Moreover, the presence of fossils (e.g., *Ostracods*, *Gastropods*, *Characeae*, and *plant debris*), along with changes in clay color and laminations (e.g., *Varves*), are likely key markers of paleoclimatic and ecological variations throughout the sedimentary infill (Marmi, 1995). Our observations of the flanks of several gullies at the margin of the sebkhas have enabled us to understand the origin of their sedimentary fill and to highlight the variable environmental conditions that prevail in these areas. It is common to observe sandy or silty loam facies (Aissoug, 1970) – although the latter are always intercalated with layers of pebbles and gravels – indicating a dynamic environment of erosion and deposition. The sand, silt, and clay layers suggest deposition during relatively dry periods with limited hydrological activity, whereas the presence of gravel and pebbles indicates the influence of high-energy runoff events induced by intense rainfall (main map, Gully 5).

Litho-structural and gravitational landforms

Landscape evolution is deeply influenced by structural control on the relief (Despois, 1952, Marmi, 1995, Benabbas, 2006). In particular, asymmetry between the flanks of the relief can be explained by a variety of factors, such as: (1) tectonic processes (folding and faults); (2) variation in the geological composition of the rocks (i.e., intercalation of limestone, sandstone, and marl rocks); (3) differential erosion driven by lithological features and sudden changes in the direction of streams, which are often associated with tectonic phenomena, such as faults.

In addition, abrupt changes and discontinuity at ridge lines and kilometre-long linear scarps have been observed, e.g., fault scarps, often limited to the sebkhas and depressed areas in the plain. All this evidence is reflected in the litho-structural landforms and features, which can be mapped and assessed.

In the study area, the scree deposits are mainly located on the slopes of Fedjoudj and partly Bou Arif. Their distribution is spatially linked to weak rocks or major fractures (Banabbas, 2006). They have fed the lower slopes, and the related deposits have subsequently been reworked by fluvial and runoff processes (e.g., colluvial talus, wadis and alluvial fans).

Aeolian landforms

The aeolian bulges along the edges of the sebkhas, known as a 'lunettes' (Hills, 1940; Boulaine, 1953, 1954; Coque, 1979 and Goudie, 2013), represent the most distinctive geomorphological feature (main map). They typically

Figure 4 - Panoramic view of Sebkha Djendli. In the background, southern escarpment of Djebel Toumbait (represents a fault scarp).

Figure 5 - Aeolian landforms. (a) General view of lunette with sparse halophytic vegetation. (b) Nebkha.

rise between 5 and 25 m above the sebkhas (fig. 5a) and appear on the ground with a much lighter tint, likely due to their gypsum content (Aissoug, 1970; Bousba *et al.*, 2022a). The crescent-shaped hills to the east and north-east of Sebkha Djendli fit the definition provided by Hills (1940), except that their length is currently limited, and they do not completely encircle the sebkha due to hydraulic erosion. On the ground, the erodible surface layers of these formations have a lumpy structure and are characterized by the remarkable presence of gypsum crystals in the form of lenses (1-5 mm in diameter). These features are likely formed by the aeolian deflation of Sebkha Djendli, which receives alluvial sediment inputs from the wadis. These sediments, originated in the northern and southern parts of the study area, are supposed to be very rich in gypsum due to lithological characteristics of the slopes (i.e., mainly made up of violet Triassic marls).

On the other hand, the chaotic topography reveals small wet areas (blow out) and dry aeolian bulges (lunettes) composed of sandy loam surrounding Sebkha Ank Djemel (main map). These formations differ from the previous ones in shape and have relatively lower gypsum content (Aissoug, 1970). The 'chaotic morphology' differs from that described by Benazzouz, (1986), particularly noticeable around Sebkha Tarf, where the longitudinal lunettes alternate with wet furrows, suggesting a network of ancient sebkhas. The observed differences in the morphology of aeolian deposits can be attributed to several factors: (1) turbulent winds from the southwest, west and northwest, along with fluctuations in wind speed, result in uneven deposition of aeolian materials, depending on particle size. For instance, sand tends to settle rapidly as wind intensity decreases, whereas finer particles may remain suspended in the air for a long time before deposition; (2) Sebkhas with bright white surfaces resulting from salt crystallization may alter local wind circulation due to their high reflectivity and smooth surface, thereby influencing the redistribution of aeolian materials and producing irregular deposition patterns; and (3) lithological formations and sporadic, intermittent watercourses in the surrounding environment may induce deformations in the marginal areas of the sebkhas, further contributing to the variability in aeolian deposit distribution.

