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Review

A Systematic Review of UAVs for Island Coastal Environment and Risk Monitoring: Towards a Resilience Assessment

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Abstract: Island territories and their coastal regions are subject to a wide variety of stresses, both natural and anthropogenic. With increasing pressures on these vulnerable environments, the need to improve our knowledge of these ecosystems increases as well. Unmanned Aerial Vehicles (UAVs) have recently shown their worth as a tool for data acquisition in coastal zones. This literature review explores the field of UAVs in the context of coastal monitoring on island territories by highlighting the types of platforms, sensors, software, and validation methods available for this relatively new data acquisition method. Reviewing the existing literature will assist data collectors, researchers, and risk managers in more efficiently monitoring their coastal zones on vulnerable island territories. The scientific literature reviewed was strictly analyzed in peer-reviewed articles ranging from 2016 to 2022. This review then focuses on the operationalization of the concept of resilience as a risk management technique. The aim is to identify a procedure from raw data acquisition to quantifying indicators for the evaluation of the resilience of a territory and finally linking the analyzed data to a spatial decision support system. This system could aid the decision-making process and uses the islands of French Polynesia and its Resilience Observatory as a case study.

Keywords: Unmanned Aerial Vehicles (UAVs); coastal monitoring; island territories; resilience assessment; spatial decision support system

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1. Introduction

Coastal environments serve as the transition zone connecting marine and terrestrial ecosystems. With approximately 40 percent of the human population living within 100 km of a coast, these regions are some of the planet's most productive and valued ecosystems [1]. Today, population densities in coastal regions are more than three times higher than the global average [2]. Unfortunately, coastal environments are subject to a wide variety of stresses, both natural and anthropogenic. While natural factors such as sea-level rise, erosion, and flooding are exacerbated by the encroaching threat of climate change, anthropogenic factors fuel this change in climate, creating a disastrous feedback loop. The increasing vulnerability of these ecosystems highlights the need to identify the limits and equilibrium of these environments in order to increase their resilience. Island territories naturally host these environments and are rendered even more vulnerable because of them. In most of these island territories, the inhabitants, agriculture, recreational activities, infrastructure, and tourism are condensed along coastal areas, which generates a linear urbanism that is particularly vulnerable to coastal risks [3].

The definitions of the terms vulnerability and resilience have been conceptualized in many ways and therefore require precision for the purpose of this study. The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability as the degree to which a system is susceptible to, or unable to cope with, the effects of potential hazards [3]. Resilience, on the other hand, “expresses the ability to resist, absorb, and recover from the effects of the hazard in an efficient and timely manner” [4,5]. Coastal management should aim to preserve, protect, develop, and restore the resources of coastal zones [6]. Thus, a sustainable system for coastal management must incorporate risk monitoring and mitigation, not only seeking to reduce the vulnerability of an environment but also fostering its resilience to future uncertainties and potential risks [5]. Vulnerability and resilience are integrated concepts used to characterize and understand how systems respond to and cope with changes.

These coastal environments can undergo rapid morphological changes, which can have important socio-economic implications, especially along coasts with high commercial, recreational, and ecological value [7]. These changes can be both naturally occurring such as receding shorelines due to storm erosion [8] or induced/accelerated by anthropogenic processes such as intensive coastal development from port expansion [7]. With increasing anthropogenic and natural pressures on island territories as well as their coastal regions, the need to increase our understanding of these specific ecosystems increases as well. A first step in doing so is to perform repetitive surveys [6]. These efforts allow for effective and efficient monitoring of these environments, which can help inform management decisions [9]. Monitoring these environments comes with challenges, and methods vary extensively based on cost, duration, and accuracy [10]. Aerial approaches are the most common today, and the most generally used methods come in the form of aerial photography (by aircraft), satellite images, airborne light detection and ranging technology (LiDAR) by aircraft, and most recently, by Unmanned Aerial Vehicles (UAVs). Each source provides unique information accompanied by both benefits and limitations. For instance, satellite images can outline shoreline changes temporally and provide remote sensing approaches; however, these images require suitable climatic conditions and have relatively low resolutions. Airborne aircraft LiDAR, on the other hand, does not require a specific weather condition in order to provide accurate Digital Surface Models (DSM), but is relatively costly compared to other sources [6].

While these monitoring methods do have their advantages, when it comes to coastal management and risk assessment, their limitations do not allow for repetitive monitoring at high temporal frequencies. This frequency is a necessity in order to obtain up-to-date information to be able to make decisions, especially when dealing with an environment that undergoes fast morphological changes [6]. Numerous studies have recently shown the effectiveness of using Unmanned Aerial Vehicles (UAVs) for coastal monitoring, refs. [6,8–18], as it allows for an increase in the frequency of monitoring campaigns at a lower cost while obtaining comparable accuracy to LiDAR data, which is the most utilized and available method today for aerial data [6]. Creating said digital models with high spatial resolution levels is important for obtaining predictive data that can adequately provide useful information for decision-makers. The use of UAVs in the context of coastal monitoring on island territories is relatively recent in the scientific literature and not extensively documented; thus, the topic would benefit from a review allowing for an agglomeration of contextualized studies to be analyzed.

The islands of French Polynesia are particularly vulnerable to five major risks: erosion, marine submersion, floods, cyclones, and tsunamis [19]. According to the IPCC definition, risk is characterized as "the potential for consequences where something of human value is at stake and the outcome is uncertain". At the same time, a risk is often represented as "the probability of occurrence of hazards multiplied by the consequences if these events occur" [3]. Certain areas of French Polynesia, specifically Tahiti, the most populated and largest island, are particularly vulnerable due to recent population booms and are therefore heavily subjected to urban development along the coastal plains and therefore exposed to coastal hazards. Monitoring these types of regions is essential when performing risk assessments of littoral zones in French Polynesia. Aerial data sources such as aerial photography (by aircraft), satellite images, and airborne LiDAR are all currently utilized in French Polynesia for remote sensing and spatial modeling in order to predict, prevent, and combat risks in littoral zones; however, UAV approaches remain relatively uncommon. Additionally, the specific geomorphology and geography of the high islands and atolls of French Polynesia do not allow for the development of the same adaptation strategies as on a continental coastline. For example, relocation is not possible when the island is entirely made up of a narrow coastal plain, such as in Tahiti or Bora Bora. Consequently, the assessment of the resilience of these coastal island environments is specific to these particular environments.

