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Two Decades without the Mediterranean Monk Seal in the Al Hoceima Marine Protected Area: Habitat Suitability Assessment and Monitoring Insights

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ABSTRACT

The Mediterranean monk seal (Monachus monachus) is an endangered pinniped species historically distributed along the Moroccan Mediterranean coast. Despite confirmed historical presence in the Al Hoceima region, no sightings have been recorded for over two decades. Between 2024 and 2025, a coastal habitat monitoring campaign was conducted within the Al Hoceima Marine Protected Area (MPA) to assess the structural availability and oceanographic suitability of haul-out caves for potential monk seal recolonization. A total of 15 sea caves were surveyed along a 40 km segment of coastline, using geospatial mapping, geomorphological characterization, and swell exposure assessment. Caves were classified into three suitability categories based on morphological depth, elevation of resting platforms above tidal influence, exposure to prevailing hydrodynamic conditions, and degree of anthropogenic disturbance. Three caves (Category A) were identified as highly suitable, exhibiting deep, sheltered configurations with minimal swell penetration and structurally stable platforms above mean sea level. Eight infrared camera traps were deployed in selected high-potential caves to monitor biological and human activity. Although no monk seals were detected (~240 camera-days), the study confirmed the integrity of several

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key marine cavities and highlighted episodic human presence, including artisanal fishing and ecotourism. These findings provide a critical geospatial and structural baseline for marine habitat monitoring in the region and emphasize the relevance of integrating coastal morphology, marine dynamics, and spatial protection in future monitoring frameworks. The results support adaptive management strategies and inform oceanographic approaches to habitat restoration and species recovery in semi-enclosed Mediterranean systems.

Keywords: Coastal Morphology; Sea Cave Habitat; Al Hoceima Marine Protected Area; Monk Seal Monitoring

JEL Codes: Q57; Q56; Q51; Q22; Q01

1. Introduction

The Mediterranean monk seal (Monachus monachus) is one of the most endangered marine mammals worldwide, with fewer than 800 individuals remaining, divided into small, fragmented populations across the Eastern Mediterranean and Northeast Atlantic [1,2]. Historically present along the Moroccan Mediterranean coast, including the Al Hoceima region, the species has not been confirmed in the area since the early 2000s [3,4]. This decline is largely attributed to habitat loss, anthropogenic disturbance, overfishing, and coastal development.

The conservation of marine cave habitats is therefore vital to monk seal survival, as these environments provide essential functions such as pupping sites, resting areas, and refuge from human presence [5,6]. Their suitability is influenced not only by structural morphology (e.g., depth, elevation, and entrance width) but also by oceanographic factors such as swell exposure, current patterns, and sea level variation. These hydromorphological processes directly affect accessibility, disturbance risk, and long-term cave stability, which in turn determine the persistence of suitable habitat for M. monachus [7–9]. Studies from Greece and Madeira have shown that excessive swell exposure can reduce cave usability, while stable hydrodynamics and concealed entrances favor pupping and haul-out [10,11].

Situated within the Alboran Sea, the Al Hoceima Marine Protected Area (MPA) is embedded in a dynamic hydrodynamic regime shaped by Atlantic inflow, seasonal upwelling, and mesoscale circulation [12,13]. The steep, karstic coastline features fault-generated caves and submerged platforms subjected to variable wave energy, particularly from easterly (Levantine) winds [14]. Such conditions place Al Hoceima at the intersection of ecological opportunity and vulnerability: while the rugged morphology creates numerous potential habitats, fluctuating energy regimes may reduce long-term stability. This dynamic makes the site an important case study for testing how geomorphology and oceanography interact to constrain monk seal habitat.

From September 2024 to May 2025, a standardized monitoring program was undertaken by the AGIR Association within the Mediterranean Monk Seal Project (MED-MSP) to assess the structural and oceanographic potential of sea caves in the Al Hoceima MPA. This effort included geospatial mapping, morphodynamic classification, and camera-trap monitoring in collaboration with the Specially Protected Areas Regional Activity Centre (SPA/RAC). The goal was to identify high-potential habitats and guide future conservation actions under the Barcelona Convention's monk seal recovery strategy. More broadly, the findings contribute to understanding how coastal morphology and oceanographic processes shape marine megafauna resilience in semi-enclosed Mediterranean ecosystems.