Besides the lunettes, other wind-formed features are observed near sebkhas, known as 'nebkhas' (Pouget, 1980; Gunatilaka and Mwango, 1987; Quets *et al.*, 2013; Goudie, 2013, 2022) (fig. 5b). These features result from the downwind accumulation of sand, silt and dust around clumps of halophytic species (i.e., *Salicornia*, *Artemisia*, *Salsola* and *Atriplex*). They are generally smaller in size, measuring between 0.5 and 1 meter in length and a few decimeters in height. According to Benazzouz (1986), they are mobile formations that can be used to infer the general directions of dominant winds. However, most of these morphotypes lack a clear direction, providing important information about local geomorphological processes and specific environmental conditions that shaped them, such as complex wind interactions and irregular topography.

Fluvial and runoff associated landforms

Field evidence revealed that the study area is facing with water erosion and loss of fertile soil, leading to several on-site damages for farming.

Water can infiltrate into the soil or run off along the slopes without a specific drainage network, unlike in mountainous areas where water flows along clearly defined watercourses. Thus, spatial pattern of overland flows influences different types of erosion in the study area.

- *Rill-interrill erosion*

In the study area, low-lying areas with gentle slopes or flat terrain are often affected by rill-interrill erosion (see main map, Gully 4a, b), either naturally or anthropogenic. Rills form naturally during rainfall when run-off water concentrates in incoherent, easily erodible soils (e.g., eolian deposits are the formations most affected by this type of erosion). Interrills, on the other hand, are subject to more diffuse erosion, often in the form of low leaching or sheet erosion.

Conversely, in agricultural areas, it is the frequent plowing of the land that plays the main role in modifying the structure of the soil. By fragmenting the surface horizons, it weakens the cohesion of the particles and leaves the surface bare, particularly vulnerable to the action of run-off water and especially irrigation water, which runs off the surface rather than infiltrating. In the absence of protective plant cover and as the soil is already saturated or compacted at depth, even a moderate rainfall can lead to surface erosion of the rill-interrill type. Although small in size, they represent the first visible forms of water erosion, if erosion persists, they can deepen and widen, forming gullies.

- *Gully erosion*

Gullying significantly influences the landscape evolution of the sebkhas (main map, Gully 1, 2 and 3), as affecting spatial pattern of drainage pathways. Transported sediments derived from upstream areas converge into the gullies and are deposited into the sebkhas during flood events, contributing to their sediment supply and affecting their chemical composition and water quality. The impacts of gully erosion on the local community are also significant, as it leads to the loss of fertile soils (figs 6a, 6b) and exacerbates flood risk.

Special attention has been paid to erosion of aeolian deposits (figs 6c, 6d), as they are unconsolidated and easily erodible compared to hard rocks and compacted clay formations in the plain, facilitating the formation of gullies and creating landscapes strongly affected by gullies, resembling badlands (main map, landscape 2 and gully 3). Once a ravine begins to form, it can act as a channel that further concentrates runoff, accelerating erosion processes (Kuhn *et al.*, 2023). Consequently, it can deepen and widen gradually over time.

Of particular interest is the role of 'piping' for the genesis and development of gullies (Harvey, 1982; Baillie *et al.*, 1986; Goudie, 2013), especially regarding aeolian deposits (fig. 6e). Underground erosion caused by 'piping' leads to the formation of natural cavities and internal conduits (i.e., Bryan and Jones, 1997), which may subsequently subside and collapse (Goudie, 2013) under the influence of gravity and surface runoff, they gradually transform into well-formed gullies. In fact, understanding the evolution of piping and gullies is essential for assessing the medium- and long-term impacts of these processes.

- *Other alluvial and runoff associated landforms and deltaic fans*

The colluvial talus at the base of the massifs consists mainly of glacis and extends over vast areas. They have a gentle slope near the plains, which becomes progressively steeper the closer one gets to the mountains. According to Vila (1977a, b, c, d), this geomorphological configuration likely indicates the massifs' uplift in very recent times. Torrential streams and gullies have cut through them, and various alluvial fans of different sizes have formed at their base.

