# Underwater Digital Twin of Yuba Island: Mapping a Large-Scale Marine Ecosystem through Photogrammetry and 3D Modeling

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**Abstract**

The project involved creating a high-resolution digital twin of the underwater environment surrounding Yuba Island, a pristine site in the Red Sea, Saudi Arabia. The goal was to replicate the experience of diving in this environment, 3D mapping approximately 147 ha underwater and 290 ha above water, completed within six months. The 3D model was designed to be highly accurate, featuring true-to-life textures and colors, and georeferenced with a depth accuracy of ±0.10 m relative to local Mean Sea Level (MSL). The mapping covered coral reefs, fringing reefs, pinnacles, sand, caves, channels, and overhead environments, covering depths from 0.5 m to 70 m, mapped at 4.5 m²/s and 1 mm/px resolution. Over 100 local fish species were documented, 3D-modeled, and incorporated with behavioral metadata to simulate natural marine life. Final deliverables included Cesium tilesets, a Virtual Reality (VR) Cube experience, and a desktop version of the model. The project team included specialists in underwater photogrammetry, commercial diving, marine biology, oceanography, software development, data engineering, and VR design, all working together to deliver the Underwater Digital Twin within the six-month timeline.

## 1. Introduction

The demand for detailed, accurate representations of underwater environments has grown steadily, driven by advances in marine science, conservation, and the need to explore fragile ecosystems (Ceccherelli et al., 2024). Coral reefs, in particular, face increasing pressure from human activities such as pollution and climate change, making effective monitoring essential for their preservation (Hughes et al., 2017). Traditional methods such as physical surveys are time-consuming, costly, and limited in their ability to capture the full complexity of these environments. Digital twins – virtual replicas of real-world environments – offer a promising solution (Grossmann et al., 2022).

Unlike static 3D models, digital twins incorporate dynamic, layered data including environmental variables, temporal changes, and biological behaviors (de Koning et al., 2023). They serve as living simulations that evolve with continuous input. This project focuses on creating a high-resolution digital twin of the underwater environment surrounding Yuba Island, located in the Red Sea, Neom Region, Saudi Arabia (Figure 1). Beyond aesthetic representation, it integrates biological activity, environmental metadata, and real-time simulation features, setting it apart from conventional 3D reconstructions.

Yuba's coral reef system presents a unique opportunity to develop a detailed, georeferenced 3D model of a complex underwater ecosystem. The goal was to replicate the diving experience of this environment, offering an immersive model that could serve as a tool for research, education, and environmental monitoring. The creation of this digital twin required cutting-edge technology and interdisciplinary collaboration. The project brought together expertise in underwater photogrammetry, technical diving, marine biology, and oceanography, supported by specialized equipment and a 40-m dive vessel. In six months, the team captured high-resolution spatial data from the island's coral reefs, pinnacles, caves, channels, and marine life, producing a highly detailed set of 3D models.

This paper outlines the methodology used to create the digital twin, including data collection techniques, modeling processes, and the project's broader implications for marine exploration, research, and monitoring.

Figure 1. Area of project: Yuba Island, Red Sea, Saudi Arabia © 2025 Microsoft

## 2. Underwater photogrammetry

Underwater photogrammetry shares similarities with terrestrial and aerial approaches but faces unique challenges due to the optical properties of water (Jerlov, 1976). Light transmission in water is significantly affected by absorption and scattering, which reduce visibility, distort colors, and degrade resolution (Smith and Baker, 1981). These challenges must be addressed to ensure the production of accurate and realistic 3D models (Sarakinou et al., 2016). Rather than using artificial lighting, we relied entirely on natural sunlight, selecting optimal times of day to capture authentic underwater lighting conditions (Agrafiotis et al., 2018). The goal was to replicate a diver's perception of the reef, ensuring that its colors and contrast were faithfully preserved.

## 3. Preliminary fieldwork

The Yuba Digital Twin (DT) project is the culmination of a four-year marine mapping initiative that included underwater scouting, visual documentation, and site assessments in the northeastern Red Sea and the Gulf of Aqaba. In 2021 and 2023, 3D models of 30 underwater areas were produced, including five newly discovered cultural heritage sites. These missions helped refine georeferencing methods, navigation strategies, and performance parameters to support an efficient workflow for the larger DT project.

Preliminary underwater scouting of Yuba in 2021 and 2023 offered a partial but representative understanding of the site, ensuring the team was well-prepared before launching the DT project.

## 4. Methods

### 4.1 Lighting and radiometric adjustments

To preserve the natural appearance of the underwater environment, artificial lighting was minimized, and a radiometric pre-processing technique was applied to maintain a consistent 5500 K daylight color spectrum across all images. This ensured that the model retained the authentic colors of the reef as perceived by a diver, regardless of the depth or lighting conditions.

### 4.2 Optical corrections

Custom underwater lenses were used to correct optical distortions caused by the refractive index of water. These lenses offered superior sharpness and resolution compared to standard options, eliminating distortions and chromatic aberrations typically associated with dome ports or Ivanoff-Rebikoff-style correctors.

