A digital twin for monitoring land use/cover and coastal change in Tobago

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Abstract

Digital twin technology presents a transformative opportunity for monitoring land use and coastal changes on small islands. These comprehensive virtual models help to mirror physical environments, thereby offering real-time data integration, simulation, and predictive analytics. The island of Tobago, in the southeastern Caribbean Sea, has diverse landscapes and coastal regions ranging from tropical forests and mangrove ecosystems to thriving coral reefs and seagrass beds. In this study, high resolution digital elevation data was used to model the topography of the island. A land use and land cover information layer, generated from high resolution satellite imagery was then draped over the elevation model to illustrate the variation across the small, mountainous tropical island. An updated high-resolution satellite image base layer of the nearshore marine environment was also integrated into the model along with polygons demarcating the distribution and extent of key coastal ecosystems such as coral reefs. The key to digital twins lies in their ability to provide accurate and up-to-date spatial data and environmental insights. This virtual replica allows for detailed analysis of changing land use and habitat loss, helping stakeholders to make informed decisions. By integrating data from various sources such as satellite imagery, geographic information systems (GIS), and in-situ measurements the digital twin facilitates comprehensive monitoring and forecasting of land and coastal changes. For Tobago, this digital model can enhance understanding and management of its dynamic coastal and land use environments, which are increasingly threatened by climate change, urbanization, and natural disasters.

1. Introduction

1.1 Study Area

The study area for this research was the island of Tobago. Located within the southeastern Caribbean region and surrounded by many smaller landmasses resides the twin island country of Trinidad and Tobago. As the southernmost islands in the Caribbean chain, they are situated near South America, to the northeast of Venezuela and northwest of Guyana. Covering approximately 4,800 km^2, and situated just 11 km off the coast of Venezuela, Trinidad is the larger of the two islands. Tobago, spans approximately 300 km^2 and is positioned 30 km to the northeast of Trinidad. It extends diagonally from the southwest to the northeast, and is approximately 40 km long. When measured at its widest section it is approximately 10 km wide. Little Tobago, an islet, can be found about 1.6 km off Tobago’s coastline to the north-east (Peters et al., 2024). A map showing the location of Tobago is given in Figure 1.

1.2 Issues in the Coastal Zone

The coastal zone can be defined as an area where the land forms a boundary with the sea. This region supports vital ecosystems where a diverse and interconnected range of species can be found. It is typically utilized for fishing and tourism practices which contribute to local economic advancement. Coastal regions can also serve as natural buffer zones, protecting coasts from natural disasters which can cause erosion and tidal inundation. Globally, coasts experience significant dynamics. Studies show that approximately 24% of the world’s sandy beaches experienced continuous erosion at rates exceeding 0.5 meters per year between 1984 and 2016 (Yuan et al., 2024; Luijendijk et al., 2018). This erosion is driven by various environmental factors including; hydrodynamic forces such as tidal energy and nearshore currents, natural weather disasters such as; tropical cyclones, floods, and droughts, and climate change induced sea level rise. Mangrove forests play a crucial role in protecting coastlines from sea level rise and storm surges, particularly in many Small Island Developing States (SIDS) prone to hurricane activity. As sea level rise continues to accelerate due to climate change, the risks of coastal erosion and flooding are expected to intensify. In Trinidad and Tobago, these issues are significant, with 69.5% of Trinidad’s coastal zone and 42.7% of Tobago’s coastal zone being identified as vulnerable to erosion and inundation (Virgil et al., 2023).

1.3 Land Use and Land Cover (LULC)

LULC maps are typically generated from remotely sensed data and are key inputs in planning and management. LULC is heavily influenced by seasonal and anthropogenic changes hence, LULC maps can sometimes be used for only a short period of time. Highly dynamic LULC changes due to anthropogenic pressures can significantly impact; land and nearshore aquatic environments, their systems, the ecosystem services they provide, as well as human livelihoods and well-being. Mapping and monitoring of these changes are crucial for protecting sensitive ecosystems in order to preserve environmental assets and maintain long-term viability of ecological services. The latest advances in geoprocessing methods, spatial data, and the internet have revolutionized LULC map creation, visualization, and dissemination. These developments have opened new opportunities for LULC mapping, facilitating timely and cost-efficient analyses at varying scales of mapping (Pulighe, 2022).
Involving stakeholders in the Land Use Planning (LUP) process allows for the development or responsible and balanced needs. Stakeholders provide insight and valuable knowledge on the problems affecting their respective regions, while taking into consideration those who will be affected by the land use changes and development of the said regions (Adade and de Vries, 2023).