After acquiring data from aerial data sources, it is necessary to analyze, structure, and store said data to make it accessible in order to extract tangible knowledge that can aid the decision-making process. Spatial decision support systems such as observatories are an efficient way to aggregate data and transmit synthesized information [20]. Such an observatory is currently under development in Tahiti. The spatial decision support system in French Polynesia, the "Resilience Observatory" stems from the ILOTS (Pacific Island Long Term Resilience) project funded by IRD-CNRS in 2015. While this project primarily focuses on the flooding risks in French Polynesia, the fundamental goal is to increase territorial resilience through the use of this spatial decision support system. Including coastal risks is a necessity when managing an environment that relies so heavily on littoral zones, such as French Polynesia. In conclusion, the Resilience Observatory serves as a tool to support decision-making to increase territorial resilience in the context of risk assessment in French Polynesia.

The objective of this paper is to review the scientific literature focused on the application of UAVs for coastal monitoring on island territories by assessing the current state of research and the primary benefits and barriers of this method of data acquisition. This review will focus specifically on the scale of coastal oceanic island territories. This study extends its analysis by identifying how this aerial data acquisition can be utilized for the operationalization of the concept of resilience and linking it to the development of a spatial decision support system in French Polynesia, which will facilitate the comprehension and acceptance of these results in order to provide useful information to decision makers.

2. Methodology

A scholarly article search on multiple databases: Google Scholar, ScienceDirect, JSTOR, and Scopus was conducted using the search terms "island UAVs coastal risks", "drone coastal risks", "atoll UAV coastal monitoring", "island UAV application coastal environment", "island UAV coastal photogrammetry", "UAV coastal management", and "island UAV coastal survey". The search was limited to articles in English and did not have a time limitation. This study did not include non-peer-reviewed articles or doctoral dissertations. Studies referencing underwater drones were not taken into consideration for this study. At times, when several articles were published by the same team on the same study site, only one of the articles was used for analysis because they used similar equipment, software, etc. A preliminary broad search was conducted on the search engines mentioned previously to select all the studies that dealt specifically with UAVs for coastal monitoring or coastal risk assessment. A total of 138 relevant papers were found concerning this specific theme. The procedure of scanning a database for relevant articles consisted of an advanced search option using the previously mentioned search terms and selecting article titles and abstracts that matched the search description. After a dozen pages, the articles either repeated themselves or no longer fit the search description, which prompted the assumption that this database had been properly scanned. This procedure was repeated for every search term on a variety of databases. Once this first compilation of articles was completed, a second selection was conducted to select studies that occurred specifically on island territories. Of these 138 papers, 28 of them used oceanic island territories as study sites. Finally, 19 of these papers were selected for further analysis as they included specific and relevant information on hardware, software, cameras, production generation, field validation methods, and benefits and limitations (see Table 1). The 9 articles not included in the final analysis were removed due to either missing information or repetition of the study site and/or object of study. The time period of the identified literature ranges from 2022 to roughly a decade ago. In 2009, articles about the use of UAVs for coastal research began to appear; however, these articles remained theoretical and analyzed the feasibility of such a tool. User-friendly photogrammetry software (such as Pix4d and Agisoft Metashape) began to appear in 2010, and in 2013, articles began applying these notions to monitoring and research. The 19 articles selected for further analysis, however, range from 2016 to 2022.

Table 1. Summary of unmanned aerial vehicle (UAV) use in island territories for coastal zone monitoring research.

Location	Platform	Sensor	Object of Study	Research Question	Production	Limitations	Reference
Lefkada Island, Greece	DJI Phantom 3 Professional	DJI FC330	Seismic rockfall	Analytical reconstruction and modeling of rockfall trajectory by UAV post-earthquake	High resolution orthomosaic and digital terrain model	- Experience required- Too many GCPs	[21]
Samoylov Island, Russia	Supercam S 250, Unmanned Systems	Sony Alpha 6000	Ice wedges	Assessing the status of ice wedge polygon degradation with UAV data	Orthophoto maps and digital terrain model maps	Photogrammetry software limitations with water surfaces	[22]
Hainan Island, China	DJI M600	Velodyne VLP—16 Puck (LiDAR)	Mangrove forests	Estimating and mapping the mangrove height and aboveground biomass	Digital elevation and surface models	Limited by loading capacity, thus weaker (lighter) LiDAR sensor	[23]
Malta, Northwestern Coast	DJI Mavic	DJI FC330	Coastal landslides	Advantages of using drones to study large, slow-moving coastal landslides	Orthomosaics and 3D models	- Restrictive regulations- Skilled operator required- Negative effect of vegetation on the point cloud	[24]
Sipadan, Malaysia, and Sasahura Ite, Solomon Isles	DJI Phantom 4	DJI FC330	Reef-island shoreline	Assessing shoreline change on the reef islands using UAV-derived models	Orthomosaics and digital surface models	- Limited spatial cover- GCPs: consumes time	[25]
Five Island Nature Reserve, Australia	DJI Phantom 4	DJI FC330	Island coastal vegetation	Technique evaluation for mapping changes in island vegetation after herbicide spraying with UAVs	Orthomosaics for pixel classification	Three-band RBG cameras provide limited spectral data	[26]
Syros Island, Greece	DJI Phantom 3 Advanced	DJI FC330	Beach rock formations	Detection and investigation of beach-rock formations in shallow waters through synergetic UAVs	Orthomosaics and digital surface models	- Light waves reduce the quality of DSM	[27]
Krk Island, Croatia	DJI Phantom 4 Pro	DJI FC6310	Geology of coast	UAV for the analysis of geological hazards due to sea level rise	Orthomosaics and 3D point cloud	- Refraction correction is required - Clear sea conditions are needed for bathymetry	[28]
Jeju Island, South Korea	DJI S1000	FLIR T450sc (thermal infrared)	Groundwater discharge	Thermal infrared mapping by UAV to assess groundwater discharge into the coastal zone	Sea surface temperature maps	Limited spatial coverage	[29]
Pegasus Bay, New Zealand	DJI Phantom 4 Pro	DJI 1 inch CMOS	Beach cusps	UAV techniques to expand beach research, beach cusps case study	Orthomosaics and digital surface models	- Weather sensitive- Non-water penetrating sensors	[30]

