Diachronic study of the great Sebkha of Oran (western Algeria) based on SAR radar images (1992–2011)

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Abstract
The Sebkha of Oran, given its large size, is considered to be a remarkable feature of the west Algeria. The study of its evolution proved to be essential, following many interrogations specifically concerning its extension and its role in the ecological balance of the region. We aim to study the changes of the Sebkha over the last 20 years. To conduct the study, we used the Synthetic Aperture Radar (SAR) imagery, which offers spatial and temporal, regular, and precise tracking of surfaces. The diachronic analysis, based on amplitude images captured between 1992 and 2011, demonstrated the possibility of mapping the sebkha at different dates in order to apprehend its evolution over this period. The results obtained reveal a southwesterly extension caused by the phenomenon of saline crystallization gradually and steadily gaining ground, which corresponds to the inclination of the basin and the main wind direction of the region.

1. Introduction

The coastal sebkha of some areas are characterized by depressions with saline solutions above a salt water slick. In many arid and semi-arid basins, the most important sebkha formations are evaporative mineral deposits [1–3]. Lowestein and Hardie [4] in Thomas [3] identified a three-stage Sebkha deposition cycle, which changed the structure of hydrochloride crystals through dissolution and redeposition and the alternation of the mud and salt layers. In terms of surface hydrology, a sebkha is essentially a “closed” system, with no flow. Hydrological inputs can be direct precipitation on the surface or from underground with potential dominance of evaporation over precipitation. Both topographic position and geological setting can influence the groundwater regime and hence the formation process of the Sebkha [3]. The term “Sebkha” refers to flat-bottomed depressions flooded by floods, where the saline soil prevents the apparition of vegetation. Usually, they are lacustrine depressions where water evaporates, dissolving salt in the watershed. However, sometimes such sebkhas are or have been in contact with the sea [5], as was the case with the great Oran Sebkha in early Tortonian. The same phenomenon occurred during the Messinian period and the Plio-Quaternary period [6].

For more than 70 years, scientists have been interested in the Sebkha of Oran. Thus, several studies have been conducted, particularly geological and hydrogeological studies of Sebkha and its problems [7–9]. The great Oran Sebkha has been the subject of a bibliographic review [10] and studies of its geomorphological, hydrogeological, biological, and chemical aspects, as well as their environmental implications [11,12]. The great Oran Sebkha was also the subject of historical, hydrogeological, sedimentology and pedology studies [13–15]. In order to determine the conditions and activities of its formation, further detailed studies have been conducted on sedimentology, tectonics, hydrogeology, geomorphology, chemistry, and biology [6,16]. The suitability of its basin water for irrigation [17] and its aquifer system [18] were investigated. Mapping of the main groups of plants in the Sebkha Basin was accomplished [19]. The geochemical analysis of the water exploration environment, the interaction of water and soil in the saline-alkali environment, and the general estimation of the global impact of water quality on soil properties have been performed [20–22]. Following many inquiries, especially concerning the expansion of Sebkha and its role in the ecological balance of the region, the study of its evolution has become essential. We intend to study the Sebkha using a diachronic analysis over a great interval of time. In order to conduct this task, Synthetic Aperture Radar (SAR) satellite images were employed. SAR radar is an efficient and rapid means of studying these phenomena, given its
capacity to function under all weather conditions and its ability to exploit radar waves using several methods. SAR measurements allow for obtaining two categories of information: (1) Energy (radiometry): power emitted and received, thanks to the amplitude of the signal; (2) Time (phase): distance between the radar sensor and the target, thanks to the phase of the recorded wave parameter. Amplitude radar images have been used in several areas and for different purposes. They have shown their utility and effectiveness in the detection of soil surface moisture in arid and semi-arid zones [23] and monitoring of deforestation, ice melt and lithology in the polar environment [24,25]. They can be used to study and detect ocean meso-scale phenomena [26], pattern recognition, spatial planning [27], crop classification [28,29], Barkhan field mobility analysis [30], geological map [31], structural map [32], the detection and characterization of marine oil slicks [33], mapping urban damage caused by natural or industrial disasters and coastal boundary changes [34], the flood extension map [35], coastal features and urban expansion [36,37]. The diachronic images (coloured composition) of radar amplitude constitute an effective means of following natural phenomena over time. In the case of hydrological phenomena, they allow for evaluating the impact of and identifying the optimal means of flood monitoring in rural territories and urban areas [38]. They have shown great utility in the detection and analysis of lake and vegetation changes [39] and improved interpretation of landscape changes in the highly complex Carpathian region [40]. The use of SAR radar imagery allows for spatial, temporal, regular, and precise tracking of surfaces, given the sensitivity of the radar signal to ground types and properties. The response of the radar signal is particularly sensitive to the topography, the ruggedness, and the humidity of the surface, which allows for determining changes which may have occurred between different data acquisitions.

In order to achieve our goal, we produced multi-date amplitude images (from 1992 to 2011) with a resolution of 12.5 m, which we calibrated, filtered, georeferenced, and orthorectified. We also generated diachronic images based on the images thus obtained, showing the radiometric changes in the Sebkha and its surrounding areas at different intervals. We drew a map of the great Oran Sebkha, extracted its morphometric parameters, and analysed and interpreted the results obtained over this 19-year period.

