High resolution topography analysis of Sidi Moussa cliff (Salé, Morocco) to assess coastal flooding susceptibility.

Imane Joudar[1,2*], Mohammed Bouchkara[1,2,3], Khalid Mehdi[4], *Bendahhou* Zourarah[1,2] and *Khalid* El khalidi[1,2]

[1] Marine Geosciences and Soil Science Laboratory (URAC-45), Earth Sciences Department, Faculty of Sciences, Chouaib Doukkali University, EL Jadida 24000, Morocco
[2] Center LittoMer of Coastal and Sea, Chouaib Doukkali University, EL Jadida 24000, Morocco
[3] National Institute of Fisheries Research, Agadir, Morocco
[4] Polydisciplinary Faculty of Khouribga (FPK), Sultan MoulaySlimane University, 25000 Khouribga, Morocco

Abstract. Moroccan coastal areas are becoming more and more exposed to hazards related to storms and sea level rise. The Sidi Moussa cliff, which is situated south of Salé, is a sensitive coastal sector regularly hit by marine flooding during extreme phenomena. This study will create a high-resolution Digital Terrain Model (DTM) of the area to better determine its morphological characteristics and its susceptibility to marine inundation. The topographic data were gathered by a differential Global Positioning System Real Time Kinematic (GPS-RTK) method. Indeed, the collected data have been treated in a geographic information system environment to generate the DTM and to conduct elevation analyses in detail. The obtained model will be a fundamental dataset for the future numerical simulation of coastal flooding and for the mapping of potentially flooded zones. This study will also offer, for the first time, a clear and detailed morphological expression of the Sidi Moussa cliff, for which no topographic data was previously available. A first look at the results shows a topography that appears irregular, where micro-reliefs and active erosion predominate, increasing the vulnerability of some sectors to wave overtopping during storms. The latter approach points out the contribution of high-resolution topographic data to the enhancement of coastal assessment and management.

1 Introduction

The coastal environments are significant transitional areas where oceanic, atmospheric and terrestrial systems interact, leading to a complex and nonlinear development of the landscapes across a wide variety of different time scales [1]. In effect, these interfaces are among the most sensitive in terms of natural forcing and anthropogenic interventions, thus,

* Corresponding author: joudar.i@ucd.ac.ma

making them among the most susceptible landscapes to the changing global environment. More than 3500km of the shoreline in Morocco serves various economic, ecological and social interests and the coastal areas are in the process of rapid multi-faceted developments [2]. Among them, a more rapid relative sea-level rise along the Atlantic coast [3,4], more intense and frequent extreme weather events, particularly winter storms generated by North Atlantic interactions, and the ongoing expansion of urban, tourist, and infrastructural development along the coast can be named [3–5]. A combination of these stressors enhances exposure of communities to marine hazards, endangers coastal infrastructure and intensifies geomorphic instability. One of the most prominent places where these cumulative stresses are occurring is the Sidi Moussa cliff that is situated on the central Atlantic coast of Morocco, just south of the city of Salé [6,7]. There is much morphological weakness in this sector: beam run-up and overtopping often override the cliff edge during high-energy storm events, particularly those ones which occur in conjunction with spring tides and lead to periodic but devastating flooding of adjacent lowlands [8]. The subjective report of historical events and recent observations in the field prove that there have been recurring flood events, which disrupt local movement, damage property, and cast doubt on the sustainability of habitats in the long term [9]. Although the Sidi Moussa cliff hs is an active part of the regional hazards, the Sidi Moussa cliff hs has never been mapped with a high-resolution topographic procedure systematically. Current cartographic products, be they the output of satellite imagery, national topographic databases, or low resolution LiDAR, do not have the vertical and horizontal accuracy to spot small but decisive terrain features. This lack of data is an essential barrier to effective risk governance along coastline. It is impossible to calibrate of validate numerical models that simulate storm surge and wave overtopping without precise elevation data. Likewise, land use planners and civil protection agencies have to live without spatially precise designations of the possible inundation mark. On a national scale, where the general policy frameworks of integrated coastal zone management are yet to be completely developed, and where climate adaptation planning is still a data scarce endeavor, these gaps only serve to hinder resiliency efforts. To satisfy this dire requirement, the present study, in the first, carries out in exemplary detail, a topographical survey of the cliff of Sidi Moussa and its near surroundings by means of a differential [10,11]. he horizontal and vertical positional resolution is in the centimeter range and the technique can capture fine scale morphological detail that would be overlooked by remote sensing techniques- especially in vegetated or shadowed cliff scenes [12]. Surveys points more than 1200 were measured in a 0.8 km^2 area that included the plateau edge, inland flood-prone corridor, and cliff face. Following that, the product was processed and interpolated using geostatical methods in geographic information system (SIG) environment to create a high resolution digital terrain (DTM) with a centimeter special resolution. This DTM gives an account of the current morphological condition and it forms a reference to monitor the changes in the future. Analysis is based on the terrain characteristics that are the most closely related to the vulnerability of coasts to flooding, including slope gradients, pathways of flow of accumulation, topographical convergence areas, and topographical elevation levels in comparison with already experienced storm water heights. This study links fine-scale topography with hydrodynamic processes; thus, it goes beyond generic hazard mapping by providing a site-specific, physically informed understanding of inundation mechanisms. Ultimately, this study delivers more than a technical dataset; it creates a foundational geospatial asset for multi-hazard assessment in the Salé coastal region. The results are meant to enable next-generation numerical flood modeling, support municipal land-use decisions, and add to the growing body of localized evidence needed to guide climate-resilient development along Morocco's increasingly pressured Atlantic coastline.

