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ARTICLE

Using the GPS Station to Study Wind and Coastal Morpho-dynamics in North-eastern Morocco

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ABSTRACT

The purpose of this work is to evaluate the potential of Global Positioning System (GPS) measurements for the monitoring of aeolian and coastal dynamics. The studied sites are the Moulouya estuary, Bouarfa's area and Tigri Chott. The study shows that GPS is used to determine the dune kinematics and the Moulouya estuary in 3-D with an annual temporal resolution and a sub-centimeter accuracy. The GPS measurements carried out between 2013 and 2021 have shown spatial and temporal variations of the dune kinematics and Moulouya estuary. The results presented here show that the GPS measurements have the capability of continuously surveying the geomorphological entities' kinematics with small and slow displacements and thus, they could complement conventional topometric techniques in a warning system.

Keywords: GPS; Monitoring; Coast; Dune; Northeast of Morocco

1. Introduction

Positioning techniques at different time and space scales have made progress in the last decades, particularly in the field of surveying and mapping or in the production of Digital Elevation Model (DEM), by digital photogrammetry [1,2], radar interferometry [3-5], DORIS system [6], or by Global Positioning System [7,8]. Although these methods are now commonly adopted for mapping, little attention has been paid, until now, to the potential use of GPS, for monitoring, occasional or continuous unstable natural sites or works of art [9].

In this context, the GPS technique has a role to play. This tool has many applications in various fields: Military and space, industry, meteorology,

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geography and geology, vehicle location, agriculture, cartography, etc. [10-12].

Today, GPS has become a common and widely used geomatics technique [13-15]. The use of GPS data makes it possible to determine the relative positions of points located up to several hundred kilometres away, with an accuracy of a few millimeters.

In order to evaluate the capacity of the GPS technique, a study was carried out in order to determine the coastal and wind dynamics in some sites of eastern Morocco. It has, in fact, shown the direction of displacement of the coastline and the dunes of the region of Bouarfa and Chott Tigri. The results obtained make it possible to evaluate the advantages and disadvantages of GPS for continuous monitoring in order to consider a device adapted to real-time.

This work makes it possible to georeference, using GPS, the data provided by the two GPS stations, and therefore to produce thematic maps. A similar study was done in the same area, but it only covered 3 years: 2013-2015 [16,17]. This paper presents, in a more detailed way, the coastal dynamics of the mouth of Moulouya, the dunes of Bouarfa and Chott Tigri, over the period of 2013-2021.

2. Presentation of the study area

2.1 Situation

A study was carried out in eastern Morocco in three different sites: The mouth of Moulouya in the north, Bouarfa and Chott Tigri in the south (**Figure 1**).

2.2 Presentation of relief and geology

The mouth of the Moulouya is experiencing significant dynamics. It was measured by multi-date photo-interpretations [18,19]. The rate of erosion was estimated at 8m/year from 1958 to 1988. The displacements of the shoreline are currently monitored using a network of markers. The continuous measurements of these movements purported to determine the coastal dynamics and validate the models of propagation of this type of dynamic.

The Bouarfa region is located in the eastern High Atlas, made up of narrow parallel mountain ranges, in an E-W direction, framing high plains (**Figure 2**). The ranges have low altitudes (1400-2100 m). The plains of Tamlelt and El Biazza have altitudes