Finally, the theoretical framework underpinning this research draws on Island Biogeography Theory and the concept of the Anthropogenic Allee Effect [15–17]. Island Biogeography provides a lens for evaluating how habitat isolation, size, and connectivity influence the persistence of small populations, while the Anthropogenic Allee Effect highlights how rarity itself can increase species vulnerability due to exploitation or disturbance. In the case of M. monachus, one expects a feedback loop where scarce, isolated habitats amplify demographic risk, while human disturbance in accessible sites exacerbates decline. Exploring this intersection helps explain why recovery has been so limited despite existing MPAs.

In this study, we therefore ask: (i) what structural and hydrodynamic cave features determine habitat suitability for M. monachus in Al Hoceima MPA? (ii) how does the interplay of biogeographical isolation and anthropogenic pressures shape habitat potential under current protection regimes? and (iii) what implications do these findings have for conservation strategies in Morocco and the wider Mediterranean?

2. Materials and Methods

2.1. Study Area

The Al Hoceima Marine Protected Area (MPA) is located on the northeastern coast of Morocco, within the Alboran Sea—a dynamic transitional zone between the Atlantic Ocean and the western Mediterranean. The area is influenced by complex oceanographic processes including the entry of Atlantic water through the Strait of Gibraltar, the formation of mesoscale eddies, and seasonal upwelling events that shape the physical and ecological characteristics of the region [7,9]. These hydrodynamic drivers strongly influence coastal temperature gradients, salinity fronts, and sediment transport mechanisms [10].

The surveyed coastal segment spans approximately 40 km and is characterized by steep karstic limestone cliffs, tectonic fault lines, narrow fjord-like inlets, and numerous semi-submerged sea caves. These features result from marine erosion and fault displacement, forming critical habitats that are intermittently connected to open sea dynamics [11]. The site's coastal geomorphology plays a central role in determining wave penetration, swell energy dissipation, and internal cave hydrodynamics, all of which are important factors in monk seal habitat selection [12].

The Al Hoceima coastline is subject to seasonal wind regimes, with prevailing Levantine (easterly) and Tramontane (northwesterly) winds generating variable swell conditions that influence cave accessibility, sediment accumulation, and haul-out safety for seals [13,14]. The presence of submarine canyons and abrupt bathymetric gradients further modulates local upwelling and circulation patterns, potentially enhancing prey availability near suitable resting sites [15]. The interplay between oceanographic variability and structural cave attributes provides a framework for evaluating habitat suitability for the endangered Monachus monachus in this semi-enclosed Mediterranean region [16].

2.2. Sea Cave Survey and Classification

Field surveys were conducted between November 2024 and March 2025 along the coastal perimeter of the Al Hoceima Marine Protected Area (MPA). A geospatial map of surveyed sites is presented in **Figure 1**, showing the scale and distribution of the 15 mapped caves along the 40 km coastal segment. This map provides essential context for site selection and subsequent classification. Survey efforts were limited to periods of low to moderate sea state, corresponding to swell heights ≤ 0.5 meters, in line with regional operational recommendations for safe cave entry and visual inspection [17].

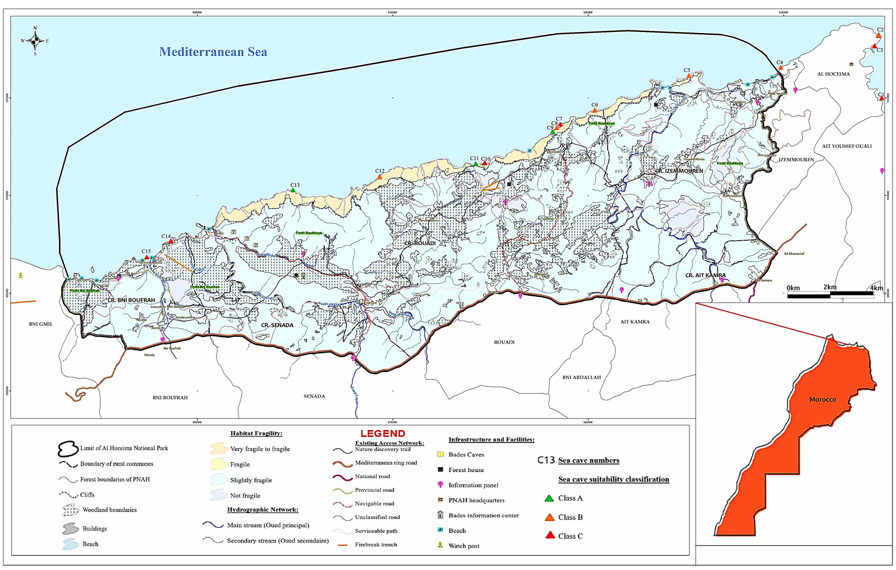

Figure 1. Location of Sea Caves Monitored in the Al Hoceima Marine Protected Area (MPA), Northeastern Morocco, with Classification of Habitat Suitability for Monachus monachus.