2. Materials and methods

2.1. Study area

The great Oran Sebkha is a salt lake located in the northwest of Algeria, 10 km southwest of Oran city, and 12 km away from the Mediterranean Sea, as shown in Figure 1.

Figure 1. Study area. Map generated from a Landsat-8 image, dated 10/05/2019.
It is located in a depression with an average altitude of 80 m, between the Murdjadjo Massif, with a maximum altitude of 589 m in the north, and the massif of Tessala, with a maximum altitude of 1061 m in the south [6]. The topography of great Oran Sebkha is flat and slopes 2 m westward (the low point is 80 m, the high point is 82 m). The two massifs which surround it represent the principal hydrographic source of the Sebkha. Morphologically, the Sebkha is elliptical, southwest/northeast oriented, and is 40 km long and 9.5 km wide (varying from 6 to 13 km). Its geomorphology, geology, hydrology, and climate background can be traced back to the lower Miocene, as shown in Figure 2. The Mediterranean climate is semi-arid and hot, characterized by rainfall between 378 and 473 mm/year [41], and average wind speeds of over 15.7 km/h, mainly in the southwest direction [42]. Sebkha salt water forms a 10–30 cm thin film that changes according to rainfall and is completely dry due to large amounts of evaporation throughout the summer [41]. Irrigation water is characterized by electrical conductivity which varies with seasons and climatic conditions [17]. The geographic coordinates of its centre are 35°32′0.24″ north latitude and 0°47′54.62″ longitude.

The great Oran Sebkha is characterized by its extremely shallow depth, ranging from about ten centimetres at its edge to approximately thirty centimetres at its centre [6]. It is fed by a hydrographic network which mainly flows from the Tessala and Murdjadjo massifs [41]. Its aspect varies according to pluviometry, drying out totally during hot periods, given significant evaporation, and filling, to the point of overflowing, following abundant precipitation and high winds during wet seasons. In this context, small amounts of water and average wind speeds can change the appearance in a short time (even over 24 h).

Regarding its sedimentary cover, the great Oran Sebkha is composed, from top to bottom, of a 1–2 m grey silt layer, genuine Sebkha sediment, followed by approximately 60 m of red conglomerate clays from the Soltanian to the Pliocene age [6]. The remainder is composed of ancient sediments, blue marls and diatomites (Tortonian and Messinian), dating to before the birth of the Sebkha. The total thickness appears to be over 500 m, and it rests on a substratum dating to the Cretaceous [6].

The great Oran Sebkha, by its central geographic position in the Oran region, occupies the western edge of the Bas Chélif watershed. The oldest lands are represented by the Mio-Plio-quaternary deposits which filled the old Sebkha Basin, as shown in Figure 3. At its edges are successive deposits of old alluvium formed by a narrow 1–2 m deep terrace. The central part of Sebkha is occupied by recent alluvium [43].

2.2. Methods

The methodology chosen for this study proceeds through the following steps: (1) Realization of amplitude SAR radar images on several dates during the rainy seasons; (2) Treatment of images so generated, calibration, filtering, georeferencing, orthorectification; (3)
Figure 3. The great Sebkha of Oran at several periods; (a) impact of the Sebkha on agricultural land (soil salinity, reduction in area and productivity); (b) variable bathymetry, change in humidity and type of sediment; (c) an environment to develop and preserve; (d) salt lake. Source photos: Internet [44].

Table 1. Radar Data.

| N° | Date         | Time    | Satellite | Orbit | Track | Frame | Centre (Lon°/Lat°) |
|----|--------------|---------|-----------|-------|-------|-------|-------------------|
| 1  | 11/12/1992   | 10:45:13| ERS-1     | 07353 | 194   | 2889  | −0.82/35.61       |
| 2  | 25/12/1995   | 10:45:30| ERS-2     | 03555 | 194   | 2889  | −0.82/35.61       |
| 3  | 28/11/1999   | 10:45:04| ERS-1     | 43769 | 194   | 2889  | −0.82/35.61       |
| 4  | 03/12/2001   | 10:43:20| ERS-2     | 34617 | 194   | 2889  | −0.79/35.61       |
| 5  | 08/12/2003   | 10:43:46| ERS-2     | 45138 | 194   | 2889  | −0.81/35.61       |
| 6  | 01/12/2008   | 10:45:16| ERS-2     | 71190 | 194   | 2889  | −0.80/35.61       |
| 7  | 05/01/2009   | 10:45:32| ERS-2     | 71691 | 194   | 2889  | −0.80/35.61       |
| 8  | 06/12/2010   | 10:46:39| ERS-2     | 81711 | 194   | 2889  | −0.81/35.61       |
| 9  | 10/01/2011   | 10:46:41| ERS-2     | 82212 | 194   | 2889  | −0.81/35.61       |

Digitization and mapping of the Sebkha at these different dates; (4) Facilitation of comparison of images by the production of coloured compositions representing different intervals; (5) Extraction of morphometric parameters of this Sebkha between 1992 and 2011; (6) Detection and analysis of changes observed during these 19 years.