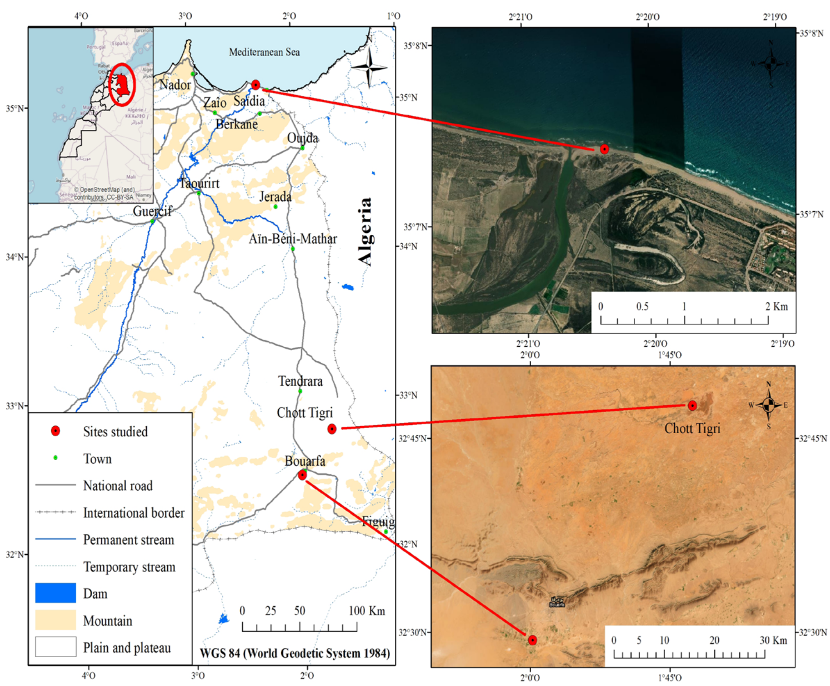


Figure 1. Studied area and location of measurement sites.

ranging from 1100 m to 1200 m. They are depressed compared to the Hauts Plateaux which border them to the north. These are large basin-shaped plains bordered on all sides by the Jurassic and Cretaceous formations of the Atlas. They have, in their center, a discontinuous backbone formed of Paleozoic sediments [20].

Figure 2. Sand beds on the northern slopes of the mountain ranges south of Maâder El Msarine (south of Bouarfa).

The Chott Tigri extends from the High Plateaux of eastern Morocco 60 km northeast of Bouarfa around 1300-1400 m altitude (plateau) and 1100-1200 (basin). It stretches 60 km from west to east and 30 km from north to south. It looks like an irregular ellipse, bounded to the north and south by almost straight cliffs (**Figure 3**). This closed basin is traversed by a little evolved hydrographic network (O.Mazer, O.Meril) meandering in the middle of recent dune formations, draining the waters towards the sebkha which occupies the center (Ed-Dechar). The series of red sandstones of Chott is Senonian. The visible thickness of these layers is estimated at 500 m [21] (**Figure 4**).

Figure 3. General view of the Chott Tigri.

Figure 4. Detail landscapes in the Chott Tigri.

It results from the destruction of the vault of an anticline by the erosion processes imposed by the climate: Torrential gullies following rare and violent rains, deflation and corrosion by the winds attacking the bare ground. This work, leading to the inversion of the relief, is less advanced in the basins of Tigri and Foum Aggaï than in the basin of Mekkám; it reaches its maximum in the basin of Tamlelt.

The Tigri is made up of a series of interlocking circular terraces, of gradually decreasing diameter and altitude, the lowest of which surrounds a central depression occupied by a daya. This vast basin with sheer edges and jagged contours runs roughly from east to west, at the foot of the Hauts Plateaux, and its edges are located at a fairly constant altitude, close to 1,350 m. The central depression is only at elevation 1148, and the highest point on the edges of the basin is at 1383 m. The various terraces are staged at relative altitudes of 27 m, 98 m, 117 m, 191 m and 227 m above the bottom of the central depression. A little to the west of the highest point of the peripheral ridge appears, at elevation 1373, a small volcanic apparatus, discovered by Ê.F. Gautier in 1914 [22] and, a little further N, a second that Russo described in 1927 [23,24].

2.3 Wind directions and speeds

According to the statistics concerning the frequency and the directions of the winds recorded at the Bouarfa station between 1984-1989, the wind roses are more starry indicating a predominance of the winds coming from the collateral points: SW, NW, NE [25]. In summer, the east winds are dominant. This East to SE or Chergui wind occurs most often in summer and its duration is from a few hours to a few days. It is accompanied by very high temperatures and causes a drop in the relative humidity of the air.