A total of 15 marine caves were georeferenced using a Garmin GPSMAP 78s handheld receiver, which provides a spatial accuracy of approximately ±3 meters under open-sky conditions. Coordinates were collected in EPSG:4326 format and stored in a geospatial database for further integration and visualization [18].

Figure 1 shows the distribution of 15 identified marine caves along a 40 km stretch of coastline within the Al Hoceima MPA. Caves are classified based on geomorphological and hydrodynamic suitability into three categories: high (green triangles), moderate (yellow), and low (red). The map also displays physical features, habitat fragility zones, hydrographic networks, and existing infrastructure within the protected area.

Each cave was approached cautiously by the survey team and visually assessed for its structural and ecological characteristics. Standardized descriptive metrics were used based on prior Mediterranean monk seal habitat assessment protocols [19,20], including:

- Cave depth and internal configuration, particularly the presence of deep recesses and chamber-like structures;
- Shelter from wave action and swell intrusion, noting orientation relative to dominant swell directions;
- Presence and elevation of dry resting platforms, ideally located above the mean high tide line to ensure suitable haul-out space;
- Signs of anthropogenic disturbance, such as litter, graffiti, rope remains, or human/animal footprints.

Photographic documentation was used to supplement field observations and enable consistent post-survey classification (**Figure 2**). No invasive sampling, habitat alteration, or artificial lighting was employed to minimize disturbance to any potential wildlife or ecosystem components. Based on cumulative morphological features and human accessibility, caves were classified into three categories of monk seal habitat suitability, consistent with prior regional and international assessments [21]:

- Category A—High Potential: Deep caves with structurally complex, sheltered interiors; presence of elevated dry zones; minimal signs of human visitation.
- Category B—Moderate Potential: Caves with partial exposure to swell or human routes, such as near artisanal fishing paths; generally suitable morphology but sporadically disturbed.
- Category C—Low Potential: Small or open caves easily accessible from the shore or sea; little physical protection or resting space for monk seals.

This classification provides a practical basis for prioritizing long-term monitoring and the strategic placement of remote surveillance devices (e.g., camera traps) in the most promising habitats.

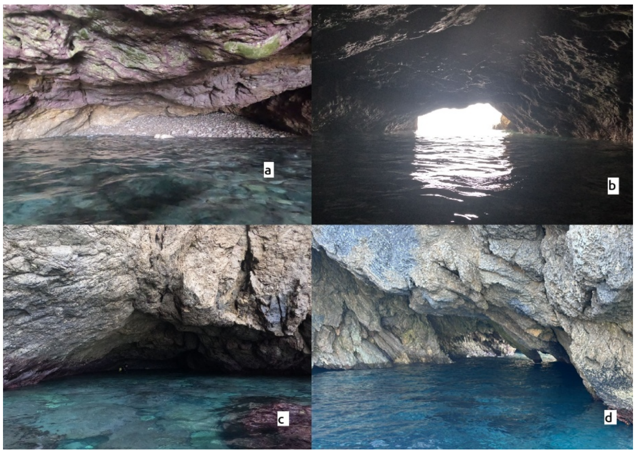

Figure 2. Photographic Views of Key Sea Caves Surveyed in the Al Hoceima Marine Protected Area (MPA). (**a**) C11—Grand Cave Tikkit: A deep Category A cave with elevated dry platform and minimal swell exposure, structurally optimal for monk seal haul-out; (**b**) C1—Cave Bateaux: A shallow Category C cave, easily accessible and frequently disturbed, offering low suitability; (**c**) C9—Taouassart Fault Cave: Another Category A site, characterized by vertical cliff walls, narrow entrance, and high internal stability; (**d**) C13—Kap Baba: A spacious, well-sheltered Category A cave located in a semi-enclosed coastal notch, exhibiting ideal geomorphology for recolonization potential.