Alluvial fans are a distinctive feature in study area (figs 6f, 6g). Their development is influenced by a number of factors (Gutiérrez, 2005), such as topography, wadis flow and climate. They are generally easy to examine, as they are well preserved and sparsely vegetated. Ocaña *et al.* (2017) indicated that areas arid regions are among the most suitable environments for studying these features.

This land is ideal for farming due to its natural fertility, resulting from the accumulation of nutrient-rich sediments from the surrounding mountains (*Calcisol*), and it's gently sloping to flat terrain. However, these landforms are prone to flooding during heavy rainfall, which poses a risk of crop loss and threatens farmer safety. Proper land management is necessary to ensure the safety of farmers and the sustainability of agriculture in the region. This includes the implementation of suitable agricultural practices and appropriate drainage systems, which are unfortunately absent in the study area.

Furthermore, many deltaic fans have been mapped (see main map), corresponding to the outlets of the various streams that frequently interrupt the sebkhas (fig. 6h). These marginal sedimentary fans are associated with sebkhas and play a vital role in their dynamics (Guiraud, 1973; Boujelben, 2015). They result from the accumulation of sandy-silty sediments, which is often driven by the erosion of aeolian deposits. In order to understand the origin and evolution of sebkhas, it is necessary to examine the hydrological and geomorphological processes that are particular to these ecosystems in detail.

Flood frequency mapping

Compared to humid areas, dry and semi-arid environments are more vulnerable to flash floods (Thomas, 2011). In particular, in sebkhas regions floods events are a common process (Guidoum, 2017; Hachemi *et al.*, 2020; Ben Ameur *et al.*, 2021 and reference therein).

The study area, which is characterised by the presence of sebkhas and a semi-arid climate, allows to easily classify 'flooded' areas directly observing the area covered by water or as marshy. The results of the multi-temporal analysis, as obtained through thresholding, are shown in Figures 7a, 7b and 7c. This approach has been proven to be valuable, as evidenced by field verification. The analysis of the maps presented in fig. 7d allows for the identification of areas potentially exposed to floods and provides insights into their extent and their spatial distribution from year to year for the period between 2016 and 2024 (fig. 7e). Previous studies have noted that sebkhas generally remain submerged for longer than surrounding areas due to the low infiltration rate. Nonetheless, we observe that submergence covers a large part of the plain rather than just the sebkhas. It is also important to note the moderate correlation between precipitation and the probability of flooding. Approximately 36.9% (R^2 = 0.369) of the variation in flood-prone areas is attributed to fluctuations in seasonal rainfall (fig. 7f). This is because

