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Shifting Sands: Navigating Coastal Erosion through Ingenuity & Planning in the UAE

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Abstract

Coastal zones across the world are continuously changing as a result of constant action from waves, currents, etc., combined with human intervention and development activities. While in the recent decades, climate change has added an acceleration to these changes and made the challenge more complicated than a few decades earlier. The coastline of the United Arab Emirates (UAE) is currently facing serious erosion, and not much different in this scenario. Natural drivers are reshaping the shore, combined with sea- level rise along with man-made factors of large-scale land reclamations and costal infrastructure development which are a considerable influence on the coastal hydrodynamics. This paper reviews the main erosion problems and their hydrogeological impacts, including a discussing saltwater intrusion into coastal aquifers caused by intensive groundwater extraction. The study also details the emerging middle eastern powerhouse's comprehensive mitigation strategies, integrating traditional hard engineering like seawalls, with innovative engineering like Ecoplage, beach nourishment, etc., as well as improvising on nature-based solutions like mangroves / coral restoration. Finally, the paper also highlights water-resource management techniques and measures, which are being implemented by the nation with the available resources including dams and desalination projects, to preserve the fragile coastal ecosystems, aquifer health and thereby ensure long-term coastal resilience. These coastal zone management approaches aligned with the local environment, show that the UAE is trying to integrate infrastructure growth with coastal environment, aiming to balance development and the stability of shoreline, and ensuring the local ecosystems, natural habitats and future generations remain safeguarded as top priority.

Keywords: aquifer recharge, beach nourishment, beach replenishment, coastal infrastructure, coastal erosion, reclamation, saltwater intrusion, water resource management.

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1. Introduction

Coastline all over the world have historically been one of the most dynamic interface markers. This is constantly felt on everyday basis in the fast-paced development scenario of today's United Arab Emirates, whose shoreline displays extraordinarily dynamic features, constantly evolving under the dual pressures of nature's relentless push and humanity's steady and focused development drive. This brief stuyd focuses on the highly valuable shoreline of UAE, which is crucial for many sectors of the nation like tourism, economy, infrastructure. Most importantly, this study is also required since the focus is on a belt of the country, where most of its population actually lives and thrives. It's a highly critical zone, but under significant threat from ongoing erosion induced due to multiple factors. While the sea has always shaped the land since time immemorial, the fast-paced transformation of the coast, in the form of building incredible artificial islands and bustling ports, does introduce an additional influence on the natural flow of things[1]Eric Blair. This has significantly accelerated the erosion rate in certain vulnerable spots, especially in places like Umm Al Quwain and Ras Al Khaimah [2] P. Subraelu, et. al. However, due credit must also be given to the top administration in the UAE for the way they are fighting back this challenge. Coastal Zone Management authorities in UAE have put together an integrated management strategy [3]E. Lamine, et. al., mixing old-school hard engineering with smarter, softer solutions, and at times, implementing some traditional nature-based fixes which are more environmentally friendly too.

The primary aim of the present brief study is to examine these challenges and the UAE's comprehensive mitigation strategies. This involves integrating traditional hard engineering structures like seawalls, etc., with innovative engineering approaches like Ecoplage, beach nourishment, and blending this with nature-based solutions like mangrove / coral restoration, to preserve coastal ecosystems, and ensure the resilience and sustenance of the vulnerable coastline of this country in the long run. The study also touches upon smart water resource management undertaken by the UAE in the form of building dams, desalination projects, etc., to ensure aquifer depletion is arrested.

2. What's Causing the Coastline to Disappear?

The deterioration of the coastline, as it is seen worldwide, has been a mix of man's own making and some of the natural forces which we humans can't fully control. Protection of the coast is directly linked to protection of major economic indicators like trade, tourism and urban planning, since a majority of the world's population lives and depends on the coast for their livelihoods, well-being and recreation, and hence is a vital key to securing the future of our world, as well as sustainable development.

2.1. The Human Touch – Key Anthropogenic Factors

- Massive Land Reclamation: Large scale coastal reclamation projects like the Palm Jumeirah set of islands which involved extensive dredging and construction [4]Al Marwan, did indeed alter wave patterns while also disrupting longshore drift as part of the hydrological and coastal coastal hydrodynamic cycle. In simple terms, building such structures often results in starving a beach just down the way of the drift or wave patterns, depriving it of sand, thereby accelerating erosion at places, which would have been otherwise fed sediments and material by the longshore drift pattern.

- Ports and Infrastructure: Building big ports and their associated breakwaters disrupts local water flow. This induces the wave energy to focus and funnel on unprotected areas nearby, increasing the rate of their erosion or washing away.

2.2. Nature's Role

- Waves and Currents: The sea is always moving sand around. The "shamal" winds, commonly observed in this region during specific months of the winter season [5] Y. Alsubhi, et, al., bring higher wave energy and are capable of significantly intensifying the erosion process.

- Climate Change Reality: Being a low-lying nation, the UAE remains one of the countries which is right at the frontline for climate change impacts, including challenges related to rising sea levels and storm surges. Surprisingly, and with sheer determination and grit, the solutions studied and implemented so far by this nation have been quite effective, as enumerated in the succeeding paragraphs.

3. How the UAE is Pushing Back

The strategies being employed in the UAE by the administrative authorities do not constitute a single magic bullet, but are a blend, primarily of hard and soft engineering approaches.

3.1. *Heavy-Duty (Hard) Engineering Approach*

Heavy duty or hard engineering solutions are mostly seen across the coastline of the UAE in the form of fixed structures, such as concrete and rock enforced defense mechanisms built to withstand the harsh impacts directly under the influence of the elements associated with the sea.

- Seawalls: One can see these defensive walls parallel to the coast at many places along the coast. These are basically walls built to absorb or negate wave energy acting on the beach and eroding it by washing away sediments from the coast constantly.

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- Groynes: Groynes are quite similar to seawalls but mostly built perpendicular to the coast, or at an angle. These are barriers sticking out into the water to trap sand, and help in cutting down the coastal stretch into sections so vulnerable portions can be dealt in a focused manner. They do their function effectively and serve the location where they are built. However, sometimes they do end up passing the erosion problem onto the next beach over.

3.2. *Soft (& Smarter) Engineering Approach*

These methods are more in tune with nature and tend to be less invasive as well as more effective and efficient in the long run.

Each location is treated independently and individually, and no single solution is implemented across the board for all locations.

3.2.1. *Beach Nourishment: The Continuous Refill*

- Explanation: This is probably the most common fix in the region. It involves physically pumping or trucking sand in massive quantities, often sourced from offshore dredging, to widen and strengthen the gradients of eroded beaches or those facing a threat of erosion. This newly infused sand creates a wider, healthier beach that acts as a sacrificial buffer, absorbing wave energy and protecting the coastal stretch.

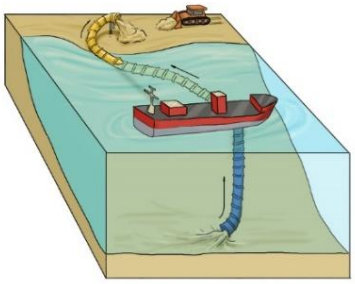


Figure 1: Beach Nourishment (Image Source: Beach Nourishment – Geography - Mammoth Memory Geography)

- Case Study Example: The Dubai Municipality regularly conducts major nourishment drives along Jumeirah and Al Mamzar beaches [6]Gulf News Report. This maintenance is essential to offset the continuous disruption to the natural cycles caused by ongoing coastal developments nearby as well as offshore.



Figure 2: Example of a Beach Stretch in Fujairah, UAE Post Beach Replenishment.

3.2.2. *Ecoplage System: Drying the Defense*

Mechanism: The simple effectiveness of the idea behind the Ecoplage is to drain the run-off from the beach out quickly. When a wave hits dry sand, the water soaks into the ground instead of powerfully running back out in the form of backwash, taking a good amount of sand with it. This loss of energy means the wave drops its suspended sediment instead of carrying the existing sand away.



Figure 3: 950-m long Ecoplage system, installed at Jumeirah beach, Dubai (Image Source : ECOPLAGE in Dubai - Ocean & Climate Platform ECOPLAGE in Dubai - Ocean & Climate Platform Jumeirah, 2011)

- Explanation: At Madinat Jumeirah, where rapid erosion was a huge issue, an innovative hybrid solution was installed in the form of a subsurface beach drainage system [7]Nadeem Hanif. A network of perforated pipes buried beneath the sand (around 1.5m deep) continuously helps in lowering the water table at the beach face.
- Results: The system stabilized the beach, proving that sometimes working in tandem with the topogarphy and the physics of the beach is more effective than just building a wall or such other hard engineering solutions, which need to be assessed on a case by case basis.

3.2.3. *Submerged Breakwaters: Reducing the Incident Wave Energy*

- Mechanism: Submerged breakwaters primarily target to reduce the incident wave energy hitting the coasts to protect them against erosion and also help in reducing the port channels from siltation / sand deposits, thereby reducing maintenance dredging costs. They can also be designed to alter the sediment transportation pattern and trap the suspended sediment being transported by the wave actions for the purpose of beach nourishment / restoration. This loss of energy means a significantly reduced impact on the existing coastal sediment deposited on the beach.

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Figure 4: Submerged Breakwaters (Image Source: ACE Geosynthetics | Nigeria)

• Explanation: These structures are often combined with other coastal defense mechanisms like beach nourishment to effectively protect the coastal stretches. They can be constructed as single breakwaters, a series of segmented breakwaters, or continuously, as per the targeted location requirements. Effective performance of such submerged breakwaters particularly depends on the breakwater's geometrical / structural characteristics, location of the breakwater including water depth at the toe and distance from the coastline, interaction pattern between the waves and the submerged breakwater, sediment transport dynamics and other local topographical and hydrodynamic factors. Palm Jumeirah project in Dubai involves combination of emerged, low-crested and submerged breakwaters [8]Ankit Singh.

• Results: The system helped in stabilizing the beach, proving once again that working with the natural aspects including the topography and physics of the beach is better than just building a wall.

3.2.4 Geosynthetic Containers



Figure 5: Geosynthetic Sand Containers (Image source: Geosynthetic Sand Containers | Global Synthetics)

Geosynthetics and Geotextiles primarily involving giant, tough, sand-filled bags and tubes, which are a smart, adaptable alternative to plain old rock walls. Such mechanisms have been used in key spots like Saadiyat Island in Abu Dhabi, Palm Jumeirah in Dubai, Al Aqah beach in Fujairah [9] L.Jackson, and many more projects across the UAE effectively in fighting the beach and coastal erosion processes.

3.3 Working with Nature: Coastal Ecosystems Replacement / Replenishment

In an even more nature resembling manner, the UAE have successfully carried out large coastal ecosystems replacement projects like large scale Mangroves plantation and Coral Reef Restoration and replacement at a number of locations across the country, primarily by getting major construction companies to balance their 'development' impacts on nature through mega ecological restoration drives and projects.

4. Hydrogeological Impacts and Mitigation

Coastal development and erosion significantly affect a very important aspect of the unseen world beneath the sand, viz. the groundwater system, which sustains both humans and the rest of the living beings in this region. These systems, while also stabilizing the beach and reducing the erosion impacts, also end up proving that sometimes working with the elements of nature, could be the best solution to our modern-day conservation concerns.

4.1. The Impact: Saltwater Intrusion

One of the primary hydrogeological issues of extensive groundwater tapping, coupled with coastal constructions is saltwater intrusion, where the sea infiltrates coastal aquifers.

• Over-extraction: The UAE has historically relied heavily on groundwater, especially for agriculture. The rate of abstraction is much higher than the natural recharge rate from scarce rainfall, which lowers the inland water table [10] R. McDonnell, S. Fragaszy.

• The Mechanism: As the fresh groundwater level drops, it reduces the natural pressure that keeps the denser seawater wedge at bay. This allows the saline water to move further inland, contaminating wells and making the water unsuitable for drinking or farming.

• Land Use Changes: Urbanization creates impermeable surfaces (concrete, roads) that hinder natural rainwater infiltration [11] W. Shon, et. al. further reducing aquifer recharge. Moreover, older infrastructure.

4.2. How the UAE is Fighting It: Smart Water Management.

The battle against aquifer depletion, especially in the UAE here, is less about physical walls and more about integrated water resource management.