Source: Souhail Karim (2024–2025 monitoring campaign).

2.3. Camera-Trap Deployment

To evaluate potential use of sea caves by marine fauna, particularly the Mediterranean monk seal (Monachus monachus), as well as to detect signs of anthropogenic disturbance, a total of eight infrared-triggered camera traps were deployed between February and June 2025 in selected caves classified as Category A and B. The devices used were Bushnell Trophy Cam HD units (20MP, low-glow infrared), chosen for their proven durability and performance in wildlife research under variable environmental conditions [22].

Camera placement prioritized elevated platforms within each cave, offering a stable field of view oriented toward the entrance or internal haul-out areas. Devices were mounted 1.0 to 1.5 meters above the cave floor to prevent interference from tidal inundation, splash zones, or sediment movement. Installation was supported by custom-designed stainless-steel brackets and corrosion-resistant anchoring systems, allowing secure attachment to uneven rock surfaces and enabling directional adjustment for optimal image capture (**Figure 3**).

Figure 3. Camera-Trap Equipment and Deployment Process in the Al Hoceima Marine Protected Area (MPA). (**a**) RECONYX infrared camera traps prepared for deployment, configured with motion-activated sensors and powered by lithium batteries to ensure prolonged operation in humid cave environments; (**b**) Custom-designed protective casing engineered to shield units from moisture, debris, and direct wave exposure inside sea caves; (**c**) Field testing of the stainless-steel mounting bracket system, allowing flexible orientation and secure anchoring of cameras to irregular rock surfaces; (**d**) Final installation of a camera trap inside a high-priority Category A cave, positioned on an elevated rock wall facing the internal haul-out platform to optimize monitoring coverage.

Initial test deployments using standard alkaline batteries revealed premature failure due to high humidity and salinity—conditions known to compromise battery lifespan in remote wildlife monitoring [23]. Subsequent deployments used high-performance lithium batteries (Energizer Ultimate Lithium®), which significantly improved operational endurance, supporting continuous function for over eight weeks per unit.

Each camera was programmed to operate continuously (24/7), using motion-activation protocols set to capture three-image bursts and 30-second high-definition video clips upon trigger. All images were geotagged with date and time metadata to facilitate spatiotemporal analysis.

The cumulative monitoring effort across all sites amounted to approximately 240 camera-days, a conservative but valuable baseline for species presence—absence surveys. Camera checks were conducted at 4 to 6 week intervals, synchronized with favorable marine weather conditions and GPS-guided cave access. Retrieved SD cards were reviewed manually, with frames analyzed for evidence of marine vertebrates (especially pinnipeds), human intrusions, light interference, and cave condition evolution.

This methodology, grounded in prior work on cryptic species monitoring and coastal cave ecology [24,25], provides a non-invasive and replicable foundation for expanding surveillance efforts in sensitive habitats.

2.4. Data Integration and Geospatial Analysis

Cave locations and classification categories were georeferenced and visualized using QGIS software (version 3.28), facilitating spatial analysis of their distribution along the Al Hoceima MPA coastline. Each site was overlaid on high-resolution coastline shapefiles and marine infrastructure layers to assess proximity to human-accessible zones such as ports, trails, and fishing routes. This allowed a first-order evaluation of potential human pressure gradients and accessibility risks.

To better understand the oceanographic setting of each cave, multi-source geospatial layers were integrated, including bathymetric contours (10–50 m) from the European Marine Observation and Data Network (EMODnet) and wave exposure indices derived from the Copernicus Marine Environment Monitoring Service (CMEMS) datasets. These included parameters such as significant wave height, mean wave direction, and current-induced turbulence at nearshore resolutions [26,27].

By combining morphometric cave data with coastal hydrodynamic exposure layers, we qualitatively assessed the vulnerability of each site to direct swell impact and turbulence. Caves classified in Category A generally corresponded with lower wave exposure zones and sheltered geomorphic niches, such as deeply incised coves or fault-fractured cliff systems. Conversely, Category C caves were often located in open, unprotected segments of coastline where persistent swell, cross-shore currents, and wind-driven surf would likely limit seal access and resting behavior.