Table 1. *Cont.*

Location	Platform	Sensor	Object of Study	Research Question	Production	Limitations	Reference
Poplar Island, Maryland USA	DJI Phantom 3 Professional	DJI FC300X	Tidal systems	Monitoring channel morphodynamics and vegetation variations	Orthomosaics and digital terrain models	Too many GCPs (RTK needed)	[31]
Maltese Islands	DJI Phantom 4 Pro	1 ″ Exmor R CMOS image sensor	Geological Surveys	Using UAV photogrammetry for digital geological surveys	Orthomosaic, digital elevation model, digitalized fractures map	- GCP accessibility - Weather conditions - Camera visibility	[32]
Sijiao Island, China	DJI Phantom 4 Advanced	DJI FC330	Dykes	Semi-automatic mapping of dyke and dyke related fractures using UAV-based photogrammetry	Orthophotos and digital elevation models	Not specified	[33]
Illawarra Coast, Australia	DJI Phantom 4	DJI FC330	Rock platforms	Identifying rocky platform morphology for hazard management	Photomosaic and digital surface models	Not specified	[34]
Qi'ao Island, China	Multi-rotor UAV platform (not specified)	UHD 185 (hyperspectral)	Mangrove species	Mangrove species classification	Digital surface models from hyperspectral images	- Water reflection- Turbidity	[35]
Lesvos Island, Greece	Iris+	Canon 130	Coastline change	Coastline change detection using UAVs and image processing techniques	Digital surface models and orthophotos	- Limited spatial coverage	[36]
Dongshan Island, China	MD4-1000 Microdrones	Pentax option A40	Beach topography	Monitoring beach topography change using UAVs	Orthomosaics and digital surface models	- A lot of GCPs for high vertical accuracy- Battery life for larger spatial coverage	[37]
Maltese Islands	DJI Phantom 4 Pro	DJI FC330	Beach litter	Optimizing protocol for beach litter monitoring	Litter density maps	- Sun glint- Turbidity	[38]
Java Island, Indonesia	Bixler UAV	Canon A2500	Coast topography	Topographic data acquisition in tsunami-prone coastal area using UAVs	Orthomosaic and digital surface model	- Battery life - Wind - Radio interference	[39]

3. Results

Of the 19 studies reviewed, the object of study varied between three main themes (Table 2): coastal geomorphology (n = ten), coastal vegetation (n = four), and lastly, disaster management (n = five). Table 1 agglomerates and synthesizes the content within these 19 studies. The following results identify the different study sites, the object and thesis of the study, the production, the two main types of UAV platforms, the variety of sensors utilized for data acquisition, the software utilized during all steps of the process, and the different methods for georeferencing the data. Table 2 additionally allows for the identification of the types of platforms and sensors according to the three main themes found within the articles reviewed. The following Tables 3 and 4 go into specific detail about each platform and sensor, identifying the brand, model, and specifications.

Table 2. Summary of the distribution of articles within the main themes.

	Number of Studies	Platform	Sensor	References
		Fixed wing		[22]
				[27]
				[36]
				[30]
Coastal Geomorphology	n = 10		RGB Camera	[33]
				[28]
				[34]
				[37]
				[32]
		Multi-rotor	Thermal infrared	[29]
			LiDAR	[23]
Coastal Vegetation	n = 4		Hyper-spectral	[35]
				[31]
				[26]
				[21]
			RGB Camera	[24]
Disaster Management	n = 5			[25]
				[38]
		Fixed wing		[39]

3.1. Platforms

While there are a variety of types of UAV platforms, two types of platforms appeared in the studies within this review: multi-rotors and fixed-wings. Out of the 19 studies reviewed, 17 of them used multi-rotor drones (Table 3). Most of these studies used DJI UAVs (n = 14) with a handful of different models. DJI UAVs are increasingly used because of their user-friendliness and high quality at a relatively low cost (depending on the model). DJI UAVs range from consumer to enterprise level, allowing for a broad assortment of models capable of fitting different needs. Two of the articles reviewed used non-DJI multi-rotors [36,37]. These studies do not give reasons for their choice of using a different brand, but some explanations can be linked to lower prices or the possibility of manipulating hardware, rendering the UAV more adapted to a specific context. The final two studies were the exception to this review and used fixed-wing UAVs [22,39]. The fixed-wing drones used by both studies were, respectively, a Supercam Unmanned System and a Bixler UAV model; however, within the other studies analyzed during the review that were not selected as the final 19, eBee-wing platforms were the most commonly used fixed-wing platforms. The two fixed-wing studies fall under two different themes (Table 2): disaster management and coastal geomorphology. The main reason identified for using fixed-wing UAVs is the possibility of a longer flight time (between 1–2 h in the air), allowing for a larger spatial coverage [22,39]. Coastal zones can be wet, narrow, and/or have rough terrain, making it difficult to find a safe and dry spot for taking off and landing. Some studies have even added buoyancy devices to UAVs to allow for water landings [40]. The studies reviewed utilized a UAV platform suited to the environments and needs; much like a plane compared to a helicopter, choosing your platform depends on the objective and parameters of the mission.

Table 3. Summary of platforms utilized within the literature review.