While many underwater imaging projects rely on dome housings and compensate for lens distortions through post-processing methods during Structure-from-Motion (SfM) – such as Bundle Adjustment (BA) and self-calibration – we opted to use lenses that were inherently designed to minimize underwater distortions, rather than rely entirely on algorithms for correction. Although BA can achieve the highest geometric level when supported by abundant Ground Control Points (GCPs) or other stabilizing observations, our approach combined custom-converted, pre-calibrated underwater lenses with sufficient GCPs to ensure consistent reconstruction quality across sessions. Our custom lenses corrected refractive distortions at the optical design stage, resulting in consistent accuracy, improved image quality, and reduced need for recalibration.

### 4.3 Data capture setup

Flexible single-camera setups, combined with Diver Propulsion Vehicles (DPVs), enabled efficient scanning of complex reef structures. This dynamic configuration ensured comprehensive 3D coverage, supported by real-time georeferencing and Global Navigation Satellite System (GNSS) tracking via ultrasound-based trilateration (Otero et al., 2022).

### 4.4 Georeferencing and navigation

Georeferencing was essential for aligning the captured models with real-world coordinates. The underwater process relied on GCPs, real-time GNSS signals transmitted between surface buoys and mobile underwater beacons located via a long baseline (LBL) acoustic positioning system (Christ and Wernli, 2007).

GCPs were surveyed through photogrammetric alignment relative to camera coordinates and validated in situ by manually positioning beacons on each GCP. The vertical (Z-axis) accuracy of each beacon was confirmed using two calibrated depth sensors.

Additionally, a special navigation system enabled real-time adjustments to the camera tracks using data from a surface GNSS receiver, 3D magnetometer, 3D gyroscope, 3D accelerometer, speed sensor, and pressure sensor. Tidal influences were accounted for using a custom tidal calendar, validated through manual seabed measurements.

### 4.5 Image capture and dive operations

Underwater image capture required constant manual adjustments due to the dynamic and often challenging lighting and environmental conditions. The operator had to continuously adjust shutter speed, ISO sensitivity, and aperture to match changing light levels, shooting angles, water depth, and surface conditions. Fully automatic exposure and interval shooting modes were avoided, as they could not adapt to the wide range of lighting conditions encountered between 0 and 70 m depth, nor to the irregular shooting rhythm. Focus was manually controlled using a combination of single-servo autofocus and mechanical lockouts to ensure consistent precision during long dives.

Image capture was conducted at a nominal resolution of 1 mm per pixel, with an average mapping speed of 4.5 m²/s – a performance target defined in the project's scope of work. Preliminary benchmark tests – including underwater georeferencing, on-the-fly corrected seabed tidal measurements, GCP deployments and recoveries, and full immersion time (descent, ascent, and any decompression or safety stops) – demonstrated the feasibility of this rate. All procedures were part of standard operations and were fully included in the time used to calculate the mapping speed, ensuring the benchmark reflected complete mission conditions. These values guided surface area estimation and daily dive planning, and were later confirmed through analysis of the final 3D model surfaces and capture times (Figure 2).

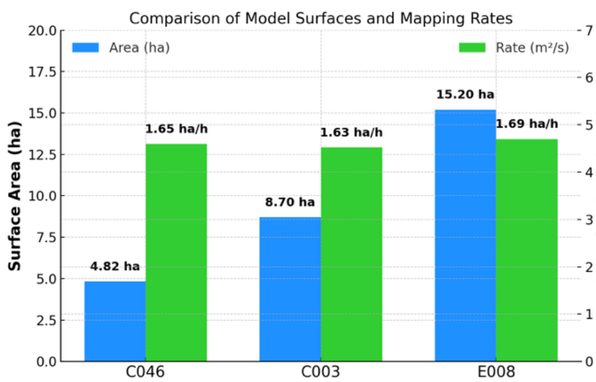


Figure 2. Observed mapping rates and surface areas during preliminary fieldwork in 2023 using identical equipment and georeferencing as in the 2024 DT project, with all mapping rates exceeding 4.5 m²/s (16,200 m²/h) and demonstrating consistent performance across varying model sizes

Mapping in a complex underwater environment required meticulous planning and operational flexibility. The vast area to be covered, combined with dynamic conditions such as tides and currents, meant that dive profiles and schedules had to be continuously adjusted. DPVs were used to extend track lengths and maintain consistent speed and camera framing. Twinset Nitrox systems ensured both safety and efficiency. The dive protocol was designed to maximize bottom time while staying within decompression limits. A typical daily camera track covered between 4 and 6 km underwater, with individual dives lasting 3 to 4 h.

Tidal influences also demanded strategic planning, particularly due to reduced visibility from sediment movement – most notably near lagoon outlets during ebb tide. These dynamic conditions made the planning phase of each dive critical. Since many deeper reef areas had not been previously scouted or charted in detail, the dive team had to make real-time decisions underwater to include features lying outside the preplanned paths. Thanks to odometry-based navigation, operators could flexibly incorporate these areas without disrupting the overall mission, then resume their original track.