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- Artificial Recharge Projects: A key strategy involves actively storing excess water underground during rare rainfall events. This helps replenish aquifers, raises groundwater levels to push back against saltwater, and secures reserves for dry periods (Aquifer Storage and Recovery - ASR). Quite a few dams have been constructed across the UAE in recent decades towards this mission, especially in areas receiving higher rates of rainfall, in comparison to rest of the desert landscape.

- Wastewater Recycling and Desalination: Given the nature of its water resource distribution and availability, the UAE is a global leader in desalination and uses advanced treatment techniques for wastewater (with 75% often used for urban landscaping), which drastically reduces the pressure on natural groundwater aquifers [12] K. Ballaith.
- Targeted Abstraction: In some specific cases, like in the Wadi Ham aquifer, modeling studies have shown that strategically pumping brackish water from the intrusion zone can help manage the interface and thereby assist in improving the overall water quality in the aquifer.

- Policy and Monitoring: Strict regulations on groundwater extraction and advanced monitoring systems using GIS and remote sensing, in implementing of monitoring and mapping coastal water bodies as well as monitoring water quality, flood risks, water storage and urban water network, which further help the government manage this scarce and important resource more effectively and prevent further depletion and contamination.

4.3. UAE's Application of GIS and Remote Sensing to Temporal Shoreline Analysis, Deterioration Monitoring, and Mitigation Planning.

4.3.1 Role of GIS and Remote Sensing in Observing the Costal Dynamics.

Geographic Information Systems (GIS) and remote sensing now form the basis of evidence based management decision making and coastal engineering by furnishing continuous datasets which are consistent, and include multiple temporal observations of shoreline position and nearshore morphology. Archives from multiple sensor sources in the form of optical satellites, SAR, aerial photography, LiDaR, and historical time series cartography, enable reconstruction of shoreline trajectories across decades, as well as incorporate seasonal timeframes, mapping the change patterns and helping in overcoming the spatial selectivity and logistical constraints of ad-hoc in situ surveys [13] Boak & Turner, 2005, [14]Hapke et al., 2016.

Within a GIS, these observations can be referenced to a common datum, screened quality w.r.t tidal stages and wave pattern effects, and also segmented along the shoreline to support reproducible metrics of shoreline evolution and change. These outputs could be in the form of standard metrics such as end point rate (EPR), linear regression rate (LRR), and shoreline change envelope (SCE) [14] Crowell et al., 1997, [15]Thieler et al., 2009. Besides, such advantages of multi-temporal analysis are also valuable because coastal evolution reflects not only natural drivers like waves, tides,and sediment transport, but also intense anthropogenic modification, such as the rapid urbanization which has been witnessed so far and also being foreseen in the future near the shoreline.

4.3.2 Detection of Coastal Deterioration Pathways Through Synoptic Monitoring

GIS and Remote sensing, through the various temporal variation analyses and metrics, provides the synoptic continuity required to detect deterioration pathways, indicating the coastal aspects like progressive erosion, beach narrowing, foredune scarping, inlet migration, and hard structure flanking, etc. specific to the site and also indicate patterns resembling the generic to regional scales, when appropriate combined with spatial analysis techniques. Advances in medium to high resolution imagery (e.g., Landsat, Sentinel 2, and other commercial constellations) and cloud based analytics have improved both temporal cadence and spatial fidelity, enabling seasonal attribution of observed shifts to storm clusters, sediment supply disruptions, or anthropogenic works [16]Luijendijk et al.,2018, [17]Vos et al., 2019. When fused with LiDaR derived digital elevation models, shoreline planform change can be paired with volumetric estimates of beach and dune capital, enhancing links to design relevant exceedance metrics [18]Saye et al., 2005, [19]Harley et al., 2011. It is pertinent to highlight that the UAE's studies have employed nearly 50 years of satellite imegery from a variety of sources including LandSat to analyze land-water boundaries and their interaction, as well as change patterns, to compare on a national scale, and arrive at meaningful and useful analyses to implement the most effective solutions. [20] Ali Khalil, M

Once again it is reiterated that the UAE has treated each location as a stand-alone entity and does not necessarily employ the same solution all across the nation, but the management solutions are tailor made to suit each location, catering to the local challenges, specific to that local coastal stretch.