	Number of Studies	Manufacturer	References
Fixed Wing	n = 2	Supercam S 250, Unmanned Systems	[22]
		Bixler UAV	[39]
Multi-Rotor	n = 17	DJI (n = 14) Quadcopter Iris+ MD4-1000 Microdrones Brand not specified	[21,23–34,38] [36] [37] [35]

Table 4. Summary of sensors attached to the UAVs in the literature review.

Sensor Type	Model and Specs	Resolution	Weight (g)	Price ($)	Reference
RGB Camera	DJI FC330 3.61 mm 1/2.3″ CMOS	12.4 Megapixels (MP)	-	1599.00 (sold with UAV)	[21,25–28,31,33,34,38]
	Canon ELPH 130	16 MP	131	199.00	[36]
	Sony Alpha6000 24.7 MP APS-C	24.7 MP	344	648.00	[22]
	DJI 1 inch CMOS	20 MP	368 (with gimbal)	1995.00 (sold with UAV)	[30]
	Pentax option A40 7.9 mm	12 MP	150	249.00	[30]
	Canon A2500 1/2.3	16 MP	135	150.00	[39]
LiDAR	Velodyne VLP—16 Puck	16 channels, ~300,000 points/s	830	8800.00	[23]
Hyper-spectral	UHD 185 hyperspectral	125 bands	490	3790.00	[35]
Thermal Infrared	FLIR T450sc (thermal infrared)	From −40 °C to +650 °C	880	5000.00	[29]

3.2. Sensors and Cameras

Out of the 19 studies reviewed in this study, 16 used Red, Green, and Blue (RGB) cameras. The other three used thermal infrared, LiDAR, and hyperspectral to observe a different spectral range (Table 4). Of the 16 studies that utilized RBG cameras, 11 of them used the factory-installed cameras that came with the DJI UAV. This is most likely due to the ever-increasing development of lightweight cameras. Studies that chose to attach their own RGB cameras (n = 4) used handheld devices such as the Sony Alpha, which has the benefit of high image resolution. There are significantly more RGB cameras used today because of the low cost and facilities that come with the photogrammetry process. Recent improvements in sensors have allowed for sensors such as thermal infrared, LiDAR, and multi- and hyperspectral to be attached to the platforms of UAVs. While the price and weight of these kinds of sensors have been decreasing with time and technological advancements, the prices remain relatively high, which explains the smaller number of studies using these sensors. Hyper/multispectral and thermal infrared sensors are particularly useful for the identification and characterization of specific materials. Different materials reflect specific wavelengths, thus rendering the possible differentiation of materials by their spectral reflectance signatures in remotely sensed images. Within the literature, studies using hyper/multispectral and thermal infrared sensors tend to analyze vegetation [29,35,41]. Table 2 reinforces this point, as out of the three studies that used sensors other than RGB cameras, two of them were in the coastal vegetation theme. RGB cameras do not have the same spectral information and are more generally used to discriminate land surface features and landscape patterns, for example, in littoral zone mapping [34,37]. Similarly, LiDAR sensors are used for elevation measurements and serve as an excellent tool for topographic data acquisition [23].

3.3. Software

The development of various flight planning, image acquisition, and postprocessing software today allows for the utilization of UAVs for coastal monitoring. The parameters and flight procedure differ depending on the object of study and research question; therefore, so does the software. A variety of different mission planning software exists; in fact, most UAV platforms come with their own software for mission planning and in-flight controls; however, most of the articles reviewed left out the specifics of which software was used. This software is utilized for programming flight time, position, and altitude and serves as an effective tool for spatially visualizing the progress of the UAV. In addition, this software generally allows for a hands-free, automatic procedure. There exists numerous software for image processing (Table 5). Most of the studies analyzed used RGB cameras with the goal of obtaining 3D models; thus, the majority of studies utilized photogrammetry software such as Agisoft Metashpae and PiX4D Mapper. This software was used for georeferencing, creating point clouds, making orthomosaics, and creating 3D models. Agisoft Metashape was the most commonly used for photogrammetry applications. Additional software was used for the more specific sensors such as LiDAR, thermal infrared, and hyperspectral. A majority of the spatial analyses utilized the GIS software ArcGIS. ROCFall and MATLAB were among the other spatial analysis software used for other postprocessing needs. Finally, almost every study listed ArcGIS as the software used for map production.

Table 5. Summary of software used by the studies in the literature review.

Workflow	Software	Uses	Reference
Mission planning	DJI Flightplanner	Flight path and planning	[24]
Imaging	Agisoft Metashape	Photogrammetry	[39]
	Photomod package	Photogrammetry	[22]
	OpenDroneMap	Photogrammetry	[38]
	EasyUAV	Photogrammetry	[33]
	PiX4Dmapper	Photogrammetry	[25]
	ERDAS Imagine	Orthophoto processing	[27]
	POSPac UAV	LiDAR point cloud	[23]
	LiDAR360	LiDAR digital model production	[23]
	ResearchIR	Thermal infrared imagery processing	[29]
	Cubert-Pilot	Hyperspectral image fusing	[35]
Analysis	ArcGIS	GIS analysis and geomorphological mapping	[37]
	ROCFall	Rockfall analysis	[21]
	MATLAB	Cross-sectional analyses	[28]
Visualization	ArcGIS	Map production	[37]

3.4. Georeferencing and Validation Techniques

As mentioned earlier, photogrammetric methods dominated this review because of the user-friendly software and cheaper sensors. In order to properly spatially represent the data, a georeferencing process must occur. Almost all available lightweight UAVs are equipped with a Global Positioning System (GPS) and a low-cost Inertial Measurement Unit (IMU) [42]. This GPS is not sufficient for proper 3D mapping applications. The most conventional method for georeferencing UAV images is with the help of Ground Control