The Chergui can also, very exceptionally, occur in winter: the air is then dry and cold. It has a noticeable effect on the fixing vegetation of the dunes, but can also orient the nebkas in the opposite direction from their usual state.

The direction and speed of the wind are represented by the wind roses (**Figure 5**). In Bouarfa, the strong prevailing winds are from W, S and ESE. At Chott Tigri, strong winds are from directions: WNW, W and SSE (**Table 1**).

In Bouarfa, from November to April, strong SSW winds dominate. In spring and summer (May-August), strong winds from the S, SSE dominate. Finally, in September and October, strong SSW winds dominate (**Table 1**).

In Chott Tigri, from November to May, strong winds from the W and WNW dominate. In summer (June-August), strong SSE and S winds dominate. Finally, in September and October, strong WSW winds dominate.

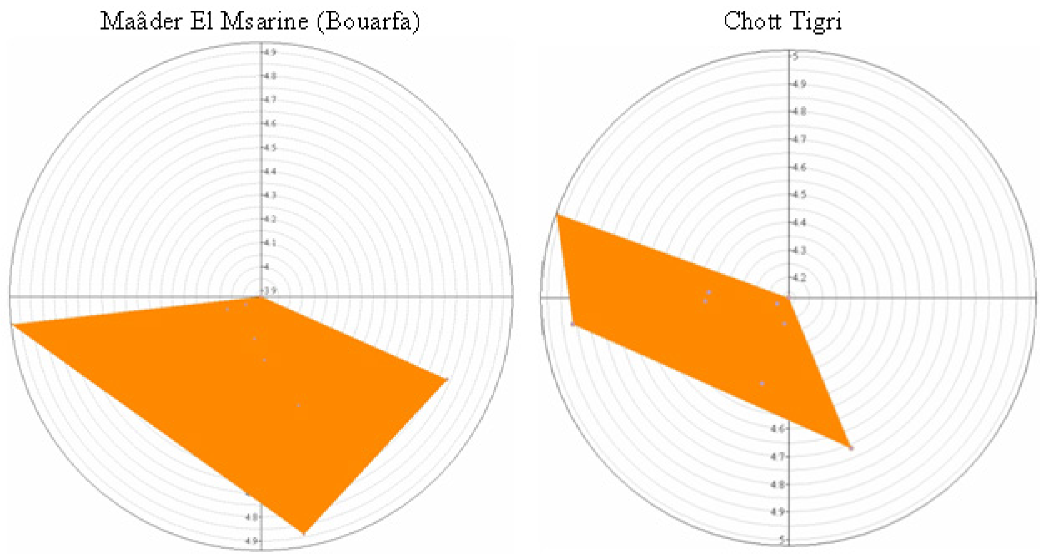


Figure 5. Wind directions and speeds (1981-2021).

Source: https://power.larc.nasa.gov/data-access-viewer/.

Table 1. Wind directions and speeds (1981-2021).

	Mader El Msarine		Chott Tigri	
	Wind Direction	Wind Speed (m/s)	Wind Direction	Wind Speed (m/s)
Janary	246	14.7	287	16.0
February	255	15.4	278	16.6
Mars	248	16.5	263	17.2
April	264	17.8	290	18.1
May	170	17.6	263	17.7
June	114	17.1	158	17.0
July	161	15.7	197	16.0
August	177	14.9	188	15.2
September	188	14.6	240	15.0
October	199	13.9	236	14.9
November	249	14.5	268	15.9
December	243	14.2	274	15.9

3. Materials and methods

The foundations of the GPS technique are developed in several references [26-32,15]. The GPS system is based on a constellation of 24 satellites in orbit around the Earth which continuously emit a radio signal coded on two frequencies (L1=1.2 GHz and L2=1.5 GHz). These signals are modulated on the phase by binary codes which contain information on the time, term C/A (Coarse Acquisition) or term P (Precise Acquisition). C/A signals can be used by everyone, while access to the P-code was restricted until the beginning of the year 2000 [33].