To accommodate unexpected extensions during capture, the system included significant battery and storage reserves. An external power supply increased battery capacity fourfold compared to standard in-camera batteries.

### 4.6 Processing

Approximately 5 ha of 3D surface were captured and processed per day using a streamlined workflow that included image capture, georeferencing, data transfer, radiometric editing, alignment, referencing, tidal corrections, and model generation. To enhance efficiency, additional data collection for VR was conducted separately, ensuring it did not interfere with the main 3D capture process.

Photogrammetry processing was performed using Agisoft Metashape Pro 2.1.4, supported by networked computing across eight high-performance workstations. The complexity of the project highlighted specific areas of the processing pipeline and algorithms that required optimization for field use. On-site, between 5,000 and 10,000 images were aligned daily to support dive path planning for the following day. Time-intensive tasks such as mesh and texture generation were automated and distributed across processing nodes connected to shared storage, significantly reducing turnaround time.

For improved mesh editing and visualization, the Block Model concept (Agisoft LLC, 2024) – originally developed for large-scale aerial surveys – was adapted to suit underwater datasets. This approach enhanced visualization performance and streamlined processing routine by generating block models from depth maps, dense point clouds, and high-poly meshes. Custom scripts further accelerated repetitive tasks such as statistical analysis, the seamless transfer of sub-aligned camera groups, and patch-based color correction for textures.

Deliverables included the VR Cube experience and its desktop version, as well as the unmodified photogrammetric models in the form of 29 Cesium tilesets for Geographic Information Systems (GIS), most with a typical polygon count of approximately 600 million faces per submodel.

### 4.7 Hardware

**4.7.1 Cameras and optical system:** Image capture was conducted using several Nikon D850 full-frame DSLRs (sensor size: 8256 × 5505 px, pixel size: 4.35 µm), housed in Seacam underwater enclosures and paired with Nikon R-UW AF 13 mm f/2.8 near-fisheye lenses. These lenses provide a 170.6° field of view. Originally developed by Nikon in the early 1990s for the Nikonos RS underwater SLR, the R-UW AF 13 mm was manufactured in limited numbers and discontinued in 1996. Despite their age, these lenses outperform all full-frame fisheyes used with dome ports in sharpness and consistency. Each unit was custom-modified by Seacam in Austria.

During dives, operators had to monitor multiple systems simultaneously: camera functions, capture status, navigation console, DPV settings and controls, and physiological data via dive computers. The use of DSLRs with optical viewfinders was deliberate and offered several key advantages in our setup. These include a direct view with zero lag and better energy efficiency. The mechanical release also provides strong tactile feedback which allowed operators to feel the shutter actuation and mirror vibration through the housing grip – critical in noisy underwater conditions when visual confirmation was impractical. Mirrorless cameras with electronic viewfinders (EVFs), while offering more display data, consume more power, generate more heat, and introduce latency-factors that are disadvantageous during continuous, fast-paced underwater imaging.

The FX-format sensor (24 × 36 mm) struck the optimal balance between compact camera size, lens compatibility, and final image resolution. Prior tests with medium-format systems in large underwater housings revealed significant image degradation. This was due to limitations in dome port size and design, which reduced depth of field and optical performance. A custom Ivanoff-Rebikoff corrector for a 16-35 mm Nikkor (at 16 mm) on a Nikon D850 was also tested before the mission but did not surpass the performance of dedicated underwater lenses. A detailed justification for the selected optics – including the limitations of domeports and the benefits of purpose-built underwater lenses – is provided in Section 4.7.2.

**4.7.2 Rationale for custom underwater lenses:** As described in the previous section, Nikon D850 cameras paired with Seacam-modified 13 mm R-UW AF lenses were used for the project. This configuration was chosen based on extensive practical experience and specific performance needs related to underwater photogrammetry.

Many existing approaches successfully rely on off-the-shelf dome housings and correct lens distortions algorithmically during Structure-from-Motion (SfM) with Bundle Adjustment (BA), and self-calibration (She et al., 2024). However, this strategy has known limitations for achieving consistent geometric accuracy – especially when using zoom lenses behind dome ports (Jung et al., 2021). Such configurations are optically 'ideal' at one focal length and confine focus range to the lens's near field due to the virtual image effect (Menna et al., 2016).

Over years of fieldwork, we tested various setups, including optical glass dome ports and lens-specific port extension tubes, with premium wide-angle lenses known for sharpness (e.g., Nikon 18 mm f/2.8 AF and f/3.5 MF, 14 mm f/2.8, 14-24 mm f/2.8, 16 mm f/2.8 Fisheye, and 16-35 mm f/4), as well as a prototype Ivanoff-Rebikoff corrector as previously described. Key challenges in this project included rapidly changing shooting distances, highly variable focal distances, and the need to use the full aperture range under extreme lighting conditions. These variations resulted from complex reef morphology and high-speed capture. Hydrodynamics and handling were also key, as was the smaller surface area of underwater lenses, which are less prone to scratches, flare, and reflections.