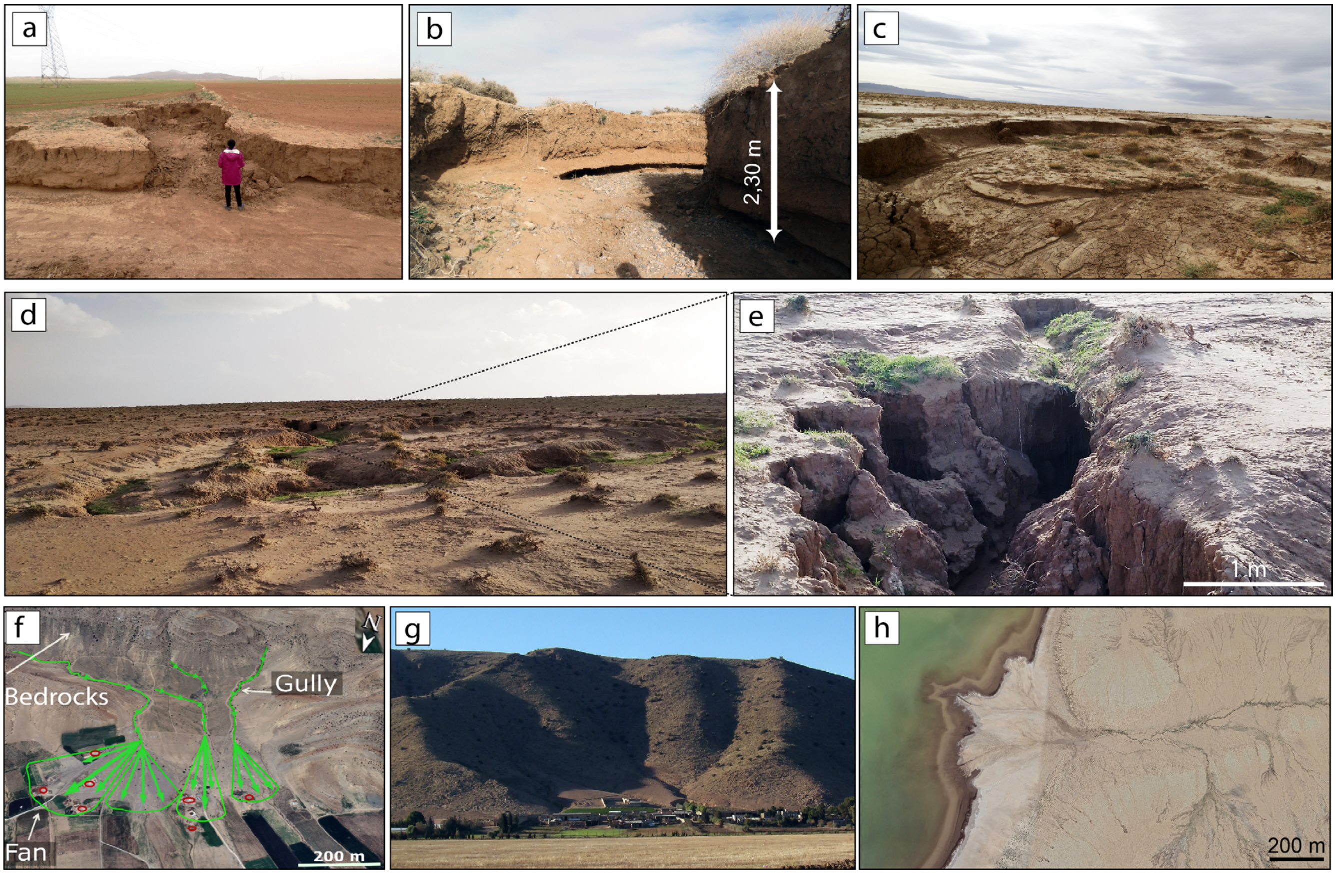

Figure 6 - (a) Gullying and loss of fertile soil. (b) Bank erosion. (c), (d) Landscape characterized by eroded lunette. (e) Piping. (f), (g) Imagery 3D (© Google Earth, 1.5 × vertical exaggerations) and field picture of north limbs of the Fedjoudj massif dissected by gullies and several alluvial fans develop at the bottom (green color), where there are agglomerations (red color). (h) A deltaic fan formed at the outlet of a temporary wadi flowing into Ank Djemel sebkha.