Differential GPS uses a network of fixed reference stations that transmits the difference between the positions indicated by the satellites and their known real positions. In fact, the receiver receives the difference between the pseudo-distances measured by the satellites and the true pseudo-distances and can, thus, correct its position measurements.

The acquisition of GPS data was carried out using two Leica 1200 GPS stations equipped with antennas, during nine campaigns, from 2013 to 2021. Stakes are installed on-site to serve as a reference. Sampling was done once a year. GPS receivers were powered by batteries. Several GPS measurements were made during the nine campaigns (**Figure 6**). Horizontal and vertical accuracy is less than 1 cm. The coordinate system used is Lambert North Morocco, Zone 1. During each campaign, different measurement points are surveyed following the general shape of the dune. For the profiles, the same points are measured each year per location even if it is variable.

GPS data were processed in RTK mode. The precise coordinates were calculated directly in the geodetic reference. The network formed by the "fixed" and "mobile" stations were processed by fixing the positions of the two stations. The calculations were carried out using precise orbits and taking into account the phase center variation models of the antennas. The final result is a vector: north-south component = X, east–west component = Y, Z component = altitude. The precision achieved is millimetric [34].

In the second step, the data undergo post-processing: Import and export by the Geo Office 7 software, then data processing and export in shapefile or ASCI using Covadis software from Autocad, Surfer or ArcGIS.

Figure 6. Fixed and mobile stations in the Chott Tigri. Note the pegs taken as a reference.

4. Results and discussion

4.1 Moulouya mouth

Through the monitoring of the mouth of the Moulouya, over a period extending from 2013 to 2021, we collected sowing of 5302 points. Visually, we see that the coastline has retreated 172 m on the right bank and 106 m on the left bank (**Figure 7**). As for the "pulley", it has moved to the southeast by 350 m.

4.2 South of Bouarfa

Dune 1 moved between 2013 and 2019① by 16.36 m towards the southeast. However, we can note a preferential displacement according to two components: towards the southwest: 19.06 m and towards the east: 14.51 m (**Figure 8**).

The surface and the volume evolve in parallel. We note a sharp drop in 2015 and 2019 where the volume becomes lower than the surface (**Figure 9**). It fell from 1558 m^3 in 2014 to 1099 m^3 in 2015, to reach 415 m^3 in 2019, a loss of 73%. This means that the dune has been

① The series ended in 2019 because of work to combat desertification, which consists of the fixation of dunes by vegetation.

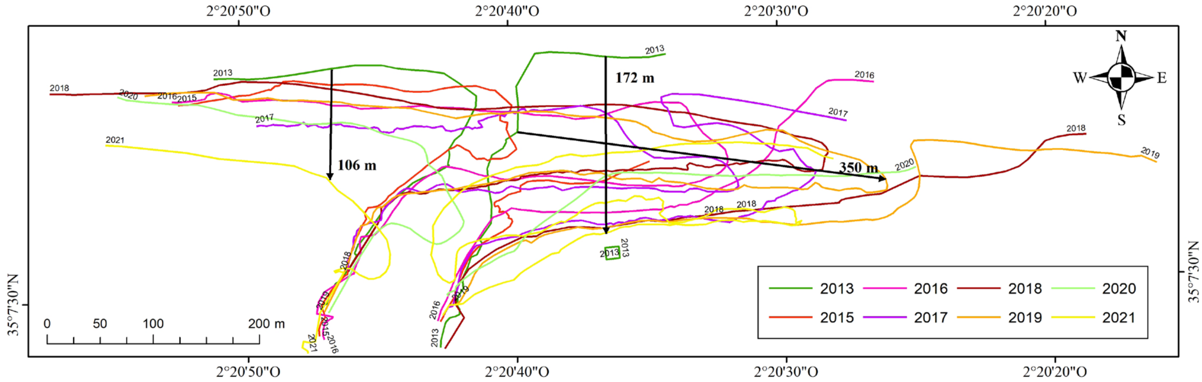


Figure 7. Moulouya mouth: Current dynamics map.

spread out and has lost its volume. The same applies to its surface area, which fell from 1,490 m^2 in 2013 to 618 m^2 in 2019, i.e. a loss of 59%.