This integrative GIS-oceanographic framework supports a more ecologically realistic evaluation of monk seal habitat suitability by explicitly accounting for both morphological integrity and physical oceanographic stressors, consistent with emerging approaches in habitat modeling for endangered marine mammals [28,29].

The methodological emphasis on cave morphology, isolation, and accessibility is grounded in the principles of Island Biogeography Theory, which predicts that habitat suitability for small, fragmented populations depends on spatial scale, connectivity, and edge exposure. Similarly, incorporating indicators of human disturbance into cave classification reflects the Anthropogenic Allee Effect, where rarity and accessibility of habitats increase human exploitation risk. This combined framework justifies the dual focus of our methods on both physical geomorphology and anthropogenic pressure gradients when evaluating recolonization potential for M. monachus.

2.5. Hydrodynamic Context and Exposure Assessment

To evaluate the hydrodynamic suitability of sea caves for Monachus monachus, exposure to marine forcing—particularly wave energy and swell orientation—was analyzed using regional oceanographic reanalysis datasets and corroborated by in situ visual assessments. The Al Hoceima coastline, situated in the dynamic western Alboran Sea, is influenced by the eastward inflow of Atlantic Surface Water (ASW) entering through the Strait of Gibraltar and subsequently modulated by local wind systems and complex bathymetric topography [30,31].

This regional hydrographic setting results in pronounced exposure gradients along the MPA, with north-facing segments generally more sheltered due to embayment and submerged ridges, while southeast-facing sectors remain exposed to direct swell energy and persistent wind forcing, particularly from the Levantine (ENE) and Tramontane (NW) directions [32].

Wave exposure analysis was conducted using multi-year averaged significant wave height (Hs) and mean wave direction data obtained from the Copernicus Marine Service (CMEMS) western Mediterranean reanalysis product (dataset ID: MEDSEA_MULTIYEAR_WAV_006_012) [33]. Seasonal storm patterns and wind fetch were further contextualized using ERA5 climate reanalysis outputs (European Centre for Medium-Range Weather Forecasts) and validated through systematic visual observations during field missions conducted between November 2024 and March 2025.

- Each cave site was qualitatively ranked into three hydrodynamic exposure classes—low, moderate, and high—based on the following integrated indicators:
- Entrance orientation relative to dominant swell directions (typically ENE–ESE vectors),
- Natural shielding provided by adjacent geomorphic structures such as headlands, islets, or submerged reefs,
- Observed wave energy transfer, characterized by internal surge, audible resonance, or submersion of haul-out platforms during mid to high tide.

This classification framework enabled the refinement of the cave suitability scoring system by coupling morphological adequacy (depth, elevation, substrate) with hydrodynamic refuge potential a key factor for monk seal haul-out behavior and pup survival [34].

Ultimately, the integration of exposure assessment with geomorphic evaluation supports the prioritization of sea caves that offer both physical shelter and oceanographic stability, thus enhancing their candidacy as viable recolonization sites under current and future marine conditions.

3. Results

3.1. Sea Cave Inventory and Classification

A total of 15 marine caves were identified and documented along the 40 km surveyed stretch of the Al Hoceima MPA coastline. Each cave was geolocated and classified according to physical suitability criteria for monk seal use (**Table 1**). Of these, three caves were classified as Category A—Kap Baba (C13), Taouassart Fault (C9), and Grand Cave Tikkit (C11), due to their geomorphological features, namely extended internal depth exceeding 20 meters, narrow and sheltered entrances that minimize swell exposure, and elevated dry platforms situated above high tide and storm surge levels.

Six additional caves met the conditions for Category B, exhibiting partial shelter and moderate potential but with some exposure to swell or signs of periodic disturbance. The remaining six caves were deemed Category C, showing limited depth, low platform elevation, or high accessibility, making them unsuitable for monk seal use.

Table 1. Georeferenced sea caves in the Al Hoceima MPA and classification categories. Coordinates are reported in decimal degrees (EPSG:4326).