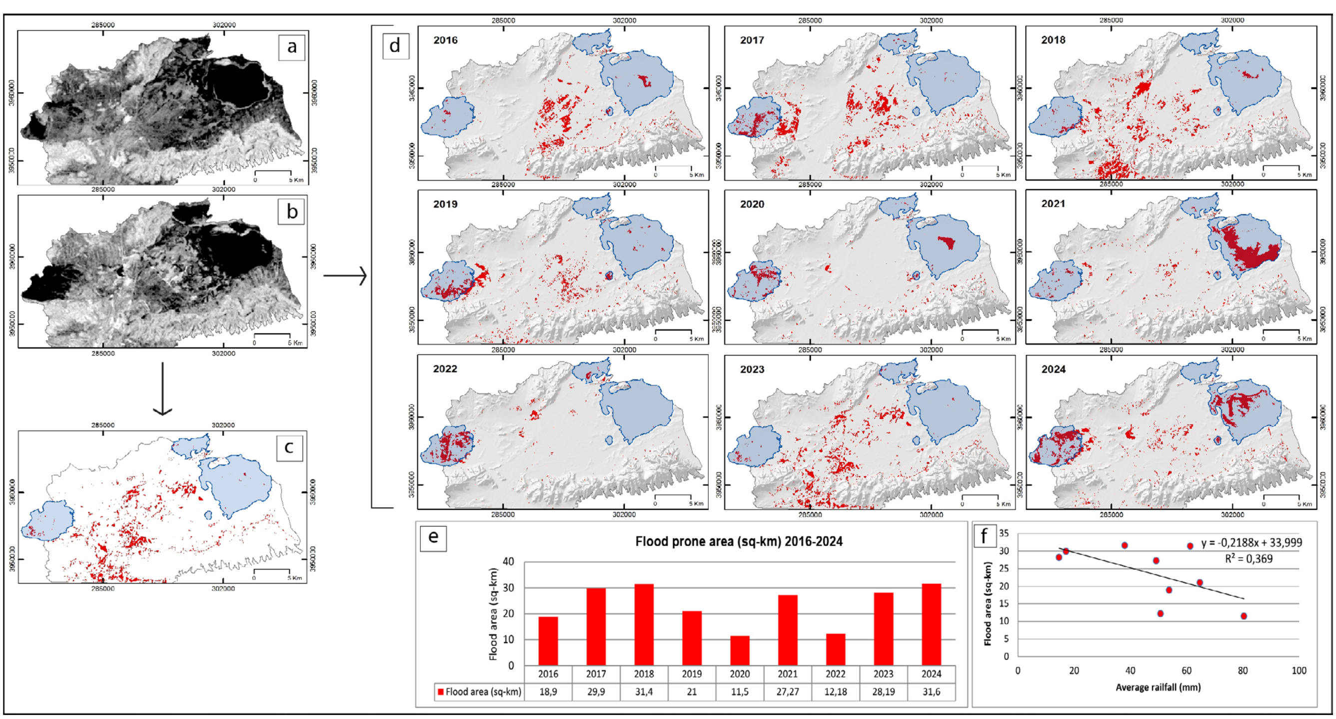

Figure 7 - The result of the thresholding approach. (a), (b) Sentinel 1's dry and wet visualization. (c) A water mask detected (red color). (d), (e) Flood prone area extraction and Graph of flooding area (km²) (2016-2024). (f) Linear regression between the average seasonal rainfall and the flooding area (2016-2024).

seasonal rainfall is influenced by various factors, such as soil type, topography and infiltration capacity. Above all, the main influencing factors in our case are the lowering of the water table, land use and irrigation. The availability of water from dams, which are located in the topographically higher catchment area in the south of the study area, enables farmers to irrigate their crops virtually all year round, encouraging agriculture. Combined with the area's gentle slope, this means that the soil is often wet, and excess water can lead to flooding. This suggests that, although rainfall is a significant factor in flooding dynamics in the study area, it is not the only factor.

The areas frequently exposed to flooding between 2016 and 2024 are highlighted in fig. 8 (i.e., the results from all the years are combined and the frequency of floods is calculated). These areas cover up to 212 km² (35%) of the total area of 600 km². This highlights the vulnerability of the Chemora, El Kouachiya and Boughrara villages to such hydrological events. Floods in the downstream expansion areas (the Sebkhas and the Boulhilet Plain) can be triggered by torrents upstream, particularly during periods of heavy rainfall. Examples include the flash floods recorded between 2016 and 2024, as well as the major flood in Wadi Chemora in 2011, according to reports in the Algerian press (*https://www.aps.dz/en/*). This illustrates the regular occurrence of these hazards. Despite floods presenting a considerable vulnerability to the surrounding area, sebkhas play a pivotal role in mitigating their impact by creating buffer zones that temporarily store excess runoff. This reduces the velocity and volume of downstream flows, thereby lowering the severity of floods in vulnerable areas.

Field observations show that the effects of flooding are evident on agricultural and pastoral lands where water accumulates with limited runoff (fig. 9a). This phenomenon has been confirmed in the field by the presence of sheet and rill erosion (fig. 9b), which contributes to sediment displacement, soil darkening indicating past land saturation and large polygonal desiccation cracks (i.e., characteristic of clayey soils subjected to wetting and drying cycles, extending over 25 cm in width and exceeding 30 cm in depth) (main map, soil 3).

The adoption of almost permanent irrigation, particularly following the completion of dam projects and the initiative to transfer water from the northernmost regions of the country to the semi-arid areas via the study area, will inevitably lead to waterlogging of soil. This is particularly true of areas with low topography, where natural drainage is slow or limited. As a result of this hydrological situation, a number of isolated marshy depressions have recently appeared in the plain (fig 9c). These are likely to be the result of localised subsidence caused by a gradual decrease in the water table, which does not exceed 50 metres (ABH, 2002; ANRH, 2005). These depressions are visual indicators of geomorphological changes. Another example is that some floods are caused by ephemeral wadis branching near Sebkha Djendli (see fig. 9d). However, the high water table (Guiraud, 1973) is also a notable cause of flooding in lower areas, such as sebkhas.