2.3. SAR radar data

The acquisition of SAR images was provided by ESA (European Space Agency) as part of a project on the detection and monitoring of risk areas in the Oran region of Algeria. We employed 9 PRI images (Precision Image) of the ERS-1/2 satellites, as indicated in Table 1. These images cover an area of 100 km (range) × 102.5 km (azimuth) with descending acquisition. The scene is illuminated to the right in a side view with an angle of incidence of 23°, in the band “C” of wavelength 5.65 cm and vertical polarization (VV). These 9 images were chosen based on their acquisition dates, corresponding to the seasons of precipitation in the region. Generally, in November, December, and January, the bed of Sebkha is filled with water, which facilitates delimitation. To better interpret the results obtained, we needed information on the daily meteorological conditions of each acquisition date, as shown in Table 2.

Table 2. Meteorological conditions of each data acquisition.

| N° | Date         | Time    | Temperature (°C) | Wind (Km/h) | Precipitation over 24 h (mm) |
|----|--------------|---------|------------------|-------------|-----------------------------|
| 1  | 11/12/1992   | 10:45:13| 10               | 2           | 0                           |
| 2  | 25/12/1995   | 10:45:30| 15               | 20          | 0                           |
| 3  | 28/11/1999   | 10:45:04| 9.7              | /           | 15                          |
| 4  | 03/12/2001   | 10:43:29| 8.3              | /           | 0                           |
| 5  | 08/12/2003   | 10:43:46| 16               | /           | 7                           |
| 6  | 01/12/2008   | 10:45:16| 10               | 17          | 18                          |
| 7  | 05/01/2009   | 10:45:32| 12               | 6           | 11.9                        |
| 8  | 06/12/2010   | 10:46:39| 15               | 9           | 0                           |
| 9  | 10/01/2011   | 10:46:41| 11               | 7           | 4                           |

2.4. Treatments

We were able to extract and produce 9 amplitude images with a 12.5 m resolution for the great Oran Sebkha, Algeria. We calibrated, georeferenced, orthorectified, and filtered the ERS-1/2 satellites images from 1992 to 2011, as shown in Figure 4:
Radiometric calibration concerns treating the generated image (amplitude) in terms of its physical representation (ground); i.e. conversion of pixel values (intensity) into calibrated radiometric backscatter (physical values): Sigma Nought ($\sigma_0$);

- Georeferencing facilitates the production of images according to a single cartographic projection system (UTM zone 30-N, WGS84);
- Orthorectification concerns correcting amplitude images in terms of terrain modelling (DTM);
- Filtering concerns eliminating Speckle effect in order to increase image readability;

Subsequently, we digitized the Sebkha and extracted its morphometric parameters. These two stages were assured by ArcGis. The digitalization was semi-automatic and controlled by hand, pixel by pixel.

2.4.1. Amplitude image

SAR sensors, active sensors embedded on orbiting satellites measure the two components of the backscattered signal, amplitude, and phase. The amplitude of a signal depends upon the physical and dielectric characteristics of the picture element. Phase depends on its geometrical characteristics, contains information on the distance between the radar and the target, and allows for measuring vertical displacements of the ground at the level of 1/2 wavelengths. Compared with platforms that only record visible information, radar images can be generated in any weather, day or night, and regardless of cloud cover. The amplitude represents the reflectivity of the pixel. It can be used directly and is comparable to optical images. It is also directly related to the surface state. As shown in Figure 5, rough and wet surfaces produce strong radiometry, while smooth and dry surfaces produce low radiometry. The image below has been calibrated, georeferenced, orthorectified and filtered, with a resolution of 12.5 m.

2.4.2. Realization of coloured compositions at different dates

The radar amplitude image provides instant information about the imaging area. Since radar is an all-weather tool, colour synthesis can give information about changes in the landscape between different dates. Through the difference of pixel radiometry between these acquisitions, the diachronic images (colour composition) of different periods allows for visualizing changes occurring in the region.

We generated colour combinations of several pairs of the study area corresponding to different satellite intervals (ERS). These are calibrated, georeferenced, and orthorectified, with a resolution of 12.5 m. We generate colour combinations in pairs by assigning green–blue to the oldest image and red to the newest image, as shown in Figure 6. The colour of each pixel of the resulting image is determined by the following formula:

$$c(p) = a(p)[GB] + b(p)[R].$$

In these images, $a(p)$ and $b(p)$ represent values based on respective pixel signal strength for the oldest and

Figure 4. Different stages of treatments; (a) Original image; (b) Amplitude image of the study area; (c) Calibration (Sigma0); (d) Georeferencing; (e) Orthorectification; (f) Filtering; (g) Digitalization and extraction (curve and surface); (h) Visual analysis and verification. Case of the SAR radar amplitude image dated 10/01/2011.
Figure 5. SAR radar amplitude images, calibrated, georeferenced, orthorectified and filtered with 12.5 m resolution.