2 Materials and methods

2.1 Study area

The study area of Sidi Moussa Salé coastline is located on the Atlantic coast of Morocco, about 7 km northeast from Rabat (Fig.1). On the one hand, this coastline is a straight, steep cliff oriented NE-SW and extends for almost 12 km. The area analyzed lies between latitudes 34°3'35"and 34°2'49" N and longitudes 6°49'3" and 6°49'44" W; it is highly urbanized and presents evidence of intense human occupation due to a well-developed corniche and sports facilities [6]. The oceanographic regime of the Sidi Moussa sector is strongly influenced by the Atlantic dynamics, with significant wave activity, semi-diurnal tides, and moderate tidal currents. The wave data from the [13], for the period 2014–2023, shows that the significant wave heights usually range between 1.0 and 3.0 m, originating essentially from the north and northwest directions. This cliff presents a rich sea scenery, with geological, morphological, and heritage factors involved [14]. The Sidi Moussa coastline is geologically composed of Quaternary sandstone dune cordon which are hewn out of marine and wind formations which are deposited on the Neogene Gharb basin [15], which are found between the Prerif and base of the central meseta. The cliffs extend between 10 and 25 m and have very fine outcrops of the Quaternary coastal formations that were formed during the Upper Pleistocene. There is also a series of paleobeaches, prehistoric caves in this region, which testify to the geological and paleoclimatic development of the Moroccan coast [16]. The region is generally a coastal region with a very active morpho-sedimentary process with erosion, local collapses and sensitivity to extreme events that are markedly high. The following properties render Sidi Moussa cliff a region of significant research on marine submersion and cliff stability.

Fig. 1. Geographical location of the Sidi Moussa cliff, Salé.

2.2 Topographic data acquisition

A detailed topographic survey was conducted along the Sidi Moussa cliff, south of Salé, on Morocco's Atlantic coast on 6 December 2021. The survey aimed to get accurate elevation data for constructing a high-resolution DTM and characterizing the coastal morphology in this exposed sector. These field measurements were carried out with a Real Time Kinematic Global Positioning System, GPS-RTK [17], which is able to provide centimeter-scale positioning accuracy by real-time correction between a base station and a rover unit (Fig.2).

This setup reduces positioning errors to a minimum, and the resulting vertical precision is sufficient for mapping of coastal terrain. Data was collected for the cliff zone and the low-lying areas surrounding it that are commonly flooded during storm surges. The surveyed points were distributed to represent the main morphological variations, including the cliff crest, mid-slope, and toe. In all cases, good tidal and weather conditions guaranteed optimal visibility and stable satellite reception during the campaign.

Fig. 2. Topographic data acquisition setup: (A) Field survey using the GPS-RTK rover in Sidi Moussa cliff; (B) Fixed base station for differential correction