The findings validate the efficacy of the methodology in offering an initial visual representation of the flooding by demonstrating that it made it possible to track the frequency of floods and pinpoint the most susceptible regions. Since not all areas can be classified as high or low risk by

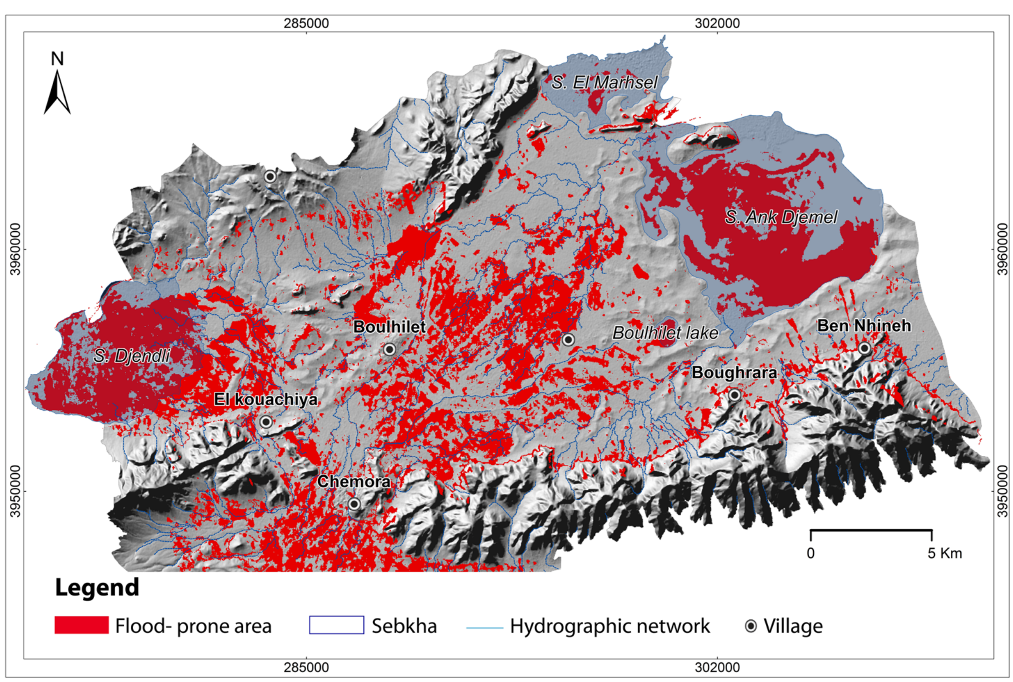

Figure 8 - The flood frequency map, derived from Sentinel-1 multi-temporal analysis, covers the period from 2016 to 2024.