1.4 Light Detection and Ranging (LiDAR)

LiDAR technology has seen substantial advancements within the past twenty years, significantly reshaping geospatial research fields such as environmental monitoring, urban planning and development, and disaster response. LiDAR utilizes laser light to obtain distances thereby creating precise 3D point cloud data, particularly when deployed on airborne platforms. This high-resolution data is instrumental in the creation of accurate digital elevation models (DEMs) and detailed 3D replicas, crucial for flood mapping and modelling, land use mapping, and risk assessment (Papadopoulou and Papakonstantinou, 2024). LiDAR’s ability to penetrate vegetation makes it highly effective in regions with dense vegetation where traditional ground or land surveying methods are limited. Recent integrations of LiDAR data with hydrological and hydraulic models have expanded its utility for enhanced flood prediction and also for supporting scenario-based simulations such as sea level rise modelling for designing mitigation strategies. The detailed topographic insights provided by LiDAR are essential for the development of resilient urban and industrial planning against natural disasters and land change (Papadopoulou and Papakonstantinou, 2024).

1.5 Digital Twin technology

Digital twins are models that replicate the characteristics and behaviour of physical entities or processes. They are used to evaluate and create advancements in the development and use of their physical counterparts. A digital twin functions as a virtual replica enabling near-real-time tracking, management, and enhancement of process performance. These virtual models allow for testing and validation of various scenarios, data analysis, pattern recognition and the prediction of future behaviours. Digital twin technology has advanced significantly within the last twenty years, becoming a powerful tool across various industries (Wang et al., 2024). In a study by Yuan et al., (2024), digital twin models were utilized to accurately track and assess the dynamic coastal topography of a newly formed tidal flat in Shanghai. Unmanned Aerial Vehicles (UAVs) were used to collect the necessary data (LiDAR point clouds and optical imagery) to create a 0.1m resolution digital elevation model (DEM) which was used to develop a dynamic risk assessment framework.

1.6 Aims of the study

The goal of this study was to develop a digital twin of the island of Tobago to be used for monitoring land use and coastal changes, including the impacts of sea level rise. A LULC layer was generated by classifying PlanetScope SuperDove satellite imagery which was then overlain on a high-resolution DEM derived from LiDAR data. Vector polygon and line layers such as coral reefs, mangroves, buildings, roads and rivers were then included for enhanced visualization and spatial analysis.

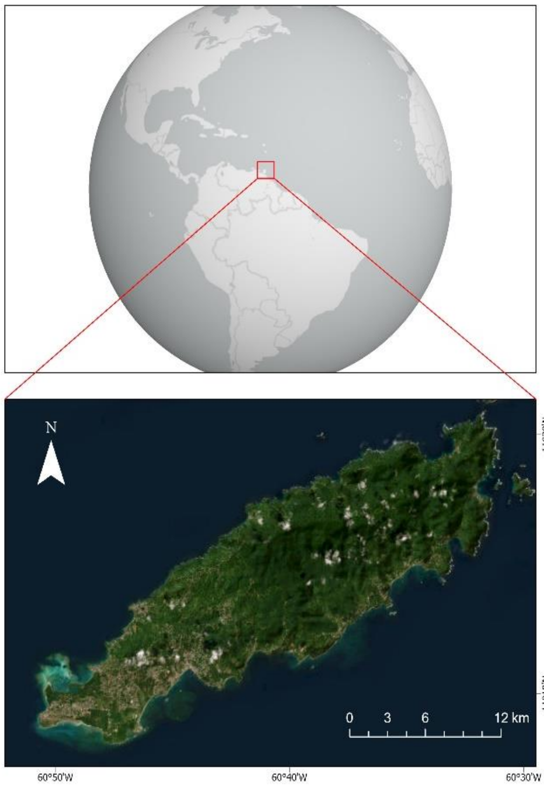

Figure 1. Study Area – the island of Tobago

2. Methodology

2.1 Satellite data acquisition

The satellite data utilized in this study was captured by PlanetScope SuperDove satellites. PlanetScope SuperDove satellites record reflectance data within 8 spectral bands (Table 1) across the electromagnetic spectrum, at a spatial resolution of 3m.

Band No.	Band Name	Spatial Resolution (m)	Wavelength (nm)
b1	Coastal Blue	3	431-452
b2	Blue	3	465-515
b3	Green	3	513-549
b4	Green	3	547-583
b5	Yellow	3	600-620
b6	Red	3	650-680
b7	Red-Edge	3	697-713
b8	NIR	3	845-885

Table 1. Showing the spectral ranges or bands of the PlanetScope SuperDove satellite

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Three separate images of the island of Tobago captured on different dates and times (Table 2), were downloaded from Planet’s data portal at https://planet.com/explorer/. Due to persistent cloud coverage in the imagery (typical of tropical regions), the cloud covered sections of each of the three images were clipped away and the remaining cloud-free portions were merged together in ArcGIS Pro to form one single cloud-free mosaic (Figure 2).

Satellite image	Image Acquisition Date	Image Acquisition Time
1	February 19, 2024	13:45:07 UTC
2	December 2, 2024	14:46:15 UTC
3	December 2, 2024	14:46:13 UTC

Table 2. Showing acquisition dates and times of PlanetScope SuperDove images used in this study

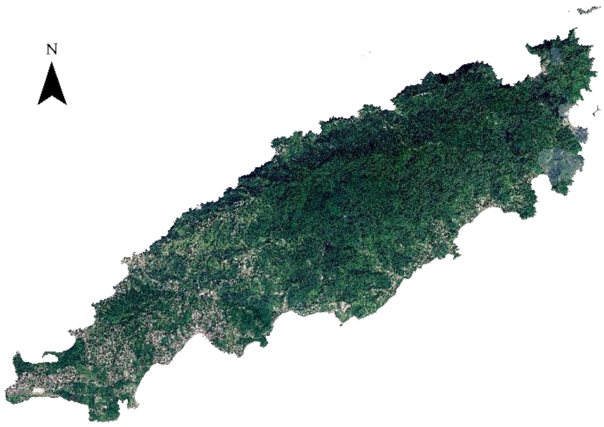

Figure 2. 2024 Cloud-free mosaic of the three PlanetScope SuperDove images used in this study

2.2 LiDAR data acquisition and processing

The source LiDAR point cloud data utilized in this study was captured in 2014 and provided by the Surveying and Mapping Division. The LiDAR point cloud data was processed using the LiDAR Aerial Survey (LAS) tools in Environmental Systems Research Institute’s (ESRI) ArcGIS Pro software. The ‘Create LAS Dataset’ tool found in the ‘Data Management’ toolbox in ArcGIS Pro was first used to compile the LiDAR point cloud data into a single LAS dataset. Following this, the coordinate system was set to WGS84 Zone 20N to match the project’s coordinate system. The ‘LAS Filter’ tab was then used to isolate ground points only, an essential step for creating an accurate DEM. A surface breakline constraint was then incorporated to improve the accuracy of the DEM. Finally, the output DEM was generated by using the ‘LAS Dataset to Raster’ tool which converted the filtered ground points into a raster DEM. The interpolation type was set to ‘Triangulation’ to produce a high quality output and the ‘Natural Neighbour’ method was selected to interpolate across gaps in the data. By using the LAS tools in ArcGIS Pro the original point cloud data was appropriately classified, rasterized and visualized into a useful DEM for the study.

2.3 LULC classification

For this step, a machine learning (ML) classification approach based on a random forest algorithm was applied (Basheer et al., 2022). The cloud-free PlanetScope SuperDove image mosaic was first radiometrically and geometrically corrected. Six land use and land cover classes were predetermined based on the goals of this study. These classes included; bamboo, forest, mangrove, savanna/agriculture, urban, and water. Training samples were then collected by digitizing representative polygons of each land use and land cover class. Samples were collected within each class across all spectral bands, ensuring that the spectral variability was effectively captured. Additionally, the Normalized Difference Vegetation Index (NDVI) was also computed to improve class separability. Next, the ‘Random Forest’ model was trained using the previously collected training sample polygons. In the image classification wizard, the ‘Random Trees’ classifier (ArcGIS Pro’s implementation of the ‘Random Forest’ algorithm) was then used to run the classification of the entire PlanetScope image mosaic to produce the final LULC map. Ground verification global positioning system (GPS) points captured in the field were then used to evaluate the LULC map and compute metrics such as the overall accuracy by running an error matrix.

2.4 3-D Digital Twin model

Once the base DEM and LULC layers were generated they were then used to produce the 3-D digital twin model. Since both layers had the same coordinate reference system they could be easily integrated and aligned. The ‘3D environment’ tools in ArcGIS Pro were used to generate a 3D local scene. The DEM was selected as an elevation surface by adding it as a ground elevation source. Next, the LULC raster map layer was added to the scene effectively causing a ‘draping’ effect of the layer over the DEM layer. This was completed by setting the feature to ‘on the ground’ thereby allowing it to conform to the terrain’s surface. Finally, a vertical exaggeration factor of 3 was added to enhance the visual effect of the elevation layer.

Additional vector polygon and line layers (Table 3) were then overlain on the resultant 3-D digital twin model for further assessment and analysis. These layers illustrated the distribution of buildings, mangroves and coral reefs around the island as well as the coverage of road and river networks. The digital twin environment allows for additional vector layers to be effortlessly integrated and updated. The overall workflow for creating the 3D digital twin model of Tobago is given in Figure 3.

No.	Layer	Type
1	LULC	Raster
2	Mangrove	Polygon
3	Coral Reef	Polygon
4	Buildings	Polygon
5	Roads	Line
5	Rivers	Line

Table 3. Vector and raster features added to the DEM

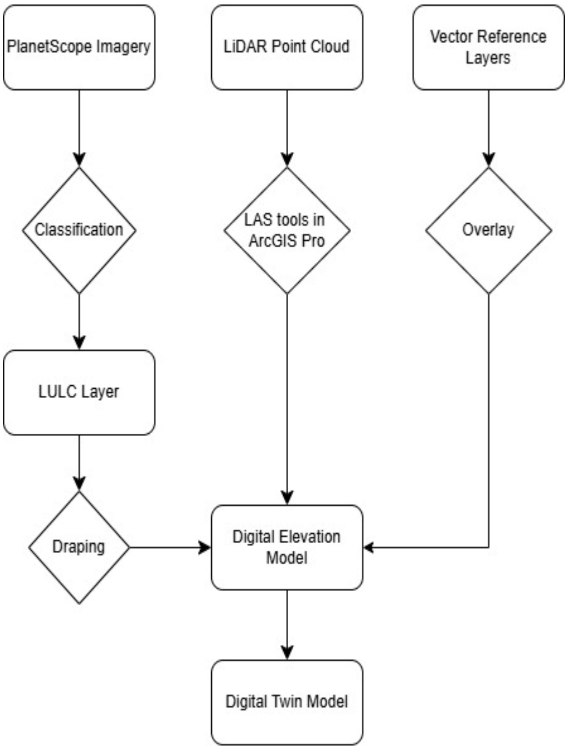

Figure 3. Workflow for creating Digital Twin Model

3. Results and Analysis

3.1 LiDAR DEM

Figure 4 below illustrates the final DEM generated from the LiDAR point cloud data processing. This 3D colourized rendering illustrates the highest points running along the main ridge of the island, symbolized in orange. The southwestern region of the island is visualized in dark blue. This very low-lying area is the most densely populated section of the island and is more susceptible to the impacts of sea-level rise.

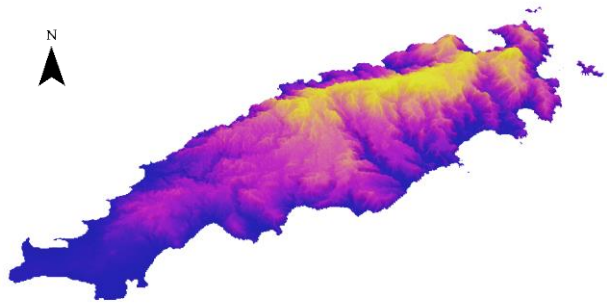

Figure 4. The LiDAR – DEM layer

3.2 Final LULC map

The final classified LULC map is shown in Figure 5. The results of an accuracy assessment performed using an independent set of GPS ground validation data indicated that an overall accuracy value of 97% was achieved for this map. Figure 6 is a 3D representation of the changes in land use and land cover across the undulating terrain.

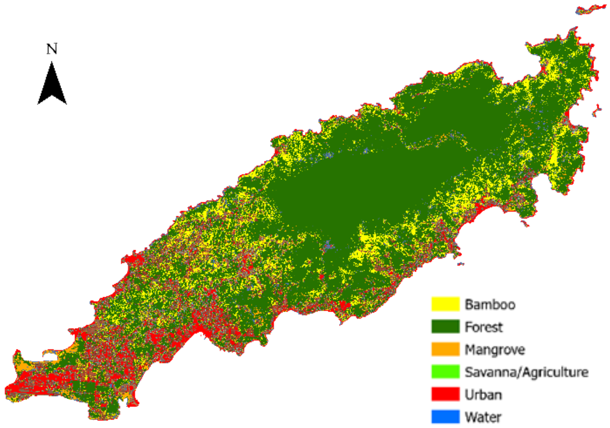

Figure 5. Final classified LULC map of Tobago

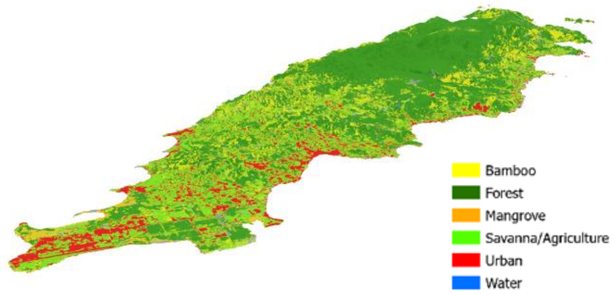

Figure 6. 3D visualization of LULC distribution

3.3 3D Digital Twin

Figure 7. Digital Twin of Tobago with Coral Reef, Rivers and Roads layers integrated

Additional vector polygon and line layers such as coral reefs and mangroves, and roads and river networks were also integrated into the 3D model of the island, illustrating the spatial patterns and relationships that may impact coastal ecosystems (Figure 7).

3.4 Sea-level rise modelling.

The 3D digital twin of Tobago was used to model and visualize the inland encroachment of water on the semi-flat, southwestern region of the island and its infrastructure. This model was based on two projected scenarios of sea-level rise derived by the Intergovernmental Panel on Climate Change (IPCC) (Fox-Kemper et al., 2021). The IPCC report suggests that the lower limit of the range of lowest projections of sea-level rise was 0.19m, whereas, the upper limit of the range of highest projections was 1.01m. These two extreme values were therefore extracted and inputted into the software to model the spatial distribution and extent of water coverage in this area of the island under both scenarios. It is important to note here that although the probabilities of this scenario occurring would be lower, the IPCC does acknowledge that a rise approaching 2 meters by 2100 cannot be ruled out.

Figure 8. Modelled impact of a 0.19 m sea-level rise on the southwestern region of Tobago

Figure 9. Modelled impact of a 1.01 m sea-level rise on the southwestern region of Tobago

4. Conclusion

The 3D digital twin model developed in this study, is the first of its kind for the island of Tobago. The distribution and extent of coastal ecosystems such as coral reefs and mangroves within a 3D model of the terrestrial environment with road and river networks included, is clearly depicted. Land use and land cover distribution and extent is also visualized on the 3D model. The digital twin model can aid in assessing the impacts of changing terrestrial systems on the nearshore coastal environment and vice versa and can be a key asset in the marine spatial planning (MSP) process. The digital twin of Tobago created in this study also establishes a framework for integrating additional datasets as they are acquired or produced. Layers representing ocean biogeochemical parameters, nearshore recreational and commercial use zones, fisheries and fish spawning sites, and models depicting the movement of pollutants, are just some of the datasets that can be incorporated in the future. Advanced equipment such as autonomous underwater vehicles (AUVs) and unmanned aerial vehicles (UAVs) can be deployed for rapid data collection above and below the ocean surface. As the model is supplemented with additional layers of higher precision and accuracy in the future, its efficiency as a prediction and management tool will also be enhanced. Future investments in the supporting software and hardware systems will also be necessary, in order to effectively process and analyse more complex datasets as the model evolves.

As artificial intelligence (AI) and ML algorithms also advance so too will the performance of digital twins. It is to be seen if the operational and governance policies that are required to support the implementation of the technology will also keep pace.

One key limitation of the study was the temporal gap between the acquisition of the LiDAR dataset and other primary data utilized. Given that the LiDAR data was collected a decade before, it is likely that topographical changes would have occurred that were not represented in the model. Notwithstanding that this was the highest-resolution elevation data available during the study, a key improvement for future research would be the acquisition and integration of up-to-date LiDAR data. This would enhance the model’s accuracy by reflecting more current landscape conditions. In addition, satellite imagery with superior spatial resolution than the PlanetScope SuperDove’s 3m which was used in this study, will greatly improve the accuracy of terrestrial feature modelling. In this case, the very-high-resolution (VHR) Planet’s SkySat 50cm imagery or Airbus’s Pléiades-Neo 30 cm imagery can add considerable value to the model.

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