While other setups offer flexibility, custom underwater lenses are designed specifically for the refractive index of water. They eliminate the need for additional calibration, minimize chromatic aberration and spatial distortions, and enable reliable edge-to-edge sharpness. This directly improves feature detection and correspondence in SfM, resulting in more robust and precise 3D reconstruction.

Together with the only other existing native underwater wide-angle zoom lens – the Seacam-converted 20-35 mm f/2.8 R-UW AF Nikkor, which has a much narrower field of view and was excluded for this reason – the 13 mm f/2.8 R-UW AF Nikkor offered the best balance of optical quality, stability, and reliability under Yuba's demanding conditions. Its optical sharpness consistently outperformed all dome port–based configurations tested.

**4.7.3 Network and storage:** *Agisoft Metashape Pro 2.1.4* was used for photogrammetry processing, employing networked computation across eight desktop computers. The workflow automated time-intensive tasks such as mesh and texture generation, enabling parallel processing to accelerate deliverables. The distributed setup allowed individual machines to execute specific pipeline steps simultaneously, reducing overall working time and ensuring that field data could be reviewed and processed efficiently on-site.

Preliminary network performance benchmarks underscored the need for a 10 GbE infrastructure. We utilized three NAS servers configured as follows: 480 TB HDD-RAID 5, 144 TB HDD-RAID 5, and 24 TB SSD-RAID 0. All servers achieved sustained read/write speeds of 900-1000 MB/s, and desktop workstations and storage units operated on uninterruptible power supplies (UPS).

## 5. Additional data collection for VR

### 5.1 Fish library

In parallel with the primary data collection, another task focused on enriching the VR experience. Detailed physiological and behavioral data were gathered for 100 local reef fish species. This included species photography (from profile, frontal, and perspective angles), filming, and site video loops, all captured using color settings consistent with those of the primary 3D modeling process. The data aimed to enhance the VR experience by supporting realistic species placement and population dynamics within the model.

For each species, metadata included 45 descriptive parameters, such as size range, depth range, density, proximity to the reef, schooling tendencies and styles, habitat, swimming speed, and individual movement characteristics. This metadata enabled the simulation of realistic fish behaviors, significantly enhancing the VR experience for both research and educational purposes.

### 5.2 VR adaptation

The Digital Twin submodels – comprising 28 underwater tilesets and the 110-m-high island – were edited in Unreal Engine. Variable environmental parameters were added, including time-of-day lighting, reintroduction of absorption and scattering for realistic underwater visibility, and surface dynamics. Additionally, points of interest (POIs) were marked for notable features, such as caves, swim-throughs, distinctive corals, and in-situ modeled species such as resting turtles or stingrays on the seabed. Intertidal zones that were too shallow for photogrammetry and inaccessible for diving were modeled with locally created reef-top mesh and textures.

As a significant enhancement, locally recorded reef fish species were 3D-modeled and integrated with a set of metadata rules for each species, including reactions to the visiting viewer with individual fleeing behavior and flight distances. Variations in the presence of marine life were inferred from cyclical video footage collected at reference dive sites at different times of day An interactive educational fish library showcasing typical Yuba species was added.

User experience could be controlled via a handheld console or through a guided tour mode. Visitors could dive virtually, with real-world parameters such as coordinates, compass, and depth displayed (Figure 3).

Figure 3. Yuba Digital Twin VR experience: implementation of local fish species with behavioral metadata and reintroduction of light absorption and backscatter (Area E039, Yuba-SW)

### 5.3 Night dive

The VR application included a night dive mode simulating underwater conditions such as light attenuation, color loss, diffusion, and backscatter. Lighting parameters derived from site-specific footage at model coordinates (Figure 4), based on 5500 K dive lamps, allowed the simulated light to closely match real conditions. Species distribution and reduced abundance were adapted according to local nighttime observations.

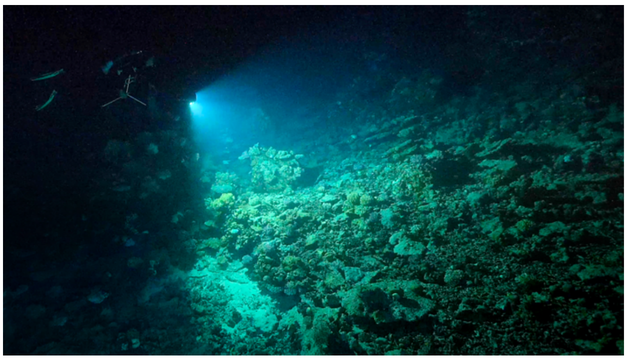

Figure 4. Data collection at night: typical dive lighting parameters and nocturnal species population changes were derived from site-specific video footage to inform and enhance the Yuba Digital Twin VR experience (Area E036, Yuba-W)


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# 6. Results

## 6.1 Spatial coverage

The Digital Twin of Yuba Island provides an accurate and complete representation of the island's underwater reef system. The total modeled 3D area spans 437 ha, with a perimeter of approximately 13.6 km. This includes 147 ha of underwater 3D surface and 290 ha above water, corresponding to a 2D planar area of 278 ha (Figure 5).