Table 3. Key for interpreting coloured composition images.

| Extreme cases of resulting colors of the colored composition | a | b | 0 | 0 < b < 1 | 1 |
|------------------------------------------------------------|---|---|---|-----------|---|
| a < 0                                                      | Black          | 0 | 0 | 0 < b < 1 | 1 |
| 0 < a < 1                                                  | Intermediate colors between light blue and red | 0 | 0 | 0 < b < 1 | 1 |
| 1                                                          | Light blue     | 0 | 0 | 0 < b < 1 | 1 |
|                                                           | Yellow/White   | 0 | 0 | 0 < b < 1 | 1 |

Interpretation keys for diachronic images:
- **Red**: Weak signal on 1st date and strong on 2nd date
- **Light blue**: Strong signal on 1st date and weak on 2nd date
- **Yellow/white**: Strong signal on both dates (no change)
- **Black**: Weak signal on both dates (no change)

most recent components. Thus, for a pixel appearing in black on image 1 (intensity of the signal equal to 0) and in white on image 2 (intensity of the signal equal to 1), we have: \( a(p) = 0 \) and \( b(p) = 1 \) where \( c(p) = [R] \), the pixel appears “red”.

The key to interpreting these images is presented in Table 3.

The diachronic image allows us to compare one location at different dates. To track the changes in the Sebkha between 1992 and 2011 based on the amplitude image, we made several pairs of coloured compositions corresponding to different intervals. We show here two of the coloured compositions. The first one generated from three amplitude images, (Green) attributed to the date December 11, 1992, (Blue) attributed to December 12, 1995, (Red) attributed to January 10, 2011, as shown in Figure 7(a). The second one generated from two images, (Green + Blue) attributed to the image of December 11, 1992, (Red) attributed to the image of January 10, 2011, as shown in Figure 7(b). These images were also calibrated, georeferenced, orthorectified, and filtered, with a resolution of 12.5 m.

The coloured compositions corresponding to the various dates, as shown in Figures 6 and 7, are intended to enable identification of the origins of the changes of the Great Sebkha of Oran. As can be seen in two-coloured compositions, as shown in Figure 7, the centre of the Sebkha, represented in different colours corresponding to the different intervals, as shown in Figure 7 (a) and (b) displays the same hydrodynamic shape. The observed colours correspond to different levels of surface ruggedness on different dates, indicating that the area concerned underwent changes more significant than the rest. Despite these different surface changes, the observed hydrodynamic shape remains unchanged, which may indicate similar origins. This phenomenon can be explained by topography because the area concerned is the deepest part of Oran Sebkha is most affected by meteorological conditions.

3. Results

Given their sensitivity to surface roughness, radar images accurately delineate the Sebkha of Oran. The
surface of great Oran Sebkha is smooth, and the level of radiometric produced is very weak, so it appears dark. In contrast, the banks of Sebkha are rough and wet, producing strong radiometric levels and therefore appear bright. The diachronic study of amplitude images has demonstrated the possibility of determining, locating and delimiting the Sebkha Oran with great precision. It allows us to draw a map of Sebkha on different dates also permits us to extract the morphometric parameters, perimeters and areas, and geographic and UTM coordinates of the Sebkha centre in different periods. It further allows for calculating the different parameters ($\Delta P$, $\Delta S$, $\Delta X$, $\Delta Y$) between acquisitions and for understanding the evolution of the Sebkha between 1992 and 2011.

3.1. Mapping the Sebkha from 1992 to 2011

The amplitude images we generated allowed us to digitize and map the great Sebkha of Oran at different
points in time (1992/2011). First, we realized a UTM projection map showing the outline of the Sebkha for each of the acquisition dates, as shown in Figure 8. Then, we realized another map showing the outline of the Sebkha uniquely for the two dates, 1992 and 2011, as shown in Figure 9. Finally, to calculate displacement, we generated a map which illustrates the centre of Sebkha at separate acquisition dates, as shown in Figure 10.

3.2. Parameters of the great Oran Sebkha from 1992 to 2011

The data treatments we realized allowed us to extract the parameters of the Sebkha in terms of its geographical and UTM coordinates of the centre (X, Y), the perimeter (P) and the area (S) corresponding to different acquisition dates, as shown in Table 4.

3.3. Comparison of Sebkha parameters between different dates

To understand the origin of the variations of Sebkha parameters over time, we compared each previously extracted parameter between two consecutive dates and calculated the average, as mentioned in Table 5. Following the same logic, we also compared the most recently collected parameter (2011) with the parameters of other dates and their average values, as shown in Table 6. The average values M1 and M2 reflect different sources, such as treatment errors and weather conditions, etc. We must consider these discrepancies as simple inaccuracies which should be eliminated and retain only morphological changes.

3.4. Comparison of Sebkha parameters between different dates

The analysis of the evolution of the Sebkha was established based on two procedures: (1) realization of graphs showing the evolution of the perimeter and the area of the Sebkha according to acquisition dates, as shown in Figure 11; (2) calculation using the following formulas (1), (2) and (3), whose results are presented in Table 7.

\[ M_1 = \frac{\sum_{i=1}^{n-1} (Pr_f - Pr_i)}{n-1} \]  
\[ M_2 = \frac{\sum_{i=1}^{n-1} (Pr_{2011} - Pr_i)}{n-1} \]  
\[ \Delta Pr_{2011-1992} = (Pr_{2011} - Pr_{1992}) \pm \frac{\sum_{i=1}^{n-1} (Pr_f - Pr_i)}{n-1} \]  

where \( \Delta Pr \) is variation of parameters; \( Pr \) is parameters of Sebkha (X, Y, P and S); \( M_1 \) and \( M_2 \) represent averages; \( n \) is number of images used; \( f \) is final date; \( i \) is the initial date.