Points or GCPs [42]. GCPs are points on the surface of the ground with known coordinates and can theoretically be made from anything; they just need to be easily recognizable on the aerial images. Most commonly used are checkerboard squares, which ensure a high-contrast pattern and are easily recognizable. In addition to the artificial GCPs, several natural points that are also easily recognizable can be used as ground control points. Independent control points, or ICPs, are also required to ensure high spatial precision and accuracy. ICPs are coordinates acquired by a Global Navigation Satellite System (GNSS) directly on the ground and serve as a survey of validation points. The ground, natural, and independent control points can all be identified spatially with the help of a higher-grade GNSS. This georeferencing process through GNSS surveying serves to measure the error between the UAV-obtained data by comparing it to in situ independent control points (ICPs). This method measures the vertical accuracy of the points, which is referred to as the root mean square error (RMSE). While not all the articles mentioned the RMSE of their models, the ones that did were all under 30 cm, with the most accurate studies reaching as little as 1.5 cm of error [31]. A study off the coast of western France compared the accuracy of a traditional UAV photogrammetry protocol to LiDAR data and states that their obtained RMSE is lower than 17 cm, which is slightly better than that of the LiDAR's [8]. Additionally, some of the studies required in situ validation in addition to the GCPs in order to complement the data acquired by the UAV and assess its accuracy. Subsequently, remote sensing analysis requires field validation to assess the reliability of the final outputs. For instance, studies creating vegetation maps, such as [23,26,35], all used in situ measurements to validate their data. These in situ measurements can take the form of pictures or samples taken on the ground to validate that the data acquired in 3D models corresponds.

4. Discussion

4.1. UAVs for Coastal Zone Monitoring in Island Territories

4.1.1. Benefits and Advantages

Recent developments and improvements in technology have allowed for UAVs to become important tools in the fields of environmental monitoring and conservation [9]. The range of types and sizes of UAVs differs widely, from light handheld UAVs to large industrial platforms capable of carrying dozens of pounds, as well as different types of platforms such as flying wings similar to planes and multi-copters closer to helicopters. This variability in platform type and size allows for UAV research to adapt to the specific object and study site. The latest technology of UAVs additionally allows for specific sensors, cameras, or even test tubes to attach on to the UAV, adding to the adaptability of this tool [41]. The accessibility, price, simplicity, and high-resolution data help show that these spatial tools are capable of complementing or even replacing other aerial data sources such as satellites and aircraft [43]. The affordability of UAVs both in time and price for coastal monitoring and research has been documented in recent scientific literature as well as within every study analyzed in this review [22,27–30,33].

UAVs have been commercialized over the past decade due to the increase in demand for this technology, which has lowered the price of these devices all the while improving their quality. This commercialization has allowed for user-friendly UAVs and software that have the capacity for pre-flight planning and autonomous flights. Another advantage of using UAVs for research is their ability to fly at lower altitudes and their maneuverability [21]. Flying at low altitudes allows for finer spatial resolution output in addition to not being affected by cloud cover and thus not being as constrained by weather conditions. Subsequently, the high levels of maneuverability provided by using UAVs increase spatial coverage and provide access to areas previously unattainable by airplanes and helicopters [37]. Although not integrated into the review because this study focuses on coastal monitoring, UAVs have, with very clear water, allowed ordinary RGB cameras to obtain information on underwater domains such as coral reef conditions, bathymetric surveys, or species identification, refs. [12,44–46], a possibility unavailable to other aerial data sources.

A factor to consider when observing elements along the coast is the altitude of the UAV. A study was conducted on the Turneffe Atoll in Belize, which analyzed the influence of altitude on tropical marine classification using imagery from UAVs [47]. This study determines which altitude is best suited for images taken in five different classes of environmental settings. When observing mangroves, the ideal altitude is 75 m; for sand, an altitude of 85 m was the best of the three altitudes compared. Seagrass is best observed at an altitude of 75 m, while coral images are more effective at 85 m. Finally, when observing the sea, 85 m was the best of the three altitudes tested [47]. Using UAVs that have the capacity to fly at these precise low altitudes allows for these spatial tools to adapt to the study site being observed.

The reviewed studies also suggest that the monitoring of coastal zones prone to disasters by UAVs has noteworthy advantages due to its rapid deployment (low time mission planning), high level of automation, and the possibility of inspecting the images on the terrain in the case of RGB camera use. These factors can allow users to catch errors early on and repeat the survey if necessary [24,30,37]. Considering these benefits, this aerial data source allows for frequent repetitive surveys, which, in the case of island territories, is an essential factor due to the high vulnerability, limited accessibility (rough terrain), and rapid morphological changes of the territory [48].

Additional advantages are low security risks and costs in case of accidents, and risk awareness capacities [6]. UAV imagery and footage can be used as a communicative tool for raising awareness in a community by highlighting environmental hazards and engaging stakeholders at various levels. High-resolution data collected from UAV platforms also has the capacity to provide a rapid overview of the disaster area [43].

Due to the technical advancements made over time, UAVs are helping with the complex task of coastal environmental disaster monitoring and have the potential to greatly increase the availability of data for spatial modeling, specifically in vulnerable and complicated to access/maneuver through territories. The technical advantages, the possibility for frequent surveys, and the capacity for community awareness and communication are advantages that allow UAVs to serve as efficient tools and have the potential to present local authorities and decision-making bodies with a more global picture of the environmental impacts [43].

4.1.2. Limitations and Challenges

Much like all other aerial data sources, there are also some shortcomings to using UAVs as a tool for coastal monitoring. Both types of platforms mentioned in the review have their respective limitations. Multi-rotor UAVs are advantageous due to their capacity to operate at low speeds, their maneuverability, and their vertical takeoff and landing abilities. Due to these benefits, multi-rotor UAVs can be used for closer data capture, such as 3D coastal mapping [49]. For these reasons, in the context of coastal monitoring in island territories, these platforms tend to be prioritized over fixed-wing aircraft. However, multi-rotor UAVs require a substantial amount of battery life and are generally limited to about 30 min of flight time (depending on meteorological conditions) [6]. Fixed-wings, on the other hand, are more aerodynamic and have the added benefit of longer flight durations, thus covering more ground, but they are less maneuverable and require extended stretches of dry, flat, and unobstructed land to take off and land. Despite a fixed-wing UAV's capacity to cover more ground than a multi-rotor, these UAVs cannot compete with manned aircraft. A comparison between the aerial coverage areas of UAVs and those of manned aircraft reveals that UAV aerial surveys are more suitable for covering comparatively smaller areas (0.01–1 km^2), while manned aircraft are a useful tool for capturing larger-scale dynamics (10–1000 km^2) [29]. Furthermore, the operational distance is limited by the radio link range with the ground control station, which is usually around 5 km [39].