Figure 5. Yuba Island and coral reef submodel areas

The model includes key reef structures (Figures 6, 7), an isolated offshore reef west of Yuba (Area E036), and a 1.8 km reef chain that extends south of the island, ending in a flat slope descending to a depth of 70 m (Area E017). A cave (Area E041), ranging from 25 to 40 m depth, was modeled using a progressive mix of ambient and artificial lighting to capture its darker interior. This was the only area where artificial light was used; all other modeling relied solely on natural light.

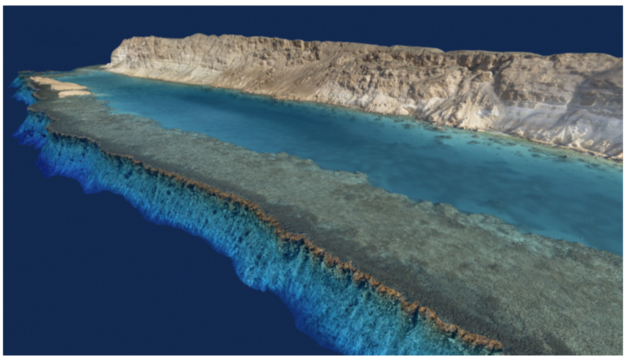

Figure 6. Textured 3D mesh model derived from underwater and aerial photogrammetry (Areas E013–E016–E037, Yuba-W)

Figure 7. Underwater 3D model of coral reeftop edges, texture resolution 1 mm/px (Area E008S, Yuba-S)

The initial challenge – the size and unknown morphology of the deeper offshore reef structures – was addressed through precise navigation and camera track control. An aerial 3D model of Yuba Island further confirmed the reef-to-shoreline connections.

This project also revealed a submerged cultural heritage site between the southern reefs (Area E007, provisionally dated to the late Roman period) and a cluster of ancient circular constructions on the island's northern summit, both now under investigation by cultural heritage researchers.

## 6.2 Tidal findings

In the absence of reliable local tide data, we performed cyclical manual tidal measurements. These revealed tidal amplitudes up to 150% greater than those reported in existing literature, emphasizing the need for site-specific tidal monitoring. Future offshore digital twin projects should include a mareograph or comparable instrument to ensure accurate tidal calibration.

## 6.3 Morphological and temporal coral patterns

A 500 m transect within the isolated reefs south of Yuba revealed that all coral pinnacles exhibited streamlined, overhanging shapes oriented southward (Figure 8). This morphological pattern was only visible in the 3D model, requiring a vantage point beyond typical underwater visibility. To our knowledge, such formations have not been previously visualized photorealistically. The existing literature contains limited documentation of this phenomenon, suggesting the need for further investigation using photogrammetric and environmental analysis.

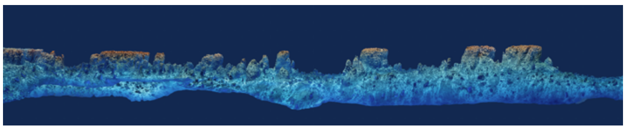

Figure 8. Streamlined coral towers (Area E008S, Yuba-S)

Using fixed color settings and uniform radiometric editing produced natural-looking underwater colors and enabled seamless integration with legacy models, assuming consistent time-of-day capture across model boundaries. Areas near lagoon outlets or regions affected by sediment spinoff showed lower coral density and were characterized by accumulations of natural rubble.

At site E003, a 16.7 ha coral garden modeled in 2024 was partially overlaid with a 1 ha model created in 2021 using the same photo equipment and settings. This enabled comparative analysis of coral growth by species over time (Figure 9). Five morphologically distinct areas across Yuba now provide such multi-year datasets, spanning reef tops and depths of 10, 20, and 30 m.

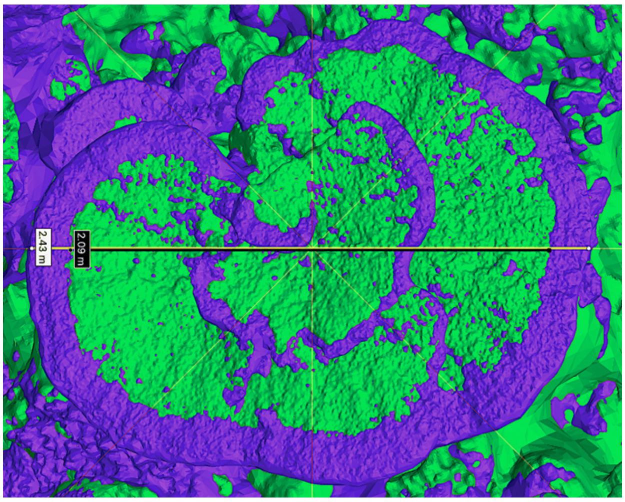


Figure 9. Visualization of 3-year coral growth: diameter of a large *Acropora hyacinthus* colony increased by approximately 11.33 cm/year. Green: 2021, violet: 2024 (Area E003, Yuba-W)