2.3 Data processing and terrain modelling

Resulting from the GPS-RTK field campaign, a high-fidelity DTM of the Sidi Moussa cliff and its low-lying area was produced within a GIS by processing the elevation points collected on this site (Fig. 3). The preliminary point cloud, made of more than 1,200 georeferenced measurements with centimetric-level vertical accuracy, was treated following a strict quality control protocol to ensure topographic integrity. Outlier detection visually combined the inspection in a 3-D environment with statistical filtering based on the deviation of the local neighborhood. This two-step approach effectively removed spurious points produced by transient signal noise, minor antenna shifts, or proximity to reflective cliff faces, while still preserving genuine micro-features such as erosion rills, shallow depressions, and cliff-edge irregularities documented during field reconnaissance. Ordinary Kriging [18] was chosen for surface interpolation because it efficiently considers spatial autocorrelation and also provides estimates of uncertainty associated with the interpolated values, which are important in modeling complicated, non-uniform terrain. A semi-variogram is fitted empirically to the cleaned dataset using a spherical model; the parameters are optimized through cross-validation to minimize prediction error. The idea of using a geostatistical technique instead of any other conventional deterministic techniques, like IDW or spline [19], was motivated by the irregular distribution of the points and the necessity of capturing minor elevation gradients that control overland flow. This DTM was interpolated, which made the centimetric-scale topographic variations explicitly representable. This ultra-high resolution is absolutely necessary for resolving fine morphological details-such as micro-scarps, surface roughness elements, and minor drainage pathways-that govern the initiation and direction of water flow during storm-driven overtopping events. Visual comparison with in-situ observations confirms that the model accurately reproduces the cliff's geomorphic complexity, including active erosional features and topographic heterogeneity. This centimetric DTM is the basis for all the other analyses that follow in this study, namely those concerning the identification of low-elevation pathways that are susceptible to marine flooding and the quantitative assessment of wave overtopping susceptibility under extreme hydrodynamic conditions.

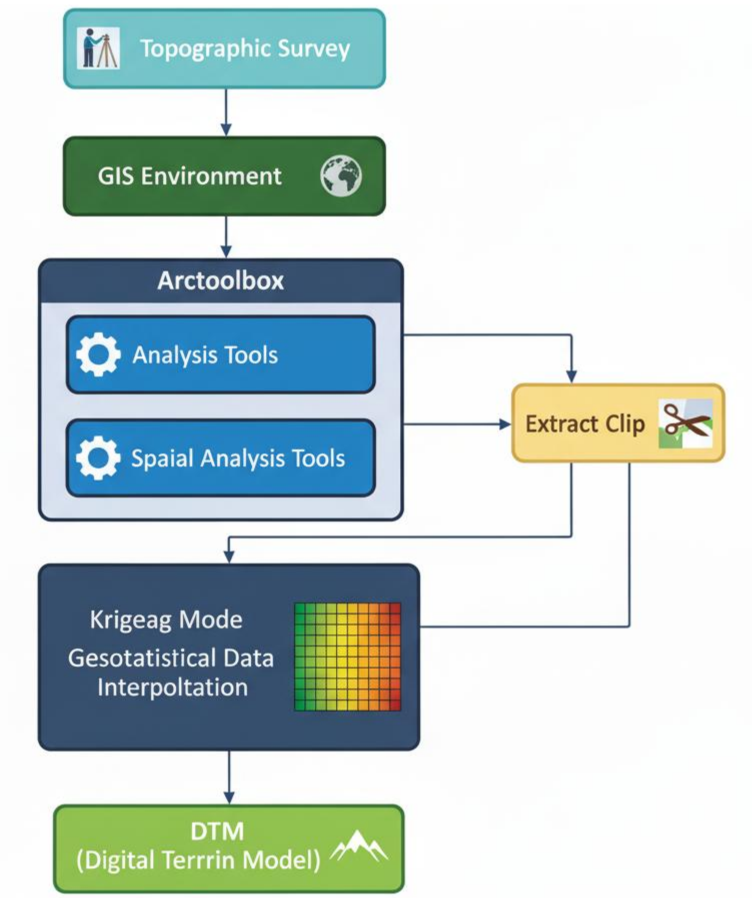

Fig. 3. Schematic workflow illustrating the methodology used for generating Digital Terrain Models (DTMs).

3 Results and discussion

High-resolution topographic surveys at the Sidi Moussa cliff on December 6, 2021, were utilized to understand the spatial patterns of erosion, deposition, and morphological variability across this dynamic coastal front. The centimetric-scale DTM, which was derived from GPS-RTK field measurements, uncovers fine-scale topographic features relevant for understanding local flood susceptibility that would otherwise remain entirely unresolved in coarser national or satellite-based elevation data.

Fig. 4. Spatial distribution of the 70 cross-shore beach profiles along El Jadida Beach.