This work allowed us to estimate the speed at which Sebkha parameters have evolved over a twenty-year period (1992–2011), \( V_p = 0.359 \text{ km/year} \) (i.e. 1 m/day); \( V_s = 0.796 \text{ km}^2/\text{year} \) (i.e. 2 m²/day). We also estimated the displacement of the centre of the Sebkha in a south-westerly direction with an average velocity of approximately \( V (X, Y) = 20 \text{ m/year} \), being 0.055 m/day and have presented detailed results in Table 8.

4. Discussion

The amplitude images and coloured compositions corresponding to two or three dates indicate changes which occurred at the centre of the Sebkha documented by strong radiometry recorded in 1992, 1995, 1999, 2008, and 2011, as shown in Figure 5. The coloured compositions confirm a difference in ruggedness (light blue/red) concentrated in the centre of the great Oran Sebkha, as shown in Figure 6. This central sector corresponds to a surface of significant roughness, surrounded by smoother layers which give rise to hydrodynamic shapes, as shown in Figure...
Figure 8. Map of the outline of the Sebkha at acquisition dates ranging from 1992 to 2011.

Figure 9. Sebkha map of covering 1992 and 2011.
7. These aspects can be explained by the topography of the Sebkha. The area corresponds to the lowest part of the Sebkha, where precipitation is highest, as shown in Figure 12. This area is the last to turn dry in hot seasons and consequently displays the highest soil chlorine levels [9]. The remainder of the surface of Sebkha undergoes a phenomenon of saline crystallization as a result of evaporation. The great Sebkha of Oran registers an average water depth of 450 mm/year. The evaporation rate, at 575 mm/year [6], is significantly higher. The Sebkha soil is composed of sometimes clayey and sometimes limestone marl, containing 20% water, 3–10% gypsum, 12–15% halite (NaCl) and a negligible percentage of sand [7]. During the desiccation period, the soil is hardened by cement, which is composed of a multitude of salt microcrystals, forming a dry and smooth

### Table 4. Parameters of the great Oran Sebkha between 1992 and 2011.

| Date       | Lon (°) | Lat (°) | X (m)     | Y (m)     | Perimeter (km) | Area (km²) |
|------------|---------|---------|-----------|-----------|----------------|------------|
| 11/12/1992 | −0.79   | 35.54   | 700562.66 | 3935106.11| 134.84         | 276.30     |
| 25/12/1995 | −0.79   | 35.54   | 700159.27 | 3934936.72| 156.04         | 292.20     |
| 28/11/1999 | −0.79   | 35.54   | 700061.72 | 3934859.46| 154.99         | 298.54     |
| 03/12/2001 | −0.79   | 35.54   | 700088.84 | 3934906.74| 153.08         | 297.17     |
| 08/12/2003 | −0.79   | 35.54   | 700136.42 | 3934935.26| 148.39         | 292.27     |
| 01/12/2008 | −0.80   | 35.54   | 699721.94 | 3934789.60| 167.32         | 302.82     |
| 05/01/2009 | −0.79   | 35.54   | 699977.83 | 3934855.61| 151.42         | 295.23     |
| 06/12/2010 | −0.79   | 35.54   | 700120.80 | 3934934.31| 148.79         | 291.29     |
| 10/01/2011 | −0.79   | 35.54   | 700146.10 | 3934901.25| 147.39         | 296.45     |

### Table 5. Comparison of Sebkha parameters between different dates.

| Difference of dates | Differences (days) | Differences (years) | ΔX (m) | ΔY (m) | ΔP (km) | ΔS (km²) |
|---------------------|--------------------|---------------------|--------|--------|---------|----------|
| 1995–1992           | 1100               | 3.04                | −403.39| −169.39| 21.20   | 15.90    |
| 1999–1995           | 1434               | 3.93                | −97.55 | −77.26 | −1.05   | 6.34     |
| 2001–1999           | 736                | 2.02                | 27.12  | 47.27  | −1.92   | −1.37    |
| 2003–2001           | 735                | 2.01                | 47.58  | 28.52  | −4.69   | −4.91    |
| 2008–2003           | 1820               | 4.99                | −414.48| −145.66| 18.94   | 10.56    |
| 2009–2008           | 35                 | 0.10                | 25.89  | 66.01  | −5.90   | −7.59    |
| 2010–2009           | 700                | 1.92                | 142.97 | 78.70  | −2.63   | −3.94    |
| 2011–2010           | 35                 | 0.10                | 25.30  | −33.06 | −1.41   | 5.16     |
| M1                  | 825.50             | 2.26                | −52.07 | −25.61 | 1.57    | 2.52     |
surface. Considering that lower humidity will cause low
signal of retrodiffusion, these arid floors will appear
dark. The smooth surface appears black or very dark and
can reflect roughness changes of less than 7.689 mm
(the roughness threshold of the ERS satellite). The rela-
tionship between the wavelength used and the surface
roughness is the determining factor [39].