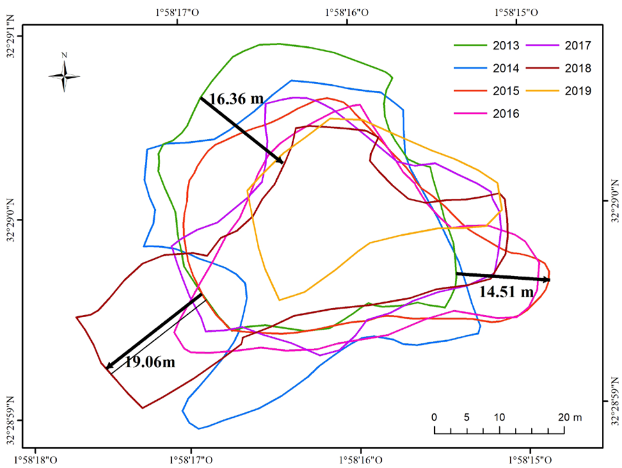


Figure 8. Evolution of the positions of dune 1 south of Bouarfa.

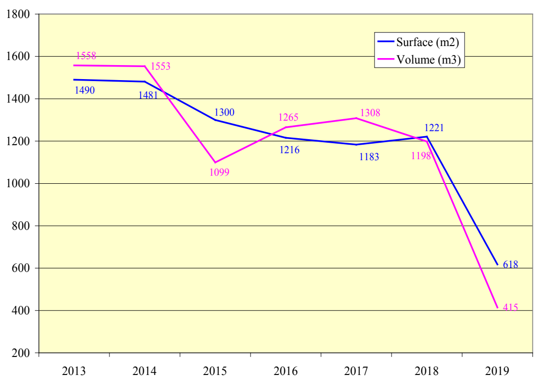


Figure 9. Variation in the surface and volume of dune 1 south of Bouarfa.

Dune 2 moved generally 25.66 m east-northeast. Nevertheless, other displacement vectors can be observed: 6.50 m to the south; 14.39 m to the southeast and 25.49 m to the north (**Figure 10**).

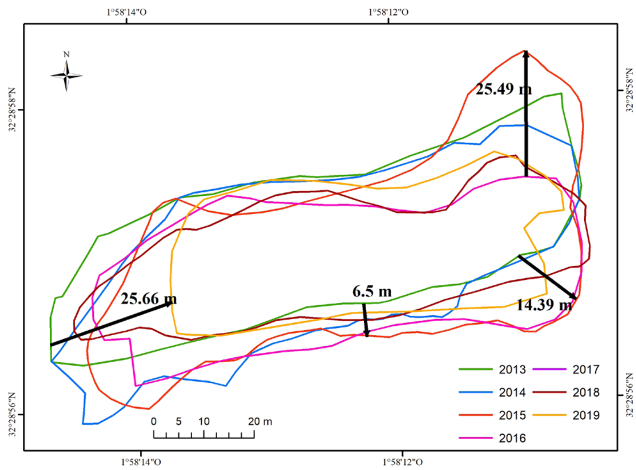


Figure 10. Evolution of the positions of dune 2 south of Bouarfa.