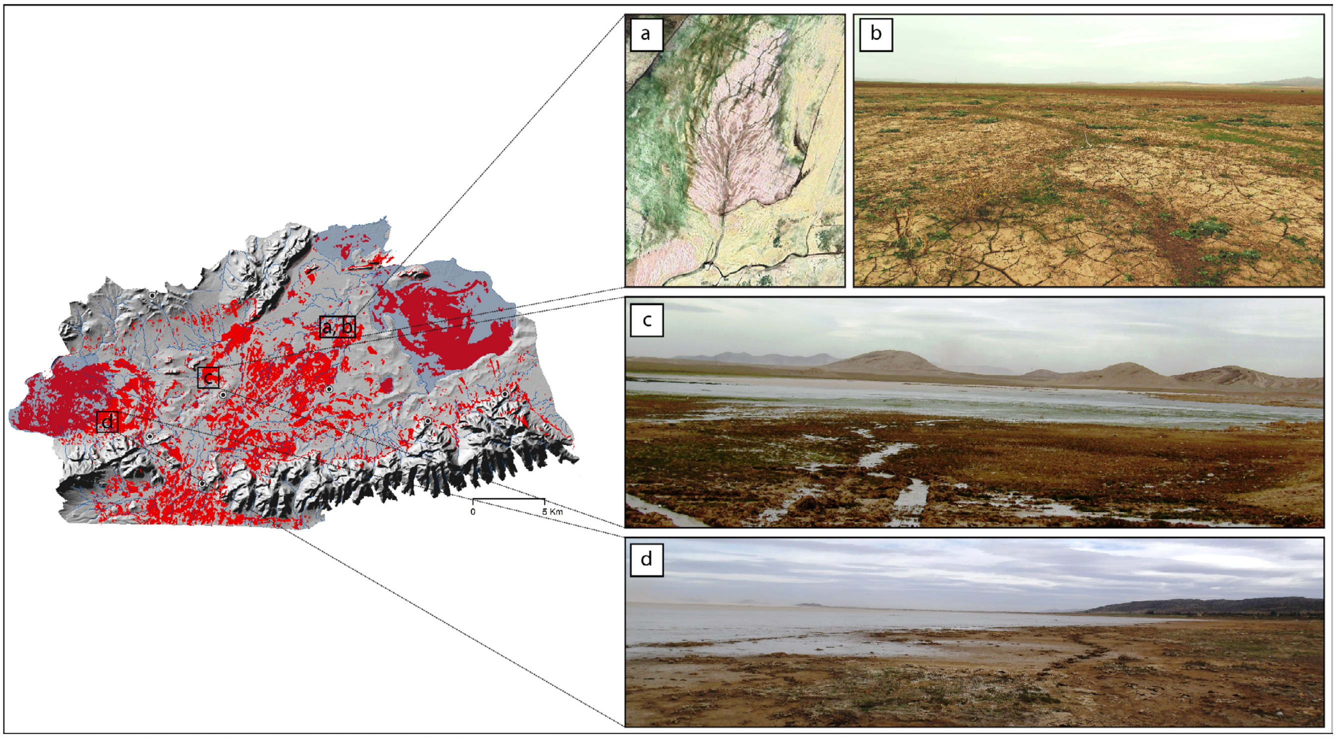

Figure 9 - Field evidence supporting the flooding model. (a) Google Earth image indicating evidence of rills and gullies during dry periods. (b) Severe rill-interrill erosion in an agricultural field. (c) Flooded area. (d) Floods spread rapidly over wide areas near Sebkha Djendli, formed by the branching of wadis.

the same standards, particularly at the level of bodies of water (i.e., sebkhas for example), where the risk of flooding is nonexistent in contrast to nearby or populated areas, this method is still insufficient to accurately estimate the level of risk. For a more thorough and accurate evaluation of flood risk, it is crucial to supplement and compare this work with a complementary method that considers morphological, hydrological, and land use factors (e.g., AHP approach).

FINAL REMARKS

This study provided a preliminary overview of the geomorphology of the Sebkhas region of the Boulhilet Plain. The results can be summarized as follows: producing the first geomorphological map of the area enabled us to explore and illustrate its different forms and features. These include sebkha, litho-structural, gravitational (e.g., scree slope), aeolian (e.g., lunettes and nebkhas) and fluvial landforms (e.g., rill and gullies), as well as those associated with water runoff (e.g., alluvial and deltaic fans). These features result from the complex interaction of various factors. Post-Tertiary tectonic movements create depressions which, due to arid climatic conditions, encourage evaporation, deflation and the precipitation of salts. This leads to the formation of sebkhas, as well as the lunettes which are found around them. The area is subject to severe soil erosion forms and features caused by running water processes that are sporadically activated throughout the year (e.g. gullying) and up to now there are no protective measures against this phenomenon. Analysis of multi-temporal flood data revealed that large parts of the study area are regularly flooded by severe and sudden flash floods, as validated by field evidence. The work presented here will serve as a basis for further studies on soil erosion and the interaction between runoff processes and salinization in one of the most suggestive areas of sebkhas region. To give the results obtained from the Boulhilet Plain, broader regional significance, similar investigations should be extended to include the entire watershed (i.e. the High Plains of Constantine), as well as other sebkha environments in Algeria with a semi-arid or arid climate.

SUPPLEMENTARY MATERIAL

Supplementary material with a geomorphological map at the scale of 1:50,000, associated to this article can be found in the on- line version at https://doi.org/10.4454/85jg6bn4

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