Cave Name	Latitude	Longitude	Category
C2—Cave Port	35.255.002	−3.915.087	B
C13—Kap Baba	35.187.210	−4.246.867	A
C5—Lalla Mimouna	35.237.843	−4.022.842	B
C1—Cave Bateaux	35.225.489	−3.914.476	C
C4—El Moud	35.241.719	−3.971.160	B
C3—Piedra Merou Winery	35.251.269	−3.919.781	C
C6—Jabroun Tunnel	35.223.081	−4.075.867	B
C7—Cave Taouassart	35.217.199	−4.095.305	C
C8—West Taouassart Caves	35.216.636	−4.096.041	B
C9—Taouassart Fault	35.212.575	−4.100.041	A
C10—Nest Îlot Tikkit	35.199.346	−4.138.936	C
C11—Grand Cave Tikkit	35.198.780	−4.143.754	A
C12—Trakna	35.193.392	−4.198.117	B
C14—Cave Nid Bades W	35.164.549	−4.315.038	C
C15—Cave Sept Portes	35.157.363	−4.329.163	C

3.2. Camera-Trap Monitoring

A total of approximately 240 camera-days were recorded between February and June 2025, across eight cave sites classified as Category A or B. These deployments aimed to detect the presence of Monachus monachus, assess cave stability under marine conditions, and validate the performance of upgraded monitoring equipment.

Key observations include the following: no monk seal detections were recorded throughout the monitoring period, corroborating prior findings regarding the species' local extirpation from the Moroccan Mediterranean coastline since the early 2000s [1]. All Category A caves—notably Kap Baba (C13), Taouassart Fault (C9), and Grand Cave Tikkit (C11)—remained structurally intact and showed no signs of collapse, sediment infill, or excessive wave intrusion, suggesting their continued morphological suitability for potential recolonization [29]. Furthermore, the new lithium-powered camera units (Energizer Ultimate Lithium), deployed after the failure of earlier alkaline battery models, operated continuously for over 8 weeks without performance degradation, confirming their appropriateness for extended deployments in humid and salt-exposed cave environments.

Visual data review revealed relatively stable ambient conditions, characterized by moderate but consistent humidity, low natural light penetration typical of semi-submerged karstic caves, and no observable marine mammal activity. Importantly, the review also confirmed minimal interference from environmental noise such as fogging, splashes, or biofouling, indicating that the monitoring setup provided reliable, disturbance-free image capture.

While negative results preclude direct evidence of monk seal presence, the successful operation of the camera traps and the confirmed integrity of key habitats lay a critical foundation for long-term surveillance and eventual detection should recolonization occur. Continued monitoring, coupled with local awareness-raising and disturbance mitigation, is recommended as part of a precautionary conservation strategy.

3.3. Human Activity and Disturbance

Over the course of the 2025 monitoring period, seventeen independent human activity events were recorded across four sea caves, primarily during spring weekends and regional holidays, when maritime traffic and coastal recreation tend to peak.

Documented activities included artisanal fishing (often involving net or line deployment near cave entrances), recreational visitation by kayaking and snorkeling groups (particularly around accessible Category C caves), and accumulation of anthropogenic litter such as plastic debris, nylon ropes, beverage containers, and food wrappers, indicating occasional landing or nearby vessel presence. In two Category C caves (Cave Bateaux and Cave Nid Bades W), graffiti marks and minor wall chipping were also detected, suggesting unsanctioned human use of these sites without attributing them specifically to tourism.

Graffiti marks and minor wall chipping were detected within two Category C caves (Cave Bateaux and Cave Nid Bades W), possibly linked to unsanctioned tourist activity.

While no direct intrusion was documented within the internal chambers of Category A caves, motion-activated camera traps and observer notes confirmed external human presence near the entrances of Kap Baba (C13) and Grand Cave Tikkit (C11). These events occurred predominantly during periods of calm sea state, which facilitates boat access and recreational approaches.

These findings underscore the latent vulnerability of even remote or structurally protected habitats to episodic human disturbance, a factor that may compromise the site's suitability for monk seal recolonization if not adequately regulated. This supports the need for seasonal zoning, awareness signage, and community engagement strategies as part of marine spatial planning in the Al Hoceima MPA.

4. Discussion

4.1. Continued Absence of *Monachus monachus*

Despite the systematic deployment of high-resolution, motion-triggered camera traps across eight priority caves in the Al Hoceima Marine Protected Area (MPA), no detections of Mediterranean monk seals *Monachus monachus* were recorded during the 2025 monitoring period. This absence of visual confirmation, across approximately 240 cumulative camera-days, substantiates previous reports indicating the species' regional extirpation along the Moroccan Mediterranean coast [1–3].