The global coral bleaching event of 2024 was observed in Yuba's shallow waters during August and September. Coral responses varied: some bleached and died, others recovered, and some showed no visible stress (Floros et al., 2004; Marshall & Baird, 2000; Stimson et al., 2002). Surface water temperatures reached 34 °C. Subsequently, bleached and dead coral became overgrown with turfing and red algae. By mid-October, temperatures declined, and by mid-November, *Porites nodifera* and related species had returned to their typical coloration and texture. These trends were confirmed through side-by-side comparison of identical model areas captured four weeks apart (Figure 10). Historical models from 2021 and 2023 across Yuba will support assessment of the extent and local impact of the 2024 bleaching event.

Figure 11. Species observations: whitetip reef shark (*Triaenodon obesus*) and green sea turtle (*Chelonia mydas*) observed at 2.5 m depth during the photogrammetry process in Area E003, Yuba-W

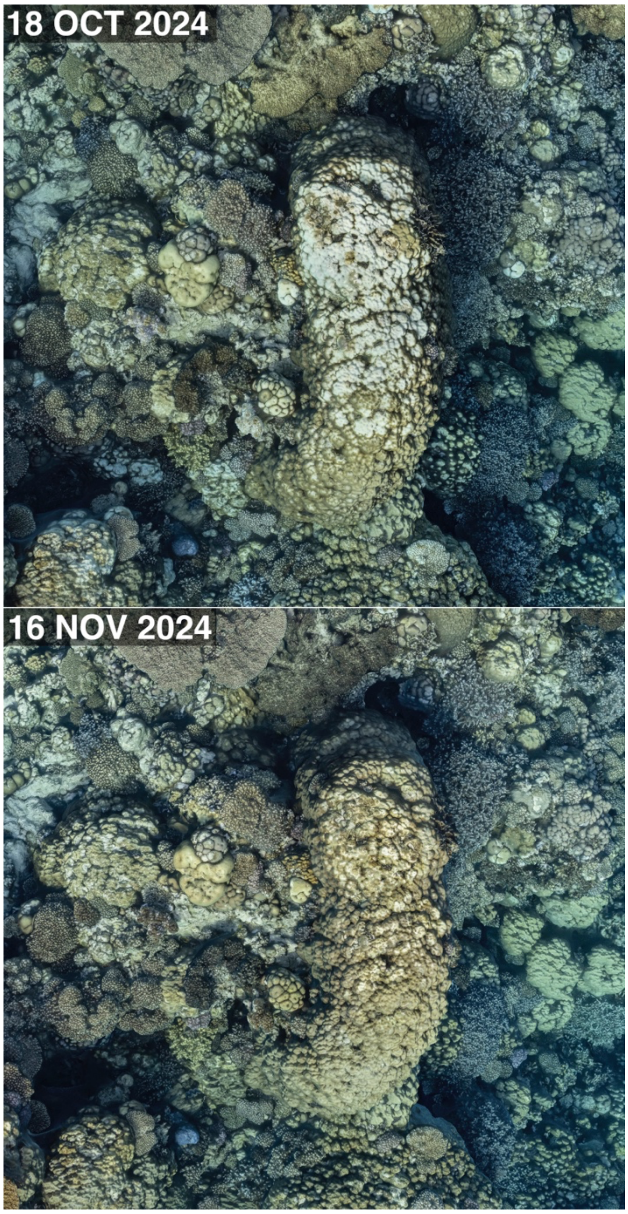


Figure 10. Textured 3D mesh models derived from underwater photogrammetry: *Porites* coral during bleaching (top) and signs of recovery four weeks later (bottom) in Area E040, Yuba-S

### 6.4 Species observations

Over four years of regional underwater surveys and six months of continuous diving at Yuba, we gathered detailed insights into the spatial distribution of larger marine species. For example, whitetip reef sharks (*Triaenodon obesus*), were most commonly found in areas subject to surface dynamics aligned with prevailing wind directions (Figure 11), while blacktip reef sharks (*Carcharhinus melanopterus*) were predominantly observed in shallow, nearshore habitats such as reef tops. Common bottlenose dolphins (*Tursiops truncatus*) more frequently crossed southern reef systems and adjacent underwater ridges than traveled along the island's fringing reefs (Figure 12). These patterns align with previously documented ecological trends. We incorporated these findings into the VR experience on locations where these species are likely to appear by visualizing their relative abundance.