The comparison of the surface and the volume shows a general decreasing trend even if we note a certain increase in the surface and the volume from 2014 to 2015. The surface is often greater than the volume, except in the year 2018. However, the volume curve descends more than the surface curve. In other words, the dune is spread out and its volume is low. This behaviour is probably controlled by the dynamics of the winds which delimit compartments in differential displacement, and by the position of the dunes in relation to the topographic surface (**Figure 11**).

It can therefore be seen that the wind speeds have a significant influence on the distribution of sandy deposits in the Chott Tigri and Maâder el Msarine. Dunes form and move in the direction of the wind, but not all dunes move at the same speed: the speed decreases with the distance from the crest which marks the beginning of the dune field. As you might expect, the wind has a crucial role in moving dunes.

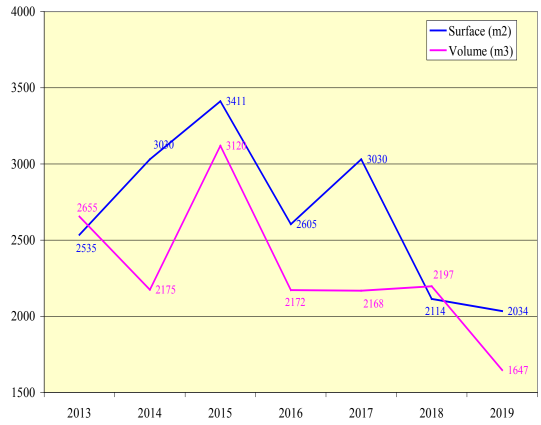


Figure 11. Variation in the surface and volume of dune 2 south of Bouarfa.

4.3 Chott Tigri

In Tigri, the general cumulative displacement of dune n°1 in 9 years of measurements is 28.95 m towards the east-northeast. However, two components can be observed: one towards the northeast: 43.11 m, another towards the east-northeast: 73.24 m and another towards the north: 15.76 (**Figure 12**).

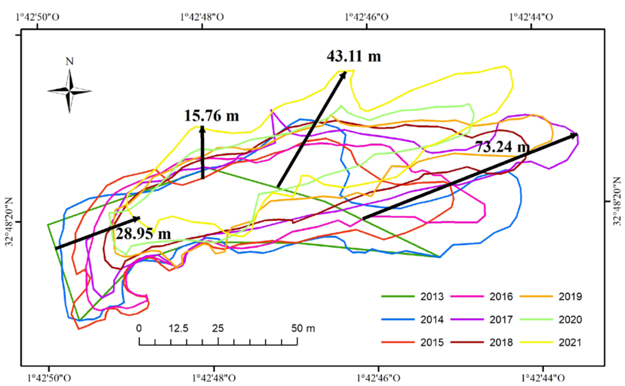


Figure 12. Evolution of the positions of dune 1 at Chott Tigri.

The surface and the volume evolve differently. The year 2014 is marked by a jump in the time series of volumes, which is particularly visible: a 100% increase compared to 2013, followed by a 36% decrease, while the surface has not changed much over the three years (**Figure 13**). This increase in volume is due to the wind, which plays a crucial role in moving the dunes.

Dune n°2 records a general movement of 79.58 m towards the east northeast (**Figure 14**).

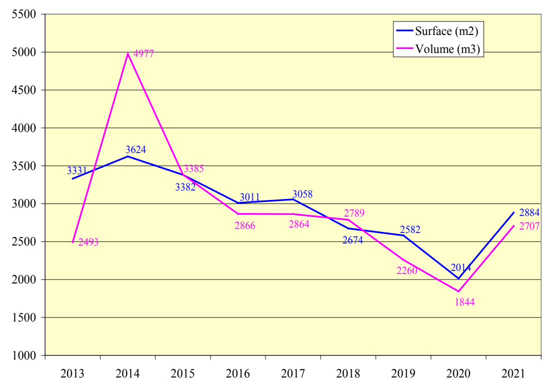


Figure 13. Variation of surface and volume of dune 1 at Chott Tigri.