4.3.3 Linking Shoreline Changes to Climate Drivers and Nearshore Hazards.

4.3.3.1 Sea Level Rise Scenario Evaluation.

Spatio-temporal evidence base is critical for climate informed risk appraisal. GIS facilitates integration of shoreline trends with sea level rise (SLR) projections, extreme water

level statistics, wave climate reanalyses, and exposure layers like population, critical infrastructure, habitats and ecosystems, etc. allowing translation from geomorphic change to consequence for assets and services [21]IPCC, 2022, [22]Nicholls et al., 2007). Scenario ensembles (e.g., SSP / SLR pathways) can be propagated through empirical shoreline models to bracket plausible futures and identify adaptation tipping points where extant defenses or nourishment regimes cease to meet performance targets [23]Ranasinghe, 2020, [24] Vousdoukas et al., 2020.

4.3.4 Spatial / Temporal Decision Support for Mitigation

For mitigation planning, GIS serves as the basis / platform for management decision making, using which, alternatives are screened, assessed as well as optimized. Soft engineering measures like nourishment, dune restoration, cobble berms, living shorelines, etc. can be spatially targeted at erosion "hotspots" derived from rate statistics and storm response footprints, with collateral benefits to habitats and carbon capture accounted via ecosystem layers [25] Bilkovic et al., 2016. Where hard structures are unavoidable, remote sensing time series datasets help diagnose downdrift impacts and form the input to design refinements like crest elevation, toe protection, permeability, etc., to reduce adverse sediment gradients [26]Dean & Dalrymple, 2002. Iterative monitoring closes the loop when post implementation imagery and surveys feed back into the GIS, updating performance indicators and enabling adaptive management cycles consistent with climate resilient pathways [27]Barnard et al., 2015, [21]IPCC, 2022).

4.3.5 Methodological Standards.

Methodologically, good practice includes (i) tidal normalization or selection of consistent tidal windows; (ii) wave runup screening, especially on reflective or armored shores; (iii) sensor fusion with uncertainty propagation; and (iv) use of standardized tools (e.g., DSAS) to ensure comparability across study epochs [15] Thieler et al., 2009, [28]Moore, 2006.

4.3.6 Integration of Monitoring Feedbacks and Coastal Management.

Together, these steps elevate shoreline analysis from descriptive mapping to decision grade intelligence, aligning engineering design with environmental stewardship and the escalating constraints of SLR and extremes. In short, the pairing of remote sensing and GIS provides not just a clearer view of how coasts are changing, but a disciplined framework for acting—earlier, more precisely, and with measures proportionate to risk.

5. Conclusion

The UAE's fight against beach erosion and its related hydrogeological challenges is a dynamic process involving sophisticated monitoring and the application of diverse engineering and nature-based solutions. The movement towards integrated, hybrid approaches, exemplified by the successful techniques like the Ecoplage system, large-scale mangrove and coral restoration projects, and advanced water resource management strategies demonstrates a high level of commitment from the top leadership, administration and governing bodies in the United Arab Emirates towards balancing rapid development with sustainable coastal resilience. The key lies in studying each location, along with the topography, hydrodynamics involved there, wave patterns affecting the locality, and arriving at GIS based solutions which are fit for purpose and tailor made to suit that particular location.

6. Further Recommendations

Different countries around the world, including the UAE, have been implementing countless techniques and strategies that fit best in the given local environment in the constant battle against the elements along the vulnerable coastal stretches all over the globe.

Advanced GIS tools, enhanced monitoring and data integration could help further development on future coastal erosion management strategies and minimize the efforts and costs involved in this fight.

Integration of satellite images, LiDAR elevation models and many other techniques will support adaptive management which allow mitigation strategies to benefit the coastal nations based on the observed responses. Alongside such efforts, it should be noted that coastal waves are a continuous pattern, with the inherent kinetic and potential energy generated by waves and ocean currents can be harnessed and converted to electrical energy to be used and disturbed around the coastal belts. Instead of doubling the cost and the efforts, different techniques and strategies are already being pursued by some nations and several research projects are also ongoing along the costal belts, which help in ensuring that the employed coastal management strategies also double up as useful investment tools, and help sustaining the coastal communities and their associated livelihoods.

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Conflict of Interest Statement

We, the authors, declare that there are no conflicts of interest related to the research, authorship, and publication of this manuscript. No financial or non-financial interests have influenced the content or findings presented. All authors have approved the manuscript and confirm that it represents our honest work.

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