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Autonomous Systems for the Environmental Characterization of Lagoons

Monica Rivas Casado, Marco Palma and Paul Leinster

Abstract

This chapter reviews the state of the art in robotics and autonomous systems (RAS) for monitoring the environmental characteristics of lagoons, as well as potential future uses of such technologies that could contribute to enhancing current monitoring programmes. Particular emphasis will be given to unmanned aerial vehicles (UAVs), autonomous under water vehicles (AUVs), remotely operated underwater vehicles (ROVs) and (semi-)autonomous boats. Recent technological advances in UAVs, AUVs and ROVs have demonstrated that high-resolution data (e.g. 0.4 cm imagery resolution) can be gathered when bespoke sensors are incorporated within these platforms. This in turn enables the accurate quantification of key metrics within lagoon environments, such as coral morphometries. For example, coral height and width can now be estimated remotely with errors below 12.6 and 14.7 cm, respectively. The chapter will explore how the use of such technologies in combination could improve the understanding of lagoon environments through increased knowledge of the spatial and temporal variations of parameters of interest. Within this context, both advantages and limitations of the proposed approaches will be highlighted and described from operational, logistical, and regulatory considerations. The chapter will be based on recent peer-reviewed research outputs obtained by the authors.

Keywords: emerging technologies, robotics, autonomous systems, environmental monitoring, UAVs, autonomous underwater vehicles, ROVs, semi-autonomous boats

1. Introduction

Lagoons are shallow bodies of water separated from larger bodies of water by barrier reefs, coral reefs, sandbars or other natural barriers such as shingle or rocks (**Figure 1**). Monitoring of lagoons is a regulatory requirement in Europe under the Water Framework Directive [1]. These requirements need to be interpreted alongside those of other directives such as the Nitrates Directive, Habitats Directive and the Marine Strategy Framework Directive and the EU strategy on adaptation to climate change [2, 3]. Implementation of these regulatory requirements has increased the focus on characterizing lagoon environments and in developing periodic and routine monitoring programmes (e.g. [4]), with government across the European Union having to reconsider their approach to lagoon monitoring.

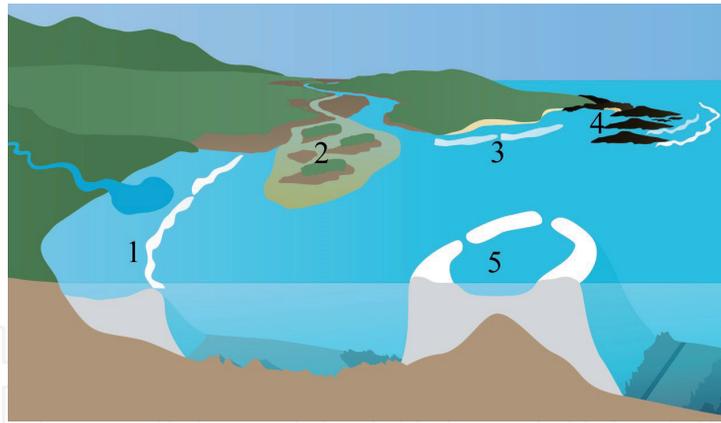


Figure 1. Schematic diagram depicting different types of lagoon environments. (1) sandbar coastal lagoon; (2) river delta and tidal lagoon; (3) coastal coral reef lagoon; (4) archipelago's lagoon; (5) atoll coral reef lagoon. Modified from IAN image library, Tracey Saxby (ian.umces.edu/imagelibrary/).

For example, Scotland's common standards for saline lagoon habitat monitoring were abandoned in 2008 as they were not considered to be fit for purpose and were not in accordance with these new regulatory requirements [3]. The development of periodic and routine monitoring programmes has required consideration of how to increase the spatial and temporal understanding of lagoon environments and has resulted in increased spatio-temporal coverage, resolution, larger data sets and more sophisticated data analysis approaches [3, 5].

The range of parameters that potentially could be monitored is wide and varied [4, 6]. **Table 1** summarizes the key parameters that are typically monitored to characterize lagoon environments [1]. These include biological, physico-chemical and hydromorphological parameters. Traditional monitoring methods rely on visual observation or direct manual measurements of these key parameters [1]. In general, such methods are highly time-consuming and costly. They can also require destructive sampling and are therefore limited in the spatial extent within which they can be implemented.

Remote sensing techniques based on satellite imagery have been used to overcome some of these limitations (e.g. [7–9]). Satellite imagery enables the monitoring of large extents. However, the resolution provided by satellite imagery is, in many cases, not sufficient to characterize a lagoon environment to the required level of detail. Information derived from satellite imagery cannot be used for physical measurements of water quality and does not enable characterization of the sub-surface properties of lagoons in the deepest areas.

Recent technological advances within the area of robotics, autonomous systems and machine learning have been identified as potential solutions to overcome the limitations mentioned above. Both robots and autonomous systems have been identified by the UK government as one of the eight great technologies [10] where the UK will be global leaders. Robots and autonomous systems that are able to monitor the environment independently of human control could revolutionize lagoon monitoring in the next decades. Such technologies have already been used in a diverse range of environments, with some authors reporting some applications in lagoons [11]. Both robots and autonomous systems require bespoke algorithms that enable them to carry out their tasks, from path planning during autonomous navigation to the analysis of the data collected. Machine learning methods enable the development and implementation of such algorithms. Machine learning techniques have already been successfully used in multiple environments to detect fish species automatically from imagery collected with underwater cameras [12] and to predict trophic status indicators in coastal lagoons [13].

Parameter	Description	
Biological	Phytoplankton	Changes in phytoplankton composition indicate changes in the dynamics of the lagoon. Changes in nutrients, salinity or environmental stressors have an impact on the primary production. Key metrics look at the presence of harmful algal species, species configuration of assemblages, phytoplankton variation over time, growth and biomass [14, 15]
	Other aquatic flora	This includes floating (emergent) and submerged plants. The key parameters used to describe other aquatic flora include community structure, taxonomic composition, abundance, coverage, diversity and species richness
	Habitat	Habitat characterization focuses on the quality and diversity of the habitat present within the lagoon and surrounding areas. Key metrics include species composition, species coverage gain/loss, habitat alteration, complexity, patchiness and stabilization [14]
	Macