Contribution of GPS and GIS in the Study of the Dynamics of the Coastline and the Mouth of the Moulouya (Northeast Morocco)

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Abstract. This study assesses the utility of Global Positioning System (GPS) data in monitoring coastal dynamics, focusing on the Moulouya estuary. The research demonstrates the capability of GPS in capturing 3D estuarine kinematics with annual temporal resolution and sub-centimetre accuracy. Analysis of GPS data collected from 2013 to 2021 reveals both spatial and temporal variations in the Moulouya estuary's dynamics. The findings emphasize GPS's ability to continuously track the kinematics of geomorphological features exhibiting small, gradual displacements. Moreover, the study underscores GPS's potential to complement traditional topometric methods, enhancing coastal monitoring and warning systems.

Keywords: GPS, centimetric positioning, monitoring, coastal dynamics, dune morphology, northeast Morocco.

Introduction

Advancements in positioning techniques, particularly in mapping procedures and generating Digital Elevation Models (DEM) via digital photogrammetry, have been notable. However, the potential use of GPS for monitoring unstable natural sites or structures remains largely unexplored. This innovative application of GPS technology offers a unique opportunity to have a significant impact, serving as a preferred tool for achieving precise positioning and having a wide range of applications across various sectors. In the modern context, GPS has not only become a standard technique in geomatics but is also widely used because of its capacity to determine the relative positions of points located hundreds of kilometres apart with millimetre accuracy, showcasing its precision and broad applicability. An investigation was carried out to evaluate GPS's effectiveness in mapping coastal dynamics in eastern Morocco. The research successfully revealed the shoreline orientation and water body movements, providing solid evidence of GPS's efficacy. These results allow for the assessment of GPS's relevance for continuous monitoring towards the implementation of a real-time system. The study involved the georeferencing of data from two GPS stations using GPS and the creation of thematic maps, meticulously outlining the coastal dynamics of the Moulouya estuary from 2013 to 2022.

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The results have already been partly published for the period 2013-2015 [1, 2] but they have been consolidated and reinterpreted up to 2022 for this new publication.

1. Presentation of the Study Area

This study was conducted at the mouth of the Moulouya (Fig. 1).

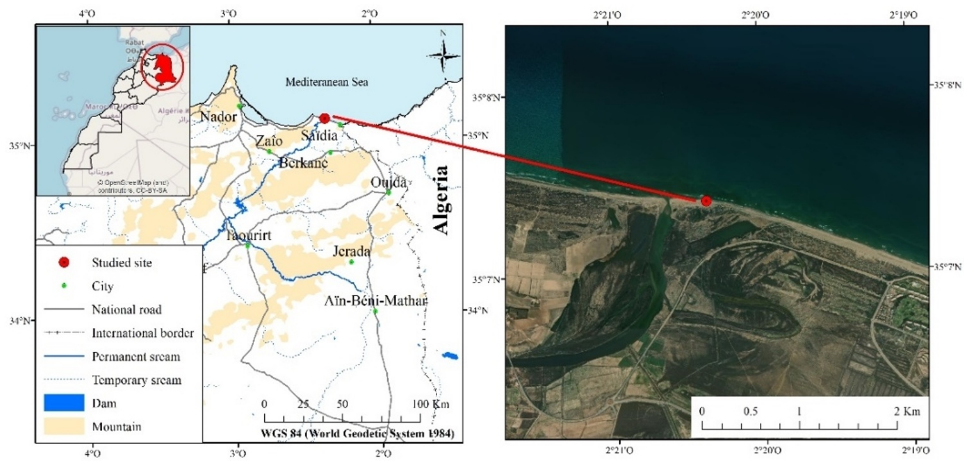


Fig. 1. Location of the study area

The Moulouya estuary, a region of significant activity, has been a central focus of our study. Extensive multi-date aerial image analyses by [3] and [4] have been instrumental. The erosion rate, a crucial parameter reflecting these dynamics, was a staggering 8m/year from 1958 to 1988. Presently, we track shoreline displacements using a network of benchmarks. These ongoing measurements not only aim to assess coastal dynamics but also to validate models of this dynamic evolution, highlighting the significance of our discoveries.