Figure 5 DTM reveals that there is significant altitudinal variation around the study area, with the cliff top reaching altitudes of over 6.2 m above mean sea level, whereas a series of coves and embayment along the cliff edge dip down to as low as between 1.8 and 2.5 m. These natural concavities are not simply morphological curiosities but rather function as preferential conduits for storm-driven water ingress [15]. The most marked erosional embayment-located near the central sector of the cliff-exhibits the lowest elevation threshold (≈1.9 m) and demonstrates clear field evidence of frequent wave impact, including sediment scour, exposed bedrock, and displaced debris. This zone acts as the principal inlet for marine overtopping, allowing energetic waves to breach the cliff edge during high-energy events and propagate tens of meters inland [20]. This geomorphic vulnerability is compounded by intense anthropogenic occupation. Lying directly atop and adjacent to the cliff edge are a football stadium, recreational grounds, and the Sidi Moussa promenade, recently expanded and upgraded with pedestrian pathways, enhanced lighting, resurfaced roads, parking areas, landscaped green spaces, and modern sports facilities. While local tourism, social engagement, and economic activity have certainly been bolstered by these developments, their siting within meters of an actively eroding, low-elevation coastal margin dramatically raises exposure to marine hazards. Field observations and local testimonies confirm that large waves indeed preferentially enter through the lowest coves, particularly the central embayment, rapidly inundating the promenade and facilities during recent storm events. The DTM, in conjunction with land-use mapping, clearly illustrates a spatial coincidence of high geomorphic susceptibility and dense human infrastructure-one of the hallmarks of coastal risk hotspots. These findings emphasize a key implication for coastal management: natural topographic controls must be at the forefront of planning decisions. The presence of low-elevation erosional notches products of long-term wave undercutting and material heterogeneity creates inherently weak points in the coastal barrier. Neglecting such features for purely socio-economic development goals invites catastrophic damage during extreme events. Therefore, sustainable management of the Sidi Moussa cliff requires an integrated strategy that: (i) preserve the morpho-sedimentary integrity of the cliff face, particularly in zones of active erosion;(ii) limit new infrastructure in identified overtopping pathways; and (iii) include nature-based or hybrid protection measures, such as dune restoration or low-crested breakwaters that work with rather than against natural processes. The centimetric DTM herein presented provides the baseline that such evidence-based interventions require to precisely delineate flood-prone corridors and assist in adopting adaptive, resilient coastal policies for the Salé region.

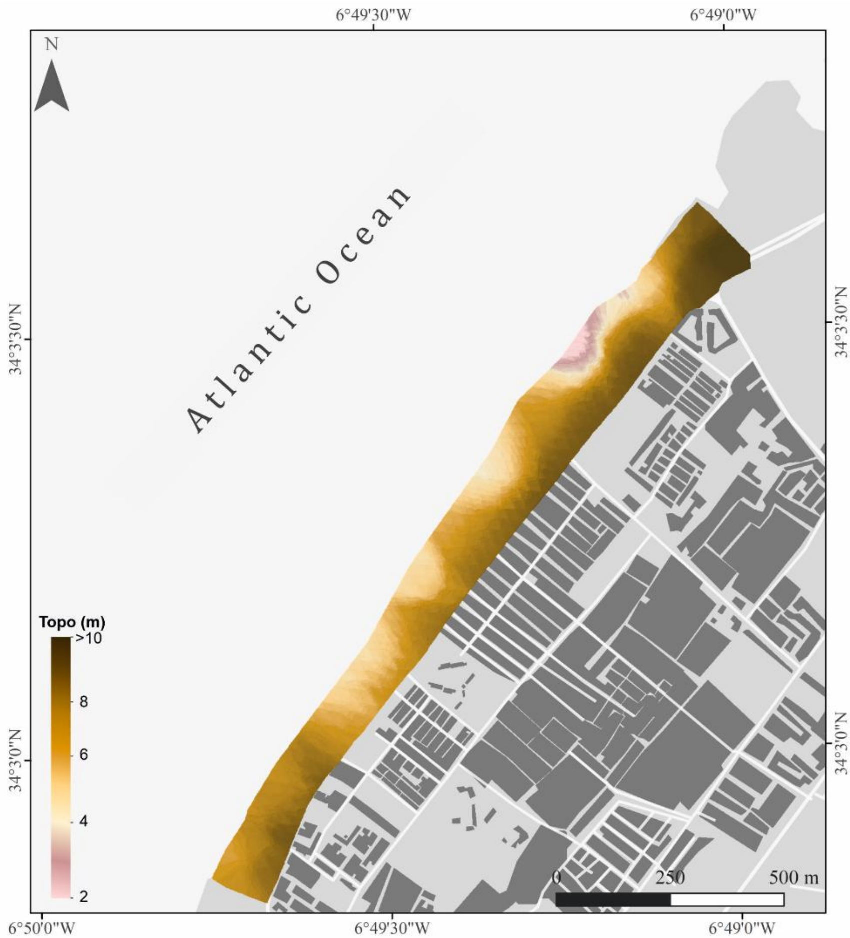

Fig. 5. Digital Terrain Model (DTM) of the Sidi Moussa cliff

4 Conclusion

This study underlines that centimetric-scale topographic data are essential for understanding coastal flood dynamics in morphologically complex settings, such as at the Sidi Moussa cliff.