Earlier studies by Mo et al. [1] documented the last confirmed sightings in the early 2000s, after which both direct observations and indirect evidence (e.g., tracks, scats) have ceased entirely. The 2025 campaign, despite integrating enhanced methodology, multi-site deployment, and extended camera endurance via lithium battery upgrades, yielded no biological indicators of monk seal presence, either in photographic or video format.

This continued absence across multiple seasons and methodological approaches suggests that natural recolonization is unlikely in the short term, even in structurally favorable habitats. Consequently, conservation strategy in the Al Hoceima MPA must prioritize proactive habitat readiness, human pressure mitigation, and capacity-building for rapid response, should recolonization occur via dispersal from extant populations in Algeria or Madeira [3,4].

4.2. Persistence of Structurally Suitable Habitats

Notably, three Category A sea caves—Kap Baba, Taouassart Fault, and Grand Cave Tikkit—exhibited optimal morphological characteristics closely aligned with the known haul-out and pupping requirements of Monachus monachus, including deep internal chambers that provide thermal and acoustic refuge, narrow recessed entrances that reduce human and swell intrusion, and elevated dry platforms that ensure protection from wave action and storm surge inundation [5–7].

The karstic and fault-controlled morphology of the Al Hoceima coastline—shaped by tectonic uplift, marine erosion, and localized sediment dynamics—has resulted in the formation and maintenance of such specialized geomorphic features [5]. Despite moderate levels of surrounding anthropogenic activity, the continued structural integrity of these caves affirms their resilience to physical degradation, a crucial factor in the long-term viability of potential recolonization zones. This aligns with habitat-based conservation approaches, which advocate for the protection of suitable, unoccupied habitats to facilitate the species' natural return when ecological or demographic conditions improve [6].

4.3. Influence of Human Activity

Although direct human intrusion into the core sections of Category A caves was not observed during the 2025 monitoring campaign, proximal anthropogenic activity was consistently recorded. This included artisanal fishing, small-scale ecotourism, kayaking excursions, and snorkeling groups, particularly during fair-weather periods in spring and early summer.

Such activity may exert indirect disturbance through vessel noise, visual disruption, and surface-level litter, which can function as behavioral deterrents for shy pinniped species such as the monk seal [7]. These findings correspond with previous microplastic surveys in the MPA that revealed elevated concentrations of surface and subsurface particles, particularly near urbanized or recreational access points [8]. While no critical degradation of internal cave morphology was observed, the cumulative impact of intermittent human pressure may reduce the probability of recolonization, especially in the absence of regulatory enforcement or buffer zone implementation.

4.4. Methodological Contributions to Oceanographic Monitoring

This study contributes to integrated marine habitat surveillance by combining geomorphological cave classification, GPS-based geospatial mapping, and automated camera-trap deployment in a hydrodynamically active coastal zone. The use of lithium-powered infrared camera traps ensured extended operational capacity under the humid, salt-rich microclimate of semi-submerged sea caves.

Logistical challenges encountered—such as battery failure in early deployments, mounting limitations on irregular substrates, and exposure to wave splash zones—were systematically addressed, producing a replicable field protocol suitable for application in other monk seal range countries. These lessons support the refinement of habitat monitoring strategies in complex Mediterranean topographies, where access, visibility, and durability present recurring technical constraints [9].

4.5. Implications for MPA Management and Conservation Strategy

From a marine spatial planning (MSP) perspective, the identification of structurally intact yet ecologically vulnerable caves suggests a series of actionable management recommendations:

- Enforce seasonal access restrictions or complete closures for Category A caves, especially during potential breeding windows.
- Integrate cave classification layers and wave exposure indices into the MPA's existing GIS zoning framework.
- Implement targeted awareness campaigns for local fishers and ecotourism operators, emphasizing the sensitivity and ecological role of candidate monk seal habitats.
- Coordinate with regional governance bodies, including RAC/SPA, MedPAN, and national park authorities, to develop long-term recolonization feasibility assessments, including the possibility of assisted return or transboundary conservation corridors.

These interventions are aligned with ecosystem-based management (EBM) principles and advance the Al Hoceima MPA's readiness for species return scenarios, while also contributing to the broader Mediterranean network of marine protected refugia [10].