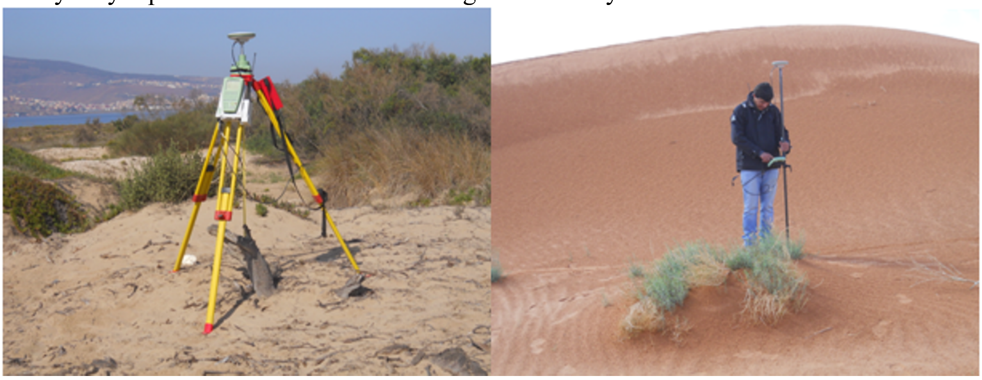
2. Method

GPS technology, a fundamental element of our investigation, is extensively detailed in various sources ([5-12]. This system, relying on a group of 24 satellites orbiting Earth, continuously transmits a coded radio signal on two frequencies (L1=1.2 GHz and L2=1.5 GHz). These signals, modulated by binary codes representing the C/A (Coarse Acquisition) or P (Precise Acquisition) terms, play a crucial role in our data gathering process. The accessibility of C/A signals to all users and our access to the previously restricted P-code signals since early 2000 [13] guarantee the precision of our data, bolstering confidence in our results.

Differential GPS utilizes a network of fixed reference stations strategically positioned in known sites to broadcast the disparity between satellite-indicated positions and their accurately known locations. These reference stations, typically situated on elevated terrain or in open areas, provide dependable benchmarks for our measurements. By receiving the difference between the pseudo-distances measured by satellites and the actual pseudo-distances, the receiver can rectify its position calculations.

The GPS data collection process was exhaustive and thorough. It encompassed the deployment of two GPS stations with antennas over nine campaigns spanning from 2013 to 2022 (Photos 1-2). On-site stakes were installed as markers to ensure measurement accuracy.

Sampling occurred annually, presenting a comprehensive evolution view over time. The GPS receivers were battery-powered to ensure uninterrupted data recording. Each campaign involved station setup, equipment calibration, and data collection over a specified duration. This yearly repetition facilitated the tracking of coastal dynamics shifts across time.



Photos 1-2. Fixed and mobile stations and RTK measurement

The GPS data were processed in RTK mode to calculate precise coordinates directly in the geodetic reference frame. The network of "fixed" and "mobile" stations had their positions fixed for processing. Calculations utilized precise orbits and accounted for antenna phase center variation models. The outcome is a vector with components as follows: north-south = X, east-west = Y, altitude = Z, achieving millimetre-scale precision [14]. Following this, the data underwent post-processing: importing and exporting were done using Leica Geo Office 7 software, then further processing and exporting in shapefile or ASCII format via Covadis, Autocad Surfer, or ArcGIS software.

1. Results and Discussion

From 2013 to 2022, 6610 points were gathered. Figure 2 illustrates a retreat of 172 meters on the right bank and 106 meters on the left bank of the coastline. Additionally, the coastal spit shifted southeast by 350 meters.

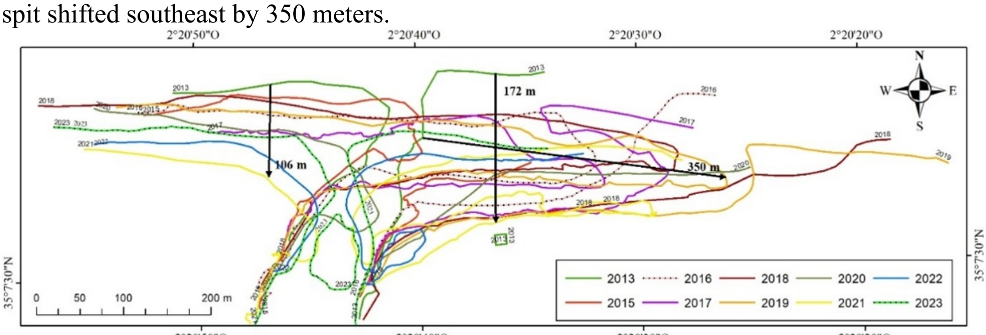


Fig. 2. Dynamics of the Moulouya estuary and coastline between 2013 and 2023

Between 2013 and 2017, the Moulouya shifted eastward by 285 meters. The coastline receded by 54 meters on the left bank and 160 meters on the right (Fig. 3). A coastal spit measuring 218 meters formed.

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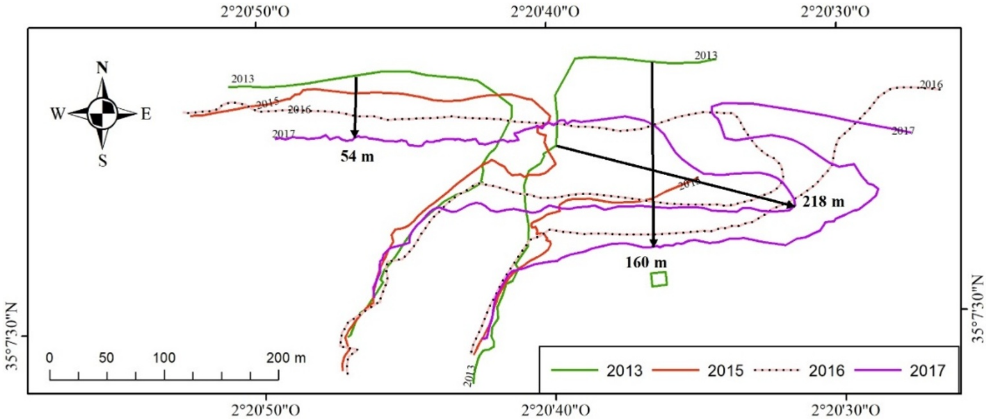

Fig. 3. Dynamics of the Moulouya estuary and coastline between 2013 and 2017

In 2018 and 2019, the advancement to the east persisted. The coastal spit extended to its peak of 350 meters, while the shore receded by 5 meters, resulting in a total of 165 meters (Fig. 4).

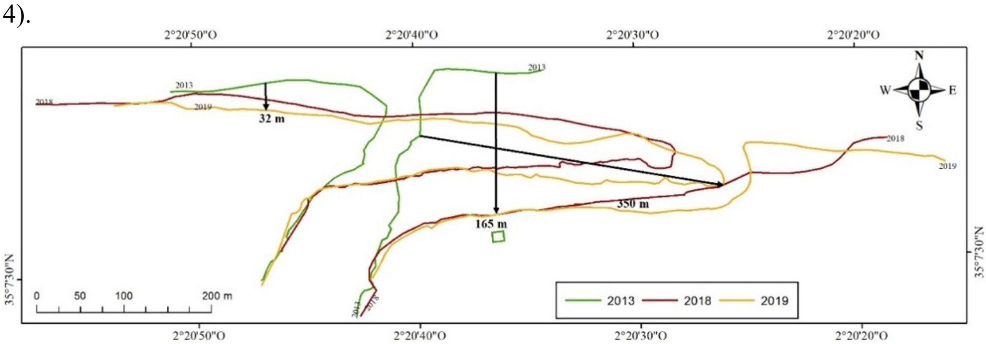

Fig. 4. Dynamics of the Moulouya estuary and coastline between 2013 and 2019

In November 2020, the Moulouya no longer flowed into the sea. Fishermen had to dig a channel to link it to the sea, enabling boat passage. The Moulouya's shape in 2020 resembled that of 2013. The coastline receded by 113 meters on the right bank and 54 meters on the left (Fig. 5).

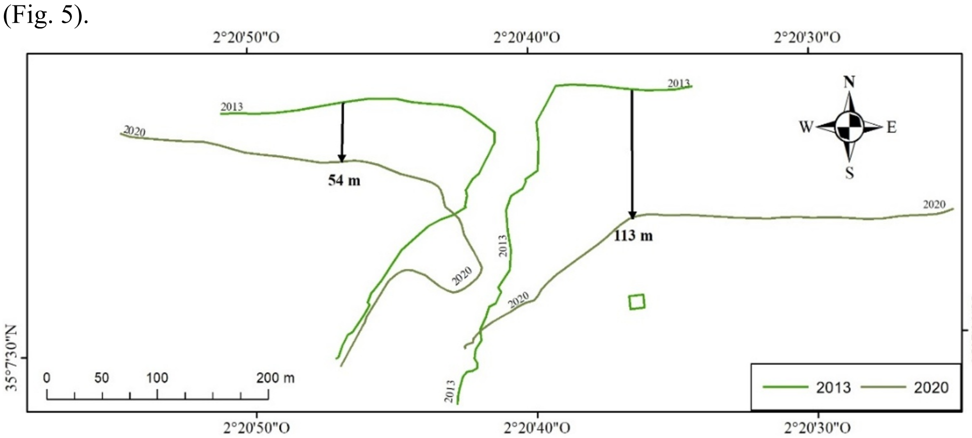

Fig. 5. Dynamics of the mouth of the Moulouya and the coast between 2013 and 2020

In 2021, the Moulouya river extended to the sea, creating an eastern arm that eventually dried up by the year's end [15]. By 2022 and 2023, the landscape resembled that of 2013, featuring a sand island emerging in the river and the coastline receding by 82 meters on the right bank and 61 meters on the left bank (Fig. 6).