A high-resolution DTM obtained with GPS-RTK surveys puts into evidence critical low-elevation pathways-especially one deeply incised central cove-that provide the main conduits during storm conditions for wave overtopping. These natural features, sculpted by ongoing erosion, substantially enhance flooding risk in an area already under pressure from dense recreational and touristic infrastructure. This close spatial coincidence of geomorphic vulnerability and human activity underlines a serious challenge for coastal management in Salé, where development has proceeded without adequate consideration to fine-scale physiographic constraints: with storm intensity and sea level continuing to rise, such mismatches are bound to lead to increasing damages and safety hazards. Our findings strongly argue for placing detailed topographic characterization at the center of coastal planning. The DTM presented herein not only clarifies the physical mechanisms behind observed inundation but also sets a reliable baseline for future monitoring, numerical modeling, and risk mitigation. Looking ahead, sustainable management will need to focus on preserving the cliff's natural morpho-sedimentary balance while deflecting development away from overtopping corridors that have been identified. It is in this way that geographically informed strategies are necessary to meaningfully advance resilience along Morocco's rapidly urbanizing Atlantic coast.

References

1. S. K. Haslett, *Coastal Systems: Second Edition* (Routledge Taylor & Francis Group, 2008)
2. M. Hakkou, M. Maanan, T. Belrhaba, K. El khalidi, D. El Ouai, and A. Benmohammadi, Ocean Coast. Manag. **163**, 232 (2018)
3. N. Mhammdi, F. Medina, Z. Belkhayat, R. El Aoula, M. A. Geawahri, and A. Chiguer, J. African Earth Sci. **163**, 103 (2020)
4. S. El Moussaoui, R. Omira, M. N. Zaghloul, H. El Talibi, and K. Aboumaria, Geoenvironmental Disasters **4**, (2017)
5. N. Erraji Chahid, M. Bouchkara, I. Joudar, A. Benazzouz, B. Zourarah, and K. EL Khalidi, J. African Earth Sci. **216**, (2024)
6. D. Chahid, L. Boudad, and O. Aicha, PALEO (2023)
7. M. Hakkou, Contribution A l'etude de La Dynamique Morphosedimentaire Du Littoral de Bouknadel-Kénitra, 2012
8. M. Snoussi, T. Ouchani, A. Khouakhi, and I. Niang-Diop, Geomorphology **107**, 32 (2009)
9. Z. Belkhayat, R. EL Aoula, and N. Mhammdi, Bull. l'Institut Sci. Rabat, Sect. Sci. La Terre **39**, 135 (2017)
10. H. F. Stockdon, D. M. Thompson, N. G. Plant, and J. W. Long, Coast. Eng. **92**, 1 (2014)
11. M. I. Vousdoukas, G. Pennucci, R. A. Holman, and D. C. Conley, J. Coast. Res. 1755 (2011)
12. M. D. Harley and M. A. Kinsela, Cont. Shelf Res. **245**, 104796 (2022)
13. Puertos del Estado,
14. J. C. Plaziat, M. Aberkan, and J. L. Reyss, Bull. La Soc. Geol. Fr. **177**, 323 (2006)
15. M. Aberkan, B. Cahuzac, and P. Carbonel, in *Bassin Sédimentaires Marocains* (Rabat, 1987), pp. 117–123
16. A. Chakroun, D. Chahid, L. Boudad, E. Campmas, A. Lenoble, R. Nespoulet, and M. A. El Hajraoui, African Archaeol. Rev. **34**, 493 (2017)
17. M. Perez-Ruiz, D. C. Slaughter, C. Gliever, and S. K. Upadhyaya, Biosyst. Eng. **111**, 64 (2012)

18. V. M. Merwade, D. R. Maidment, and J. A. Goff, J. Hydrol. **331**, 731 (2006)
19. I. M. Kiš, Rud. Geol. Naft. Zb. **31**, 41 (2016)
20. M. Aberkan, Etude Des Formations Quaternaires Des Marges Du Bassin Du Rharb (Maroc Nord-Occidental), université de Bordeaux 1, 1989