Figure 12. Species observations: common bottlenose dolphins (*Tursiops truncatus*) were frequently encountered at the southern reef ridges (Area E008N, Yuba-S)

The use of DPVs facilitated observation of undisturbed reef species behavior compared to conventional scuba diving. Green sea turtles (*Chelonia mydas*), for instance, frequently remained stationary while DPV divers passed. Similarly, circular high-speed approaches toward stingrays – such as bluespotted ribbontail rays (*Taeniura lymma*) and larger cowtail stingrays (*Pastinachus sephen*) – even enabled accurate 3D capture, as the animals remained still even when approached within typical flight distances (Figures 13, 14).

Swimming scuba divers, by contrast, tend to move irregularly, emit concentrated bubbles, and use broad fin strokes – behaviors that may be perceived as more intrusive. DPV divers move with greater directional consistency and speed, which appeared to reduce the perceived threat. This enabled minimal or delayed escape responses from reef fish and allowed for more naturalistic behavioral observations.

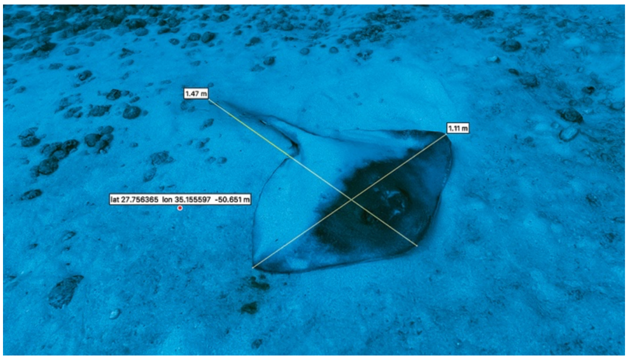


Figure 13. Textured 3D mesh model. Large cowtail stingray (*Pastinachus sephen*), partially covered with sand, modeled in situ at 50 m depth (Area E017, Yuba-S)

Figure 14. Textured 3D mesh model and SfM camera positions: cowtail stingray (*Pastinachus sephen*) modeled in situ at 23 m depth (Area E008S, Yuba-S)

### 6.5 Limits

The intertidal zones of Yuba Island are characterized by broad, flat lagoons with limited underwater visibility. They were beyond the scope of our diver-based project. However, these zones, along with the extensive flat reef tops, could be effectively studied using complementary techniques such as Airborne Laser Bathymetry or sonar-based methods, which have shown strong potential for shallow water mapping (Mandlburger, 2021).

## 7. Conclusion

The underwater digital twin of Yuba Island presents significant opportunities for marine research, monitoring, and exploration. By delivering a highly detailed, georeferenced 3D model of the coral reef ecosystem, the project enables new forms of scientific inquiry and long-term ecological observation. The capacity to explore and interact with this environment virtually – without physically disturbing it – offers a non-invasive approach to studying reef habitats over time.

This digital twin serves as a valuable asset for both marine biology and conservation. It provides an immersive and interactive representation of the Yuba reef system, supporting data-driven decision-making by enabling researchers and conservationists to identify vulnerabilities, monitor environmental trends, and assess ecosystem health. It also functions as a tool for public education, raising awareness of reef ecosystems and the urgency of their preservation.

### 7.1 Applications

Although this case study focused on a coral reef ecosystem, the techniques and infrastructure developed here are transferable to a variety of underwater environments. Potential applications include:

**Submerged archaeological sites**, where non-invasive 3D documentation is vital for preservation and study.

**Offshore energy infrastructure**, such as pipelines, wind farm bases, and subsea platforms, where spatially accurate digital twins assist in inspection, maintenance planning, and risk assessment.

**Marine and freshwater habitat mapping**, including tropical, temperate, and cold-water ecosystems such as coral gardens, rocky reefs, benthic zones, lakes, and riverbeds. These environments can benefit from digital twins to support ecological monitoring, biodiversity assessment, and restoration planning.

**Virtual training environments** for technical divers or marine researchers, where immersive simulations improve preparedness while reducing real-world risk.

These examples highlight the adaptability and scalability of the Yuba methodology across scientific, industrial, and cultural domains.

### 7.2 Vision and outlook

The integration of advanced technologies such as multi-temporal photogrammetry and virtual reality further enhances the capabilities of the digital twin. This project sets a precedent for future large-scale marine mapping initiatives, emphasizing the importance of interdisciplinary collaboration in addressing environmental challenges. It stands as a powerful tool for biodiversity preservation, public education, and the long-term sustainability of marine ecosystems.

Completed in early 2025, the Yuba Digital Twin spans 147 ha of high-resolution underwater 3D modeling, making it one of the largest and most detailed models of its kind to date. This achievement marks a significant milestone in marine exploration and spatial analysis, unlocking new opportunities to understand underwater ecosystems, hydrodynamics, and reef structures. The Yuba Digital Twin combines machine vision with human insight, bridging the gap between traditional static 3D models of underwater environments – which typically eliminate caustics, waterborne color effects, and moving marine life considered 'ghosts' – and the immersive experience of real divers.

Just as early explorers laid the groundwork for modern science, the pursuit of curiosity across disciplinary boundaries remains essential – even when its immediate benefits are not always clear. High-resolution underwater digital twinning allows researchers to expand scientific understanding, develop innovative documentation methods, and gain new perspectives on the marine world. These advances provide a solid foundation for future research, shaped by emerging questions and evolving technologies.

## Copyright



## References

Agisoft LLC, 2024. Photogrammetry + LiDAR – Agisoft Metashape. agisoft.com/pdf/metashape_presentation.pdf

Agrafiotis P., Skarlatos D., Forbers T., Poullis C., Skamantzari M., Georgopoulos A., 2018: Underwater Photogrammetry in Very Shallow Waters: Main Challenges and Caustics Effect Removal. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci*., XLII-2, 15-22. doi.org/10.5194/isprs-archives-XLII-2-15-2018.

Ceccherelli, G., Chiabrando, F., Gallitto, F., Lingua, A., Longhi, V., Maschio, P., Matrone, F., Menna, F., Nocerino, E., Scalici, M., Secco, S., & Tanduo, B., 2024: Multitemporal seagrass mapping and monitoring of Posidonia meadows and banquettes for blue carbon conservation: The Poseidon project. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.,* XLVIII-1, 65–72. doi.org/10.5194/isprs-archives-XLVIII-1-2024-65-2024

Christ, R.D., Wernli Sr., R.L., 2007. *The ROV Manual: A User Guide for Observation-Class Remotely Operated Vehicles*. Butterworth-Heinemann, Oxford, pp. 96–103.

de Koning, K., Broekhuijsen, J., Kühn, I., Ovaskainen, O., Taubert, F., Endresen, D., Schigel, D., & Grimm, V., 2023. Digital twins: Dynamic model–data fusion for ecology. *Trends in Ecology & Evolution*, 38(10), 916–926. doi.org/10.1016/j.tree.2023.04.010

Floros, C., Samways, M., Armstrong, B., 2004: Taxonomic patterns of bleaching within a South African coral assemblage. *Biodiversity and Conservation* 13, 1175–1194. doi.org/10.1023/B:BIOC.0000018151.67412.c7

Grossmann, V., Nakath, D., Urlaub, M., Oppelt, N., Koch, R., and Köser, K., 2022: Digital twinning in the ocean – challenges in multimodal sensing and multiscale fusion based on faithful visual models, *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci*., V-4-2022, 345–352. doi.org/10.5194/isprs-annals-V-4-2022-345-2022.

Hughes, T., Kerry, J., Álvarez-Noriega, M. et al., 2017. Global warming and recurrent mass bleaching of corals. *Nature* 543, 373–377. doi.org/10.1038/nature21707

Jerlov, N.G., 1976. *Marine Optics*. Elsevier, Amsterdam, 231 pp.

Jung, Y.-H., Kim, G., Yoo, W.S., 2021. Study on Distortion Compensation of Underwater Archaeological Images Acquired through a Fisheye Lens and Practical Suggestions for Underwater Photography – A Case of Taean Mado Shipwreck No. 1 and No. 2. *Journal of Conservation Science*, 37(4), 312–321. doi.org/10.12654/JCS.2021.37.4.01

Mandlburger G., 2021: Bathymetry from Images, LiDAR, and Sonar. *PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science,* Vol. 89, Issue 2, 69-70. doi.org/10.1007/s41064-021-00153-0

Marshall P.A., Baird A.H., 2000: Bleaching of corals on the Great Barrier Reef: differential susceptibilities among taxa. *Coral Reefs*, 19(2), 155-163. doi.org/10.1007/s003380000086

Menna, F., Nocerino, E., Fassi, F., Remondino, F., 2016. Geometric and Optic Characterization of a Hemispherical Dome Port for Underwater Photogrammetry. *Sensors*, *16*(1), 48. doi.org/10.3390/s16010048

Otero, P., Hernández-Romero, Á., & Luque-Nieto, M.-Á., 2022. LBL System for Underwater Acoustic Positioning: Concept and Equations. DOI:10.48550/arXiv.2204.08255

Sarakinou I., Papadimitriou K., Georgoula O., Patias P., 2016: Underwater 3D Modeling: Image Enhancement and Point Cloud Filtering. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci*., XLI-B2, 441-447. doi.org/10.5194/isprs-archives-XLI-B2-441-2016.

She, M., Seegräber, F., Nakath, D., Köser, K., 2024. Refractive COLMAP: Refractive Structure-from-Motion Revisited. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Abu Dhabi, UAE, pp. 12816-12823. doi.org/10.48550/arXiv.2403.08640

Smith, R.C. & Baker, K.S., 1981. Optical properties of the clearest natural waters (200–800 nm). *Applied Optics*, 20(2), 177-184. doi.org/10.1364/AO.20.000177

Stimson J., Sakai K., Sembali H., 2002: Interspecific comparison of the symbiotic relationship in corals with high and low rates of bleaching-induced mortality. *Coral Reefs*, 21(4), 409-421. doi.org/10.1007/s00338-002-0264-3