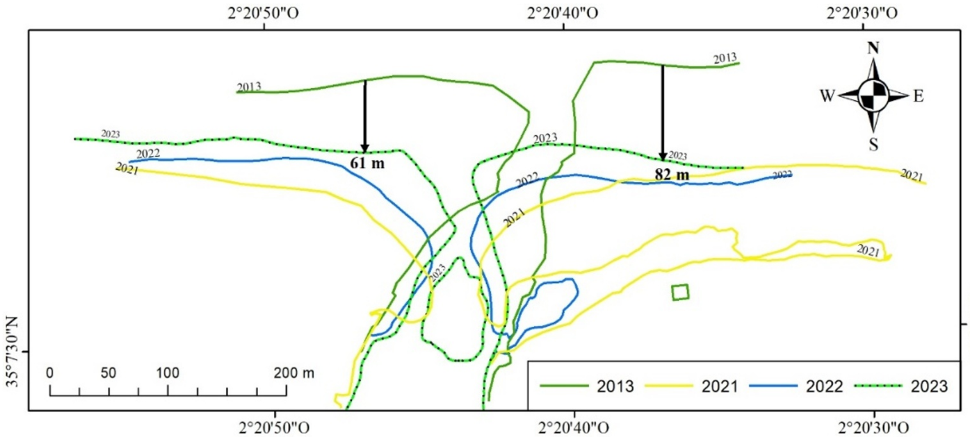

Fig. 6. Dynamics of the Moulouya estuary and coastline between 2013 and 2023

Understanding the significant changes in the dynamics of the coastline and the mouth of the Moulouya River is essential. These changes, influenced by weather conditions and human activities, have significantly altered the landscape. In March 2016, the once powerful Moulouya River, now dry, stopped flowing into the sea. Its reduced flow, a result of drought and excessive water extraction, was redirected eastward. The interaction of coastal drift and winds led to the creation of a coastal spit, transforming the area into a sandy beach. By 2021, this spit had extended to an impressive 350 meters. A thorough examination of the time series data should be conducted after each storm to illustrate the periodic fluctuations in these dynamics and the alterations in the course of the waterway and the coastline.

Conclusion

The utilization of GPS technology in eastern Morocco represents an innovative approach to measuring and monitoring coastal dynamics. This technology, equipped with the unique capability to offer three-dimensional positioning, provides unprecedented insights. The GPS-derived results enable the precise quantification of the 3-D movements of these spaces, down to the millimetre.

The observed spread of measurements stems from shifts in the waterway's direction, predominantly towards the east. This spread signifies the variability and unpredictability of the waterway's trajectory, which is a crucial aspect in comprehending and regulating the coastline dynamics. Measurements taken between 2013 and 2022 also emphasize the spatial (compartmentalization) and temporal (annual) alterations in the coastal movements, offering valuable information for coastal management strategies.

Nevertheless, the application of GPS for such purposes is constrained by the expenses associated with the equipment and its upkeep. Despite these challenges, GPS can monitor the dynamics of geomorphological features with slight and gradual movements, potentially complementing traditional topometric methods in an early warning system. To tackle these limitations, future research could concentrate on developing more cost-efficient GPS systems tailored for monitoring coastal dynamics or exploring alternative technologies that could deliver comparable precision at a reduced cost.

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Author contribution
All authors (Abdelkader Sbai, Omar Mouadili & Khadija Benrbia, Mohammed Hlal, Ahmed Amghar) reviewed and approved the final manuscript, with Abdelkader Sbai and Omar Mouadili carrying out the field measurements, Khadija Benrbia, Mohammed Hlal and Ahmed Amghar taking care of the data processing and the production of the maps and figures. Abdelkader Sbai wrote the text with contributions from all the co-authors. Mohamed Dellal revised the text from a language point of view.

Ethics approval and consent to participate
Not applicable

Consent for publication
All the authors have agreed to publish this article.

Competing interests
The authors declare that they have no competing interests.

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