The maps and morphometric parameters obtained
between 1992 and 2011 indicate the extension and
displacement of Sebkha in the southwesterly direc-
tion. The biggest change was in 2008, with a perimeter
of 167.32 km and an area of 302.83 km², followed
by the changes recorded in 1999 with 154.99 and
298.54 km². The lowest observations were in 1992,
which were 134.84 and 276.30 km², as shown in Table 4.

These results correspond to the recorded daily precip-
itation of 18, 15, and 0 mm, respectively, as shown in
Table 2. Although this may suggest that the extended
range depends on the total amount of precipitation,
this assumption has not been verified because of the
value of 295.23 km² (2009), the rainfall is 11.9 mm/day,
which is lower than in 2001 (297.17 km²) and 2011
(296.45 km²) with quantities of 0 and 4 mm/day, respec-
tively, as shown in Figure 11. Regarding the dis-
placement map, similar observations can be made for
wind speed, as shown in Table 2. In order of loca-
tion, as shown in Figure 10, we find: 2008 (17 km/h),
2009 (6 km/h), 1999 (? Km/h), 2001 (? Km/h), 2010
(9 km/h), 2003 (? km/h), 2011 (7 km/h), 1995 (20 km/h)
and 1992 (2 km/h). Therefore, the assumption that the

Table 6. Comparison of Sebkha parameters between the last date and the other dates.

| Difference of dates | Differences (days) | Differences (years) | ΔX (m) | ΔY (m) | ΔP (km) | ΔS (km²) |
|---------------------|-------------------|-------------------|--------|--------|--------|--------|
| 2011–1992           | 6604              | 18.09             | -416.56| -204.86| 12.55  | 20.15  |
| 2011–1995           | 5495              | 15.05             | -13.17 | -35.47 | -8.65  | 4.25   |
| 2001–1999           | 4061              | 11.13             | 84.38  | 41.79  | -7.6   | -2.09  |
| 2011–2001           | 3325              | 9.11              | 57.26  | -5.49  | -5.69  | -0.72  |
| 2011–2003           | 2590              | 7.10              | 9.68   | -34.01 | -1     | 4.18   |
| 2011–2008           | 770               | 2.11              | 424.16 | 111.65 | -19.93 | -6.37  |
| 2011–2009           | 735               | 2.01              | 168.27 | 45.64  | -4.03  | 1.22   |
| 2011–2010           | 35                | 0.10              | 25.3   | -33.06 | -1     | 5.16   |
| M1                  |                   |                   |        |        |        |        |
| M2                  |                   |                   |        |        |        |        |
| 2011–2010 with correction | -322.08       | -165.02           | -416.56| -204.86| 12.55  | 20.15  |

Figure 11. Evolution of the perimeter and the surface of the Sebkha on the basis of different dates; (a) Perimeter of the Sebkha (—); (b) Surface of the Sebkha (—).

Table 7. The evolution of Sebkha between 1992 and 2011.

| Difference of dates | Differences (days) | Differences (years) | ΔX (m) | ΔY (m) | ΔP (km) | ΔS (km²) |
|---------------------|-------------------|-------------------|--------|--------|--------|--------|
| 2011–1992           | 6604              | 18.09             | -416.56| -204.86| 12.55  | 20.15  |
| M1                  | 825.50            | 2.26              | -52.07 | -25.61 | 1.57   | 2.52   |
| M2                  | 2951.88           | 8.09              | 42.42  | -14.23 | -4.47  | 3.22   |
| 2011–1992 with correction | -322.08       | -165.02           | -416.56| -204.86| 12.55  | 20.15  |

Table 8. Average speed of Sebkha parameter evolution between 1992 and 2011.

| Period               | Centre coordinates (X; Y) | Perimeter (P) | Area (S) |
|---------------------|---------------------------|---------------|----------|
|                      | VX                         | VY            | VP       |
| Average speed        | m/year                     | m/day         | km/y     |
| m/year               | m/day                      | m/day         | km²/day  |
| 1992–2011            | -17.80                     | -0.048        | 0.359    |
| 1999–2001            | -13.17                     | -0.025        | 0.359    |
| 2001–2010            | -10.26                     | -0.025        | 0.359    |
| 2003–2011            | -7.6                       | -0.025        | 0.359    |
displacement of the centre of the Sebkha is related to the wind speed must be eliminated. To verify the results obtained and in the interest of eliminating information due to processing errors or weather conditions (precipitation, wind, etc.), we applied formula (3), retaining only morphological changes, as shown in Tables 7 and 8.

This analysis shows that weather conditions played a central role in the evolution of the great Oran Sebkha. It can also support the hypothesis of extension and displacement in the southwest direction corresponding to the basin topography and the main wind direction in the area. The extension of the Sebkha is caused by the phenomenon of salt crystallization, which develops gradually but steadily. This phenomenon is considered to be a marker that distinguishes the Sebkha from the rest of the basin.