In addition, there are many laws and regulations that limit where and how far you can fly the UAV, depending on the country. France's airspace, when dealing with UAVs, is relatively controlled compared to other countries, requiring a certain amount of preparation and paperwork, especially in French Polynesia because of the proximity of the airports. Thus, specific permits and licenses are required. A variety of studies listed respecting these regulations and acquiring licenses and authorizations as a challenge to overcome [24,38,45].

Environmental conditions are a non-negligible factor that light or commercial UAVs can encounter when monitoring coastal areas compared to other environments. The first is the weather, more specifically, wind and rain. High winds cause platform instability, which reduces image quality and puts more strain on the battery life, reducing the surface coverage of a flyover [39]. Some drones have the capacity to be waterproof and highly stabilized, thus withstanding high winds and precipitation; however, the UAV platforms reviewed in this study did not have these advantages. This problem is decreasing as operational developments of UAVs increase at a rapid pace. Today, lightweight UAVs can easily operate when wind gusts are lower than 25 km/h. Another weather condition limitation mentioned by several studies is the reflection of the sun, specifically in the intertidal and mangrove studies, as well as the issue of turbidity to be able to see through the water [28,35,38].

The second issue is posed by crashing waves or large bodies of water, which can prevent the application of matching techniques. In these cases, masking techniques are used to avoid these areas from being used for point matching, essentially treating these areas independently in terms of ground control [6]. Other studies mentioned difficulties with the postprocessing software. One study [22] encountered complications with mosaicking as well as having to manually contour water bodies because of the limitations in the photogrammetry software. Studies also mentioned complications such as a negative effect of vegetation on the point cloud [24] or limitations in the spatial analysis software for rock fall analysis [21]. The consequences of distortion within the images captured affected a variety of studies as well [21,35,38].

The majority of small commercial UAVs are not suitable for lifting, so attaching LiDAR sensors or higher-capacity cameras is impossible. Attaching a sensor requires a larger UAV, which increases the price of the platform. One of the studies [23] mentioned that the sensor capacity was limited due to the UAV's inability to lift a heavier LiDAR sensor. Subsequently, despite the large number of sensors (GPS, IMU, etc.) on board a UAV, the produced sensor data does not have the precision required for georeferencing applications, hence the need for GCPs [18]. GCPs in general posed problems to several studies [21,25,31,32,37]. For instance, GCPs in long-term beach studies were identified as a challenge since the beach was constantly changing. Additionally, GCPs cannot be placed on the water and can be moved by incoming tides. Setting out evenly distributed GCPs for image capture due to the inaccessibility of some coastal areas proved to be challenging [25]. The entire GCP process, from laying out the targets to processing the GPS points, was listed as a time-consuming challenge [21,25,37].

A solution to these issues is using a Real Time Kinematic (RTK)-equipped UAV [42]. The RTK system is a precise positioning technique that uses a carrier phase processing GPS signal [50] on board the UAV to provide high-performance positioning accuracy of a few centimeters. Studies have shown that an RTK UAV is capable of using zero to one GCP to properly georeference the data [31]. Using an RTK-equipped UAV thus removes the need for GCP, which has three distinct advantages. The first is the decreased time taken to complete the surveys; the second is the accessibility that it offers; for instance, less accessible coastal areas like coastal cliffs or wetlands are now as simple to survey as an open beach; and the third is being able to do all this while obtaining similar or even higher resolution data [51].

A variety of studies have analyzed the advantages of using RTK-GNSS methods. The authors of [52], for instance, compared the precision of data acquired by RTK-UAV with and without GCPs and found little to no difference in horizontal precision with a slight decrease in vertical precision (+/−4 cm). The study concludes that both the mean values and the standard deviations show that the lack of GCPs did not significantly affect the final reconstruction of the 3D model of the coastal section [51,52]. Thus, in the context of coastal monitoring in island territories, the RTK method would be most beneficial due to the limited amount of GCPs required, thus allowing for larger surface coverage over a shorter time period and access to previously complicated terrains.

In conclusion, when choosing a UAV platform, the type of sensor/camera, different software, etc., depends on the objectives and parameters of the study; however, when analyzing a coastal island territory, there are several options that will facilitate the operationalization of such a tool. Based on the articles reviewed and the limitations identified, multi-rotor UAVs are more adapted to the specific context of coastal island territories. This study recommends using multi-rotor UAVs over those with flying wings because of the facilitated maneuverability that multi-rotors provide as well as their stability during strong winds and more extreme weather. This is especially necessary during takeoffs and landings. A lot of coasts on island territories are narrow or lack a suitable landing strip due to the presence of water, tides, or rocky shores. Additionally, the use of UAVs equipped with RGB cameras for photogrammetric applications is well adapted to this type of territory and allows for a relatively fast data acquisition method that can be repeated over a period of time. Other factors that have shown to be effective are the use of pipeline user-friendly software such as Pix4D or Agisoft Metashape when conducting photogrammetric analyses. RTK-GNSS is another solution to a limitation that appears often in the literature. Placing GCPs on the littoral is time-consuming and sometimes impossible due to the tides. This method (as described previously) removes the need for GCPs and is thus recommended when operating on coastal island territories.

