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Drone-Based Coastal Monitoring Under Harsh Monsoon Conditions: A Case Study of E-Fence at Pantai Batu Rakit

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Abstract: Coastal monitoring is essential for understanding beach morphology changes, particularly in regions prone to seasonal storms. Monsoonal storms erode sandy beaches worldwide including Malaysia coast. This study evaluates the feasibility of using unmanned aerial vehicles (UAVs) for coastal monitoring under harsh monsoon conditions at Pantai Batu Rakit, Terengganu. UAV-derived beach profiles were validated against high-precision RTK-GPS measurements using root mean square error (RMSE) and the coefficient of determination (R^2). Results demonstrated a strong correlation between UAV and RTK-GPS data, with RMSE values ranging from 0.093 to 0.103, confirming the accuracy of drone-based topographic surveys. The study also examined the role of sand-trapping E-Fences in mitigating coastal erosion through sediment accumulation and shoreline stabilization. Despite photogrammetric limitations near the waterline, UAV surveys proved to be a reliable, cost-effective, and efficient method for coastal assessment, even during extreme weather conditions. The ability to rapidly collect high-resolution data enhances long-term coastal management. Future research should explore integrating LiDAR-equipped UAVs and hybrid survey methods to improve data accuracy and nearshore terrain analysis.

Keywords: Coastal monitoring, Coastal hydrodynamics, UAV, RTK-GPS, Sand trapping fence

1. Introduction

Beach regions, area where the land and sea meet encompass exceptional ecosystems that serve as crucial reservoirs of biodiversity [1], [2]. They play a vital role in providing various essential services to the environment, such as sustaining food production, safeguarding against storm surges, facilitating recreational activities, and preserving cultural heritage [3], [4]. Beach and marine areas are considered to be one of the most important spaces globally when it comes to management and conservation efforts [5].

Monitoring coastal environments is essential for understanding morphological changes and assessing vulnerability [6]. Beach topographic data can be acquired using ground-based methods like RTK-GPS and terrestrial LiDAR or aerial approaches such as photogrammetry and UAVs [7]. While ground surveys offer high accuracy, they are labor-intensive with limited coverage, whereas airborne LiDAR and photogrammetry, though effective, are often costly [8]. UAV-based surveys offer a cost-effective alternative for monitoring coastal changes and sediment dynamics. Their ability to capture high-resolution spatial and temporal data with minimal manpower makes them highly efficient for routine assessments. Their efficiency in data collection makes them particularly beneficial for large-scale and remote coastal monitoring [9].

Despite their advantages, UAVs face operational challenges in harsh coastal conditions, particularly during extreme weather events such as monsoons [10]. Concerns remain regarding their performance in strong winds condition. To address these, this study aims to: (1) validate the accuracy of UAV-derived beach profiles by comparing them with in-situ RTK-GPS measurements using RMSE and R^2 and (2) to assess the feasibility of drone-based monitoring for coastal management, particularly under harsh monsoon conditions.

Additionally, E-Fence help mitigate coastal erosion by promoting sediment accumulation and dune formation, strengthening shoreline resilience [11]. When integrated with UAV-based monitoring, they provide a sustainable solution for preserving beach morphology and managing sediment transport, especially in erosion-prone areas facing extreme weather events.

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2. Material and Methodology

2.1 Study Area

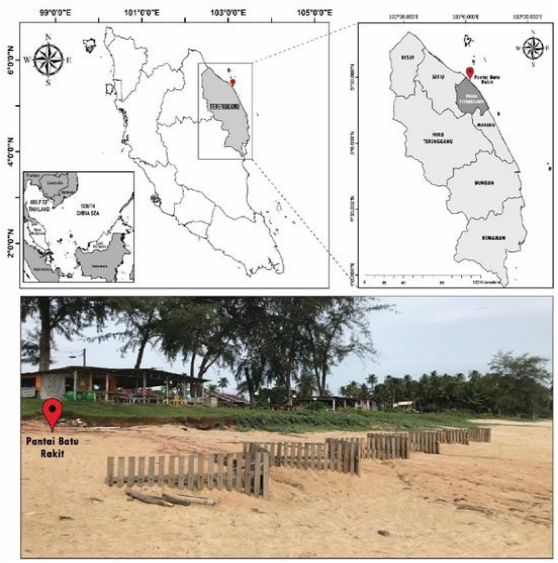

Fig. 1 - Study area located at Pantai Batu Rakit Terengganu

Pantai Batu Rakit, situated on the east coast of Kuala Terengganu, Peninsular Malaysia (103°2.760'E–103°2.940'E, 5°27.150'N–5°27.060'N), is highly susceptible to erosion due to its straight shoreline exposure to the South China Sea [12], [13], [14]. To mitigate erosion and encourage sediment deposition, a sand-trapping E-Fence was implemented at the site. The E-Fence, measuring 18 meters in length, consists of eight transects; six within the structure and two outside for comparative analysis.