4.6. Influence of Coastal Hydrodynamics on Habitat Availability

The availability and persistence of monk seal-suitable habitats in the Al Hoceima MPA are tightly modulated by local and regional hydrodynamic regimes. The coastline sits within the western Alboran Sea, a transitional zone influenced by the eastward advection of Atlantic Surface Water, semi-enclosed bathymetric features, and seasonally shifting wind patterns, including Levantine and Tramontane systems [11].

The three Category A caves are notably situated within cliff-shadowed or semi-enclosed embayments, minimizing fetch and significantly reducing swell intrusion. By contrast, most Category C caves are oriented eastward or southeastward, making them directly vulnerable to storm-driven wave impacts during the winter season. This hydrodynamic segmentation, shaped by bathymetric refraction and wave shoaling, determines not only physical platform stability but also the consistency of dry surface conditions, a prerequisite for pup-rearing success in M. monachus [12,13].

Future studies should include numerical wave modeling, long-term acoustic disturbance monitoring, and the integration of hydrodynamic parameters into habitat classification frameworks to improve predictive accuracy and resilience-based zoning in the MPA.

The interpretation of these findings can also be framed through Island Biogeography Theory and the Anthropogenic Allee Effect. From a biogeographical perspective, the isolation and small number of suitable caves (Category A) reduce the probability of natural recolonization, as limited habitat patches support fewer individuals and are more vulnerable to stochastic loss. At the same time, the Anthropogenic Allee Effect suggests that the rarity and accessibility of these caves can paradoxically increase human disturbance, since scarce and easily reachable habitats tend to attract exploitation and visitation. Together, these frameworks highlight a dual causality: physical isolation decreases recolonization potential, while human activity amplifies extinction risk, reinforcing the urgency of proactive conservation in the Al Hoceima MPA.

5. Conclusions

This study presents the first integrated oceanographic and geomorphological assessment of sea cave suitability for *Monachus monachus* within the Al Hoceima Marine Protected Area (MPA), combining GPS-based coastal mapping, morphodynamic cave classification, wave exposure analysis, and automated camera-trap surveillance. Despite the deployment of high-resolution motion-triggered cameras and extensive field surveys across 15 coastal caves, no monk seal presence was detected, corroborating earlier evidence of the species' local extirpation.

Nonetheless, three Category A caves—Kap Baba, Taouassart Fault, and Grand Cave Tikkit—were identified as structurally and hydrodynamically suitable for recolonization, featuring optimal physical conditions such as deep cavities, low-exposure entrances, and elevated dry platforms. These features closely match the known haul-out and pupping requirements of the species, situating the results within the wider literature on monk seal ecology [26].

These findings underscore the importance of protecting potential habitat refugia, even in the absence of current species presence, in accordance with precautionary conservation strategies. Human activity near high-priority sites, although indirect, poses a latent risk to habitat integrity and must be managed through zoning, enforcement, and awareness-raising. Furthermore, the strong influence of regional hydrodynamic regimes—particularly wave energy gradients driven by Atlantic inflow and local wind fetch—was shown to critically shape habitat viability [1,22].

Interpreting these results through the lens of Island Biogeography Theory and the Anthropogenic Allee Effect highlights a dual vulnerability: the isolation and scarcity of suitable caves lower recolonization probability, while their accessibility increases disturbance pressure. This feedback underscores the need for proactive protection of rare but structurally optimal habitats to reduce extinction risk and enhance long-term recolonization potential [34].

The methods and monitoring protocols developed in this study offer a replicable framework for monk seal conservation across other parts of the species' range, especially in similarly dynamic and topographically complex coastal regions. Future management of the Al Hoceima MPA should integrate geomorphological and hydrodynamic data into its spatial planning tools, ensuring long-term readiness for potential natural recolonization or assisted return initiatives.

Author Contributions

Conceptualization: S.K., H.B.; Methodology: S.K.; Field Investigation: S.K., H.B.; Camera Deployment and Equipment Setup: S.K.; Data Curation: H.B.; GIS and Geolocation: S.K.; Visualization: H.B., S.K.; Writing—Original Draft Preparation: S.K., Writing—Review and Editing: H.B., S.K., H.C.D.; Supervision: H.C.D. All authors have read and approved the final version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the findings of this study are not publicly available due to privacy and ethical restrictions. Data may be obtained from the corresponding author upon reasonable request and with permission from the relevant authorities.

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Conflicts of Interest

The authors declare no conflict of interest.

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