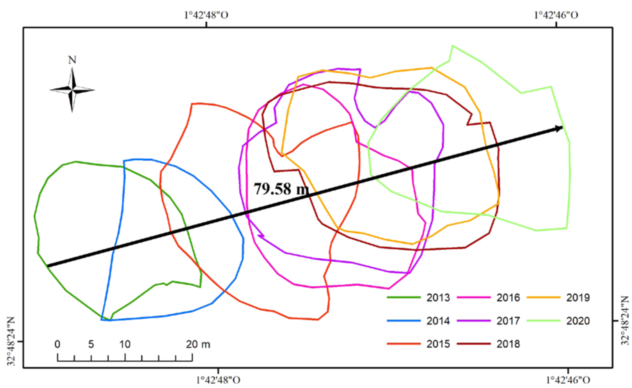


Figure 14. Evolution of the positions of dune 2 at Chott Tigri.

The surface and volume curves evolve in parallel with a general increasing trend (**Figure 15**).

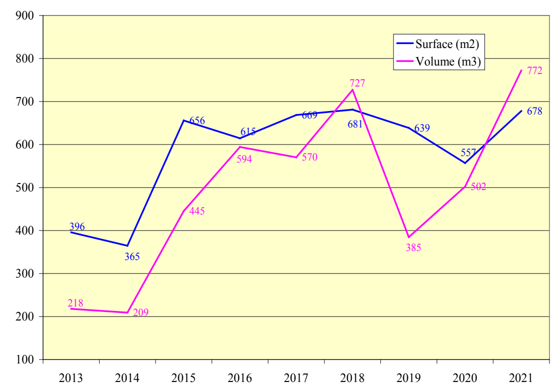


Figure 15. Variation of surface and volume of dune 2 at Chott Tigri.

The comparison between the results obtained over the years 2013 to 2021 indicates respective average speeds of 6 and 3 m/year for the dunes of Bouarfa and 5 and 10 m/year for the dunes of Tigri. These annual variations are probably due to wind speed.

The different results of this study are summarized in the following **Table 2**.

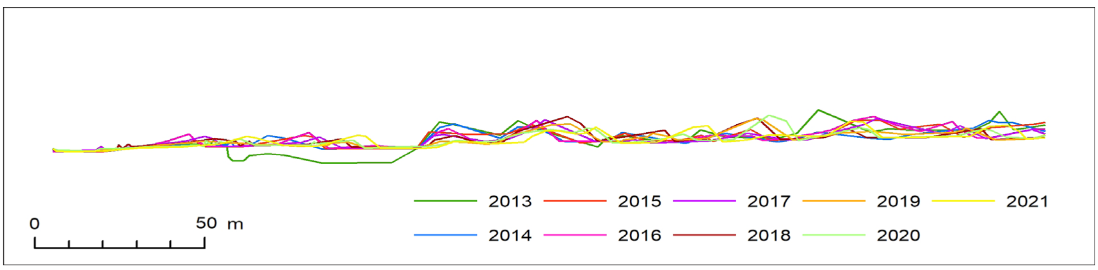
4.4 Topographic profiles

The results obtained from two micro-topographic profiles of the Chott Tigri dunes are interesting (**Figure 16**). Their comparison (2013-2021) shows significant annual changes: Erosion in some compartments and sedimentation in others. In other words, ridges have been eroded and new ones have been created. This is due to the remobilization of the sands by the wind.

But why do the dunes slow down and change shape? This is of course due to the wind which affects the study area and carries the flow of sand.

Table 2. Synthesis of the dynamics of the coast and dunes of eastern Morocco (2013-2021).