During the Northeast Monsoon, erosion is often exacerbated due to the region's unprotected nature [15]. Wave heights during this season range between 1.0 and 2.0 meters, while the Southwest Monsoon results in lower wave heights of less than 0.8 meters [16], [17]. Wind direction significantly influences sediment transport, with the northeast monsoon winds predominantly affecting the area [18], [19]. The coastal slope is relatively gentle, with a gradient angle of 10° [20].

2.2 Data Collection

RTK-GPS was used as the primary tool for beach profiling, referenced to WGS1984 UTM 48N, offering centimeter-level precision. Beach profiling was conducted across eight transects extending from the vegetation zone to the low tide line in November 2023 during the Northeast Monsoon season. This approach assessed the E-Fence's effectiveness in supporting dune restoration under extreme weather conditions. RTK-GPS data was processed using Profiler 3.2 XL, an Excel-based software for topographic analysis. The collected data was saved in PNT format to minimize errors and later converted into distance-elevation graphs.

To complement RTK-GPS-based beach profiling, UAV-based surveys were conducted using a DJI Mavic 2 Pro drone to obtain high-resolution aerial imagery for comprehensive topographic mapping. The drone was flown using the Pix4D Capture, which facilitated automated flight planning with predefined grid line routes. Flight missions maintained a consistent altitude of 120 meters above ground level, ensuring standardized data acquisition with a ground sampling distance of 2.82 cm/pixel. To enhance spatial accuracy, 10 strategically placed Ground Control Points (GCPs) were utilized. The collected images were processed using Pix4D Mapper and ArcMap software to generate a Digital Terrain Model (DTM). The validation of UAV-derived elevation data was performed by comparing DTM profiles with in-situ RTK-GPS measurements from Transects 1 to 8.

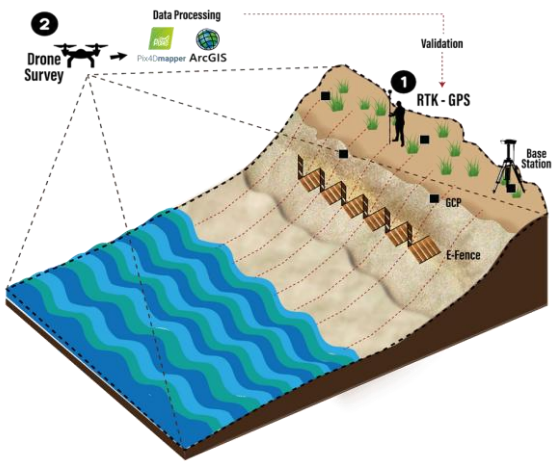

Fig. 2 - Methodology used to achieve objectives; (1) Beach profiling RTK-GPS, (2) Mapping drone survey

2.3 Data Analysis

The accuracy of UAV-derived elevation data was assessed using two statistical methods: Root Mean Square Error (RMSE) and the coefficient of determination (R^2). RMSE was used to quantify the vertical accuracy of the elevation model by calculating deviations between UAV and RTK-GPS datasets. R^2 was employed to evaluate the correlation between the two datasets, ensuring the reliability of drone-based topographic surveys. The equations used for RMSE and R^2 calculations are presented as Equation 1 and Equation 2, accordingly:

$$RMSE = \sqrt{\sum \frac{(H_{s\,measured} - H_{s\,model})^2}{n}} \quad (1)$$

Where:

H_s is the actual value,
H_s model is the predicted value,
n is the number of observations

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y}_i)^2} \quad (2)$$

Where:

y_i is the actual value,
$\hat{y}_i$ model is the predicted value,
$\bar{y}_i$ is the mean of actual values

3. Result and Discussion

The validation of UAV-derived beach profiles against RTK-GPS measurements demonstrated a strong correlation, as indicated by the coefficient of determination (R^2). Most extracted profiles closely followed the elevation patterns observed in RTK-GPS data, confirming the effectiveness of

UAV surveys in capturing coastal morphology. The comparison of Digital Terrain Model (DTM) data obtained from UAV surveys with RTK-GPS elevation profiles across Transects 1 to 8 yielded RMSE values ranging from 0.093m to 0.17m (Figure 3), signifying a high level of agreement and the accuracy of drone-based topographic surveys [21].

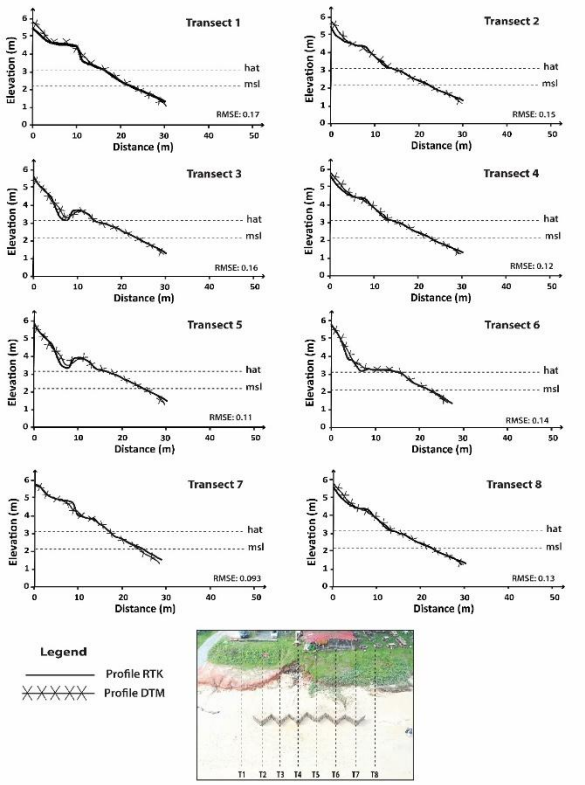

Fig. 3 - Root mean square error (RMSE) in between RTK-GPS and drone survey

To further emphasize the effectiveness of UAV surveys under monsoon conditions, the high R^2 values support the reliability of drone-based assessments (Figure 4). The values obtained for each transect were consistently close to 1, demonstrating the high accuracy of the data collected [22]. The close alignment between UAV-derived and RTK-GPS profiles suggests that drone surveys provide detailed and reliable elevation data, which is particularly beneficial for dune morphology simulations and coastal erosion studies [23].

However, discrepancies were observed, particularly near the waterline, where sudden drops in elevation were detected. These variations can be attributed to the limitations of aerial photogrammetry. Since drone-based photogrammetric techniques rely on surface reflections, they are unable to penetrate the water column effectively. The drop effect observed beyond the waterline suggests that additional survey methods, such as bathymetric LiDAR may be required to improve data accuracy. Despite these challenges, the strong correlation between UAV and RTK-GPS data confirms that drone-based surveys can be effectively used for coastal monitoring. The ability to rapidly collect and process data enhances coastal management efforts by providing accurate topographic, particularly under extreme weather conditions. This study confirms UAV surveys as a reliable tool for coastal monitoring, enhancing management strategies in monsoon-affected regions.

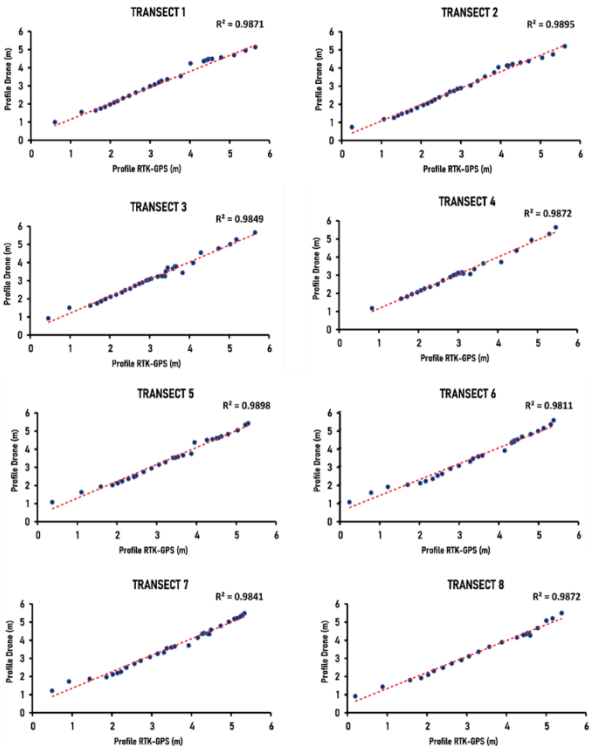

Fig. 4 - Coefficient of determination (R2) in between RTK-GPS and drone survey

4. Conclusion

In conclusion, the effectiveness of UAV-based surveys in monitoring coastal changes, even during harsh storm conditions. The strong correlation between UAV-derived and RTK-GPS beach profiles, indicated by high R^2 values and low RMSE, demonstrates the reliability of drone-based topographic mapping. Despite some discrepancies near the waterline, UAV surveys remain an efficient tool for monitoring coastal area. The ability of drones to operate in extreme weather conditions highlights their potential for improving coastal management strategies. For future research, the integration of more advanced UAV technology, such as high-resolution LiDAR-equipped drones, is recommended to enhance data accuracy, particularly in complex coastal environments. Additionally, further studies should explore methods to interpolate waterline data captured by drones, improving their capability to analyze nearshore processes. These advancements would strengthen the role of UAV surveys in long-term coastal monitoring.

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