4.2. Quantification of UAV Data for Resilience Evaluation

4.2.1. Postprocessing and Analysis of UAV Data for the Quantification of Indicators

The first step in coastal monitoring and risk assessment is collecting raw data. As stated earlier, UAVs can serve that purpose while solving a variety of challenges that exist with the current methods. Once the acquisition of data is complete, the data must be treated in order to provide an assessment or prediction, which can come from identifying contextualized indicators. Some of the questions we must ask ourselves are: What indicators for coastal management and natural risk assessment can be computed from UAV data? Additionally, what are the different methods for quantifying these indicators? There are a variety of indicators available to assess the status of a coast. Such as land use, beach slope, and width, just to name a few. The studies analyzed in this review each had their own indicators and demonstrated the capacity of UAV-derived models to quantify indicators and provide insight on the status of a coast. The UAV-generated models and ortho-mosaics from these studies can provide the raw data needed to quantify indicators such as the evolution of a shoreline [25,51] or the rock spread for landslide evaluation [24]. Previously, studies that have conducted this type of indicator quantification have generally had to rely on spatial databases and models that are acquired by satellite or manned aircraft. UAVs would allow for more site-specific models, obtaining them at a higher repetitive frequency, which is a crucial aspect when monitoring and analyzing coastal zones on island territories.

4.2.2. Using Indicators to Evaluate Territorial Resilience

The major natural disasters that have occurred in recent decades have mobilized the world of research, which has revisited the concept of resilience, in particular to analyze the traditional models of response to natural disasters and the post-crisis management mechanisms. For resilience to be an applicable concept that will help guide management and inform policy decisions, the identified indicators ultimately require quantification [53]. Thus, the next logical step is to identify how these models and indicators can be used for the evaluation of resilience? Additionally, which indicators have a positive/negative impact on community resilience? A small handful of studies have begun to operationalize this concept of resilience by quantifying indicators in such a fashion [54–57]. These studies assess resilience in a holistic manner and categorize resilience indicators into several broad dimensions that can include social, economic, infrastructural, and natural dimensions, by using indicators such as access to sanitation and electricity, demand for water supply, drainage of infrastructure, shoreline evolution, and surface elevation, respectively. According to [57], most studies of natural factors today rely on annual censuses and thus aggregated data, which does not allow for a zoom on at-risk areas [57]. While this study did not use UAVs to acquire data, UAVs would allow for site-specific research and could have been used to efficiently carry out the objective of this study. Acquiring site-specific data is important when dealing with oceanic island coastal territories due to their dynamic and vulnerable nature. Site-specific data also allows for local governments and decision makers to identify potential hot and/or cold spots of resilience and the main factors at work in particular locations, therefore aiding in the making of more site-specific decisions to improve local resilience to future disasters [57]. This processing and analysis of data can provide support for making decisions regarding the management of coastal environments.

4.3. Application of a Localized Spatial Decision Support System: Resilience Observatory

A decision support system by definition is a system that promotes interactive and integrated data and expert knowledge on a simplified scale that is accessible to support decision-making [58]. This kind of system, which tends to be computerized (i.e., a website or server), aims to accumulate obtained data from the specific study zone as well as applied and practical experience under a single framework, therefore linking and facilitating communication, for instance, between laboratories and their scientists and local knowledge and applications [20,59]. The environments of island territories are constantly changing and are quite susceptible to natural and anthropogenic pressures, thus requiring precise representation of their spatial processes and features [58]. This is why the term *spatial* is integrated into the spatial decision support system. Additionally, coastal regions can at times fall under the jurisdiction of different actors in the local, provincial, and federal governments [60]. These actors can have their own data sources and agendas when assessing risks, possibly creating conflict and preventing a coherent vision of the risks for decision-makers [60]. The development of a decision support system can provide a solution to this issue by essentially centralizing the collection, organization, and processing of data in a comprehensive way [20]. This data can then be rendered available in an "open-source" format, allowing for the redistribution of data among actors.

Gonçalves and Henriques (2015) argue that frequent surveys to detect and quantify associated morphological changes are essential for efficient coastal management. A coastal monitoring program must therefore accomplish the following objectives, (according to them):

Identify and quantify to better understand the causes of coastal evolution;
Identify the temporality of the processes that are related with coastal evolution;
Define the geographic extent of the influence of these processes;
Determine the relationship between coastal dynamics and climatic factors;
Predict coastal evolution and improve forecast models;
Provide support for coastal development and management;
Assess the impacts of the management measures.

Utilizing UAVs and spatial decision support systems can allow for these objectives to be carried out. Applying such a system in a specific location requires the system to take its surrounding environment into context. The Resilience Observatory will act as a spatial decision support system in the context of French Polynesia, with a main goal of increasing the territorial resilience of the island to various threats, whether natural or anthropogenic.

The utilization of UAVs in French Polynesia is relatively recent, and its development to serve as an effective and efficient tool for the territory has just begun [12,13,17,44,45]. This aerial data tool provides valuable information and is capable of providing the raw data needed to fulfill the objectives listed by Gonçalves and Henriques (2015) for effective coastal management. However, it is through linking this aerial data source with a spatial decision support system such as the Resilience Observatory that this data becomes tangible knowledge that can aid the decision-making process. The utilization of the Resilience

Observatory as a spatial decision-support system in French Polynesia is also still in the embryonic phase. Some studies have been conducted on the operationalization of the concept of resilience and its application to an observatory [43,61–66]. These studies have begun to identify the role that the Resilience Observatory will play, its internal functions, existing strategies and tools aimed at facilitating the operationalization of the concept, and how it will valorize data to support said observatory. Ref. [62] identifies the different tasks of the Resilience Observatory and breaks them up into three different categories (Figure 1). This review aims to show that using UAVs as data sources and their postprocessing procedures for analysis can efficiently and effectively support the first two tasks: data collection and indicator production.