		Retreat from the coast (m)	Displacement of the littoral spit towards the East (m)		
Moulouya mouth	Left Bank	106	350		
	Right bank	172			
		Displacement to the Southeast (m)	Displacement to the South-West (m)	Displacement to the East (m)	
Dunes south of Bouarfa	Dune 1	16.36	19.06	14.51	
		Displacement to the East-North-East (m)	Displacement to the South (m)	Displacement to the Southeast (m)	Displacement to the North (m)
	Dune 2	25.66	6.5	14.39	25.49
Dunes at Chott Tigri		Displacement to the East-North-East (m)	Displacement to the North-East (m)	Displacement to the East-North-East (m)	Displacement to the North (m)
	Dune 1	28.95	43.11	73.24	15.76
	Dune 2	79.58			



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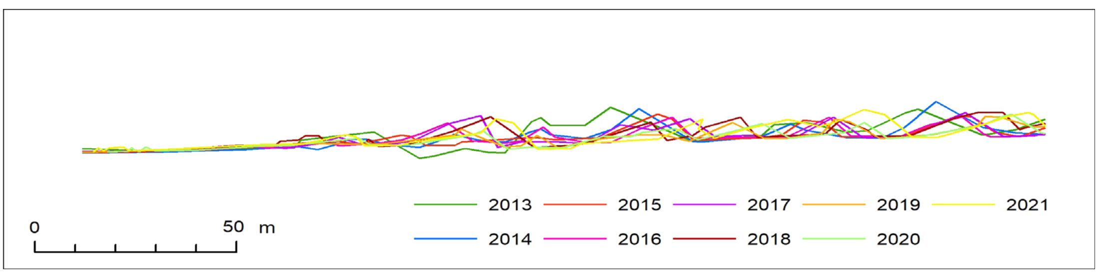

b

Figure 16. a. Micro-topographic evolution of the profiles of Chott Tigri (289 m) between 2013 and 2021 (site 1, scale 1 cm = 2 m); b. Micro-topographic evolution of the profiles of Chott Tigri (237 m) between 2013 and 2021 (site 2, scale 1 cm = 2 m).

Dunes create roughness, which slows down the wind. Thus, the wind pulls more sand from the first dunes, which causes the dunes to move more quickly.

The crests of the first dunes are devoid of vegetation cover. Dune movement is too rapid for plants to take root. Vegetation only appears from a hundred meters. When the dunes become slow enough, the plants settle, preferably at the ends of the dunes, or in the inter-dune corridors and help to immobilize these areas.

This type of dynamic had already been observed on coastal dunes [35] and inland, as is the case of Sand Hills in Nebraska [36].

It is our belief that a detailed time series analysis should be conducted after each storm to show the periodic variations of these dunes and their seasonal patterns. The variation of the mean hourly winds at the climatic station of Bouarfa must be correlated with the movements of these dunes.

5. Conclusions

This should clearly explain the main conclusions of the article, highlighting its importance and relevance.

GPS is therefore suitable for measuring slow movements of the shoreline and dunes. Its use in eastern Morocco is a first for the measurement and monitoring of coastal and wind dynamics. It offers the advantage of delivering three-dimensional positioning. The results obtained make it possible to quantify the 3-D kinematics of these spaces with an accuracy of a few millimeters.

The dispersion of the measurements observed, in particular for the dunes, results from the variations in the direction of the winds with a preferential movement towards the east-northeast for the Tigri and towards the southeast and north for the dunes of Maâdre El Masarine (south of Bouarfa). The measurements carried out over the years 2013 to 2021 also make it possible to highlight the spatial (compartmentalisation) and temporal (annual) variations in the kinematics of the dunes and the coastline.

The use of GPS for this type of application has been however limited due to the cost of the equipment and its maintenance. Despite these difficulties, GPS has the capacity to follow the dynamics of geomorphological entities with weak and slow movements and could therefore constitute, a warning system, a complement to conventional surveying techniques.

Author Contributions

The two authors carried out the various measurements by GPS in the field. Omar MOUADILI took care of the data processing (Covadis and ArcGis software) and the production of the maps. Abdelkader SBAI wrote the text.

Conflict of Interest

There is no conflict of interest in the publication of this article.

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