5. Conclusion

This work demonstrates the interest of SAR radar imagery in monitoring saline depressions prone to flooding, such as sebkhas and the risk of soil salinization. The diachronic analysis conducted using SAR radar amplitude images, allowed us to detect, track, and analyse the extension of the Sebkha of Oran with remarkable precision over almost 19 years (1992–2011). These changes are due mainly to meteorological conditions. Our study demonstrated an extension and a displacement of the centre of Sebkha in a southwesterly direction. This extension is caused by the phenomenon of saline crystallization, which is gradually but steadily gaining ground, corresponding to the inclination of the basin and the predominant wind direction of the region.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

[1] Briere PR. Playa, playa lake, Sabkha: proposed definitions for old terms. Arid Environ. 2000;45:1–7.
[2] Glennie KW. Desert sedimentary environments, past and present – a summary. Sediment Geol. 1987;50:135–166.
[3] Thomas DSG. Arid zone geomorphology: process, form and change in drylands. 3rd ed. London; Oxford: Wiley-Blackwell; 2011; p. 624.
[4] Lowestein TK, Hardie LA. Criteria for the recognition of salt-pan evaporites. Sediment Geol. 1985;32:627–644.
[5] Perthuisot JP. Les vicissitudes conceptuelles sur la genèse d’un bassin salin: la Sebkha El Melah (Tunisie). COFRHIGEO. 1981. Available from: http://www.annales.org/archives/cofrhigeo/Sebkha-el-melah.html.

[6] Moussa K. Etude d’une sebkha: La sebkha d’Oran (Ouest algérien) [Thèse de Doctorat en Sciences de la Terre]. Oran: Univer. Oran; 2006; p. 1–205.

[7] Soletanche. Grande Sebkha d’Oran: Géologie et Hydrologie. Rapport inédit du Service de la Colonisation et de l’Hydraulique. Alger; 1950. p. 1–84.

[8] Perrodon A. Etude géologique les bassins néogènes sub-littoraux de l’Algérie occidentale. Publications du Service de la carte géologique de l’Algérie. Nouvelle série; Bulletin n°. Alger; 1957;12:1–345.

[9] Hassani M. Hydrogéologie d’un bassin endoréique semi-aride, le bassin versant de la grande Sebkha d’Oran (Algérie). [Thèse]. Grenoble: Université de Grenoble; 1987. p. 1–304.

[10] Kebir LW. Rapport bibliographique sur la grande sebkha d’Oran. Rapport Centre National des Techniques Spatiales. 1993: 1–19.

[11] Moussa K. Quelques aspects géomorphologiques, hydrogéologiques, biologiques et chimiques de la sebkha d’Oran; implications environnementales. Dans: Séminaire national sur l’Agronomie et l’Hydraulique en zones arides et semi-arides; 8-9-10 Novembre1999; Ouargla.

[12] Moussa K. Quelques aspects géomorphologiques, géorhumorphologiques, hydrogéologiques, biologiques et chimiques de la sebkha d’Oran (Algérie) implications environnementales. 5th international conference on the Geology of the Arab World (GAW-5); 2000 February; Cairo.

[13] Moussa K. Histoire d’un bassin sédimentaire endoréique: la sebkha d’Oran. 4ème Séminaire de Géologie pétrolière, C.R.D; 13-15 November 2000; Boumerdès.

[14] Moussa K. La recherche des ressources hydriques: Méthodologie systématique intégrant les méthodes des sciences de la terre et de la vie, cas de l’étude de la sebkha d’Oran. 11ème Séminaire National de Science et de la Terre; 28–30 octobre 2001; Tlemcen.

[15] Mekki A. Etude géologique de la grande Sebkha d’Oran; cas du secteur d’EL Amria-Bou Télés [Stratigraphie, Sédimentologie, Pédologie] [Mémoire Ingénieur d’Etat]. Université Oran. 2002: 1–123.

[16] Moussa K. Carte géomorphologique de la grande sebkha d’Oran; description et interprétation dynamique. Bulletin de l’ORGEM; 1er janvier 2006. p. 47–62.

[17] Benziane A, Boualla N, Derriche Z. Aptitude des eaux du bassin de la Grande Sebkha d’Oran à l’irrigation. J Appl Biosci. 2012;56:4066–4074.

[18] Benziane A. Le système aquifère de la Grande Sebkha d’Oran: considérations géologiques et hydrogéologiques. Bullet Inst Sci. 2013;35:77–92.

[19] Moussa K, Boughalem M, Lachgueur M, et al. Contribution to the study of the vegetation of the Oran’s Great Sebkha basin (west Algeria); characterization and Cartography. Agric Sci. 2014;4:273–279.

[20] Boualla N, Benziane A, Ait-Mokhtar K. Geochemistry exploration environment analysis of waters: the case of the basin of the Great Sebkha of Oran. Water Supply. 2017;17(6):1801–1812.

[21] Boualla N. Interaction eau – sol en milieu salin (Cas du Bassin de la Grande Sebkha d’Oran). [Thèse de Doctorat]. Oran: Univ Sciences et Technologie; 2018. p. 1–159.

[22] Boualla N, Adjdir M, Benziane A, et al. Estimating generalized of global impacts to water quality on soil characteristics in basin of the Great Sebkha of Oran. Appl Water Sci. 2019;9(4):1–10.

[23] Troufleau D, Audoin A, Vidal A, et al. Importance des corrections radiométriques dues au relief pour les données SAR du satellite ERS-1: Applications à l’hydrologie. Xème Journées Hydrologiques. 1994;Orstom:635–650.

[24] Budkewitsch P, D’orio MA, Harisson JC. SAR Expressions of geology in the Canadian Arctic. Proceedings for the 26th international symposium on Remote Sensing of Environment / 18th Symposium of the Canadian Remote Sensing Society; 1996 mars 25–29, Vancouver. p. 88–91.

[25] Budkewitsch P, D’orio MA, Harisson JC. C-band radar signatures of lithology in arctic environments: preliminary results from Bathurst Island, Northwest Territories. in Current Research 1996-B; Geological Survey of Canada; 1999. p. 67–72.

[26] Laborde P, Deveaux M. Etude des apports et limites du Radar a Ouverture Synthétique dans l’observation de l’océan a la Mesoéchelle à partir des images SAR ERS-1 recueillies lors de la compagne Sémaphore. Rapport d’étude, série Hydrographie, Service Hydrographique et Océanographique de la Marine (SHOM), Centre Militaire d’Océanographie, Bureau de recherche et d’étude SHOM-Météo. Rapport d’étude n° 001/96; Février 1996. p. 1–40.

[27] Rudant JP, Baltzer F, Lointier M, et al. Apport des images radar satellites ERS-1 et JERS-1 dans le domaine de la cartographie générique et thématique en contexte tropical humide. Soc Franc Photogram Téléd SFPT. 1996;142:15–33.

[28] Bruniqel J, Lopes A. Analysis and Enhancement of multitemporal SAR data. Image and Sign Proces of Remote Sens. 1994;2315:342–353.

[29] Lopes A, Sery F. Optimal Speckle reduction for the production model in Multilook Polarimetric SAR imagery and the Wishart distribution. IEEE Trans Geosci Remote Sens. 1997;35(3):632–647.

[30] Hachemi K, Thomas YF. Analyse de la mobilité d’un champ de Barkhanes (Mauritanie) à partir des images SAR. Conférence internationale de Géomatique et d’Analyse Spatiale SAGEO (Spatial Analysis and Geomatics); 2013 septembre 23–26; Brest. p. 273–286.

[31] Singhroy V, Saint-Jean R. Effects of relief on the selection of RADARSAT-1 incidence angle for geological applications. CIRS. 1999;25:211–217.

[32] Wade S, Ndoye A, Mbaye M. Fusion d’images optique et radar: application à la cartographie du massif gréisque de Bambarji (Faleme, Senegal oriental). Rev Téléd. 2001;2:119–127.

[33] Mercier G, Derrodey S, Pieczynski W. Segmentation Multiscale de Nappes d’Hydrocarbure. Trait Signal TS. 2001;2:119–127.

[34] Ba K, Wade S, Ndiaye I, et al. Cartographie Radar En Zone Côtière A L’aide D’images Multidates RSO D’ERS-2: Application Au Suivi Environnemental de la Langue de Barbarie et de L’estuaire du Fleuve Senegal. Rev Téléd. 1994;17(4):239–242.

[35] Brivio A, Colombo R, Maggi M, et al. Integration of remote sensing data and GIS for accurate mapping of flooded areas. Int J Remote Sens. 2002;23:429–441.

[36] Hachemi K, Thomas YF, Senhoury AOM, et al. Etude de l’évolution du trait de côte au niveau du port de Nouakchott (Mauritanie) à partir d’une chronique d’images SAR. Geo Eco Trop. 2014;38:169–178.

[37] Hachemi K, Thomas YF, Senhoury AOM, et al. Multitemporal analysis of the city of Nouakchott (Mauritania) based on ASAR images. Geoinfor Geostat. 2015;3:1–7.
[38] Mcmillan A, Morley JG, Adams BJ, et al. Identifying optimal SAR imagery specifications for urban flood monitoring: a hurricane katrina case study). In: 4th International workshop on Remote Sensing for Disaster Response; 25–26 September 2006; Cambridge.

[39] Hachemi K, Abdellaoui A, Ozer A, et al. Apport de l’imagerie radar SAR (images d’Amplitude) pour l’analyse du changement dans la région de Buzau (Roumanie). Rev Geomorfo. 2009;11:63–72.

[40] Hachemi K, Abdellaoui A, Grecu F, et al. Association d’images diachroniques avec un MNA pour une meilleure interprétation des changements de paysage dans la région de Buzau (Roumanie). Rev Geomorfo. 2010;12:53–65.

[41] Bakkar H, Ait Menguelet Z. Sebkha d’Oran (Oran) 23.000 hectares. Fiche descriptive des zones humides algérienne d’importance internationale. RAMSAR; 28/01/2001; 2001. p. 1–5.

[42] Rouch J. La variation du vent en altitude à Oran. Ann Géog. 1920;29:222–227.

[43] Moussa K, Saint Martin JP. Esquisse géologique de la grande Sebkha d’Oran. Bullet Service Géolog National. 2011;22(3):275–283.

[44] The Sebkha of Oran. Photos; Source: https://www.google.com/search?q=photos+sebkha+d%27oran&tmb=isch&source=univ&client=firefox-b-d&sa=X&ved=2ahUKEwi0y8HWkI_mAhUl8aBoKHSRDgQsAQ6BAgKEAE&biw=1366&bih=654