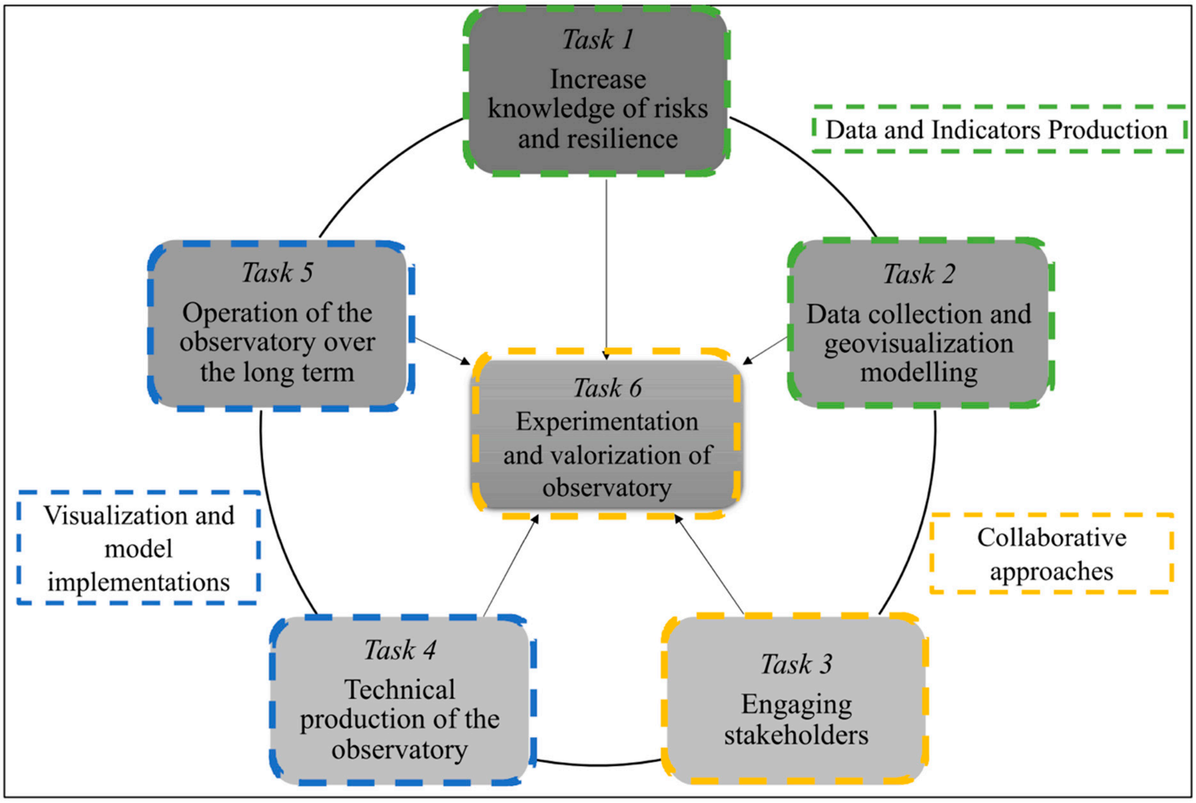

Figure 1. Resilience Observatory tasks [62].

UAVs and a spatial decision-support system such as the Resilience Observatory are both spatial tools that have great potential in the context of coastal risk management. The use and development of these tools can be effective for the management of the increasingly vulnerable and dynamic coasts of island nations like French Polynesia [43]. However, they require further efforts for a well-developed application, since they are relatively unprecedented in the context of French Polynesia, for the Resilience Observatory to continue solidifying. These efforts include the introduction of frequent, repetitive surveys of the coast by UAV as well as immediate surveying pre- and post-disaster. We have conducted preliminary efforts within the islands of Tahiti, Bora Bora, and Rangiroa in French Polynesia. These islands were selected due to their high tourism and urban development. UAV flights were carried out to obtain high-resolution digital models as well as ortho-mosaics in order to demonstrate the capacity of UAVs for data acquisition in this specific domain. This data can then undergo the postprocessing treatment of quantifying indicators to evaluate the resilience of the territory to natural risks. This analyzed data can then be linked to the Resilience Observatory under construction to begin identifying and forming the pathways between raw data acquisition and decision-making [43]. Additionally, similar field missions have been conducted on the western coast of France in Charentes Maritime on the island of Oléron. These efforts are in the hope of being able to develop a methodology that can be applied on a larger scale to different types of oceanic island coastal territories. This methodology intends to identify the link between aerial data acquisition, specifically by UAV, and spatial decision support systems in order to implement the concept of resilience as an effective and integrated risk management technique [67].

5. Conclusions

Aerial data sources are an important tool for monitoring coastal regions and assessing risks. This review focuses on UAVs as an aerial data source for coastal monitoring and risk assessment in island territories. There has been a significant increase in the use of UAVs for this purpose, and the trend will most likely continue to increase due to technological advancements and cheaper prices for both fixed-wing and multi-rotor UAVs. Maneuverability, sensor attachments, survey repetition, not being limited by cloud cover, accessibility, automation, and rapid acquisition all while obtaining high spatial resolution models are among the most beneficial aspects of UAV application within this domain. This review reveals that the main limitations of using UAVs for coastal assessment on island territories are the limited spatial coverage due to flight time, susceptibility to rain and wind, and the time-consuming GCP process for the georeferencing procedure. The GCP issue, however, has been solved by upgrading the GPS on the UAV to an RTK system. In the context of coastal monitoring on island territories, this study identified that certain factors are more suited for this specific context, such as using multi-rotor UAVs rather than flying wings, RTK GNSS systems for georeferencing, and RGB cameras for photogrammetric applications. With the continuing improvements in UAV technology, data collectors are more and more equipped with efficient tools for risk monitoring and assessment in vulnerable island territories. This aerial data can be used to evaluate the resilience of a territory, which can greatly benefit risk management and prevention techniques. Spatial decision support systems, such as the one currently being built in French Polynesia (the Resilience Observatory), are an effective approach for agglomerating data from a variety of aerial sources. Linking these aerial data sources to the Resilience Observatory can efficiently process raw data into tangible knowledge to aid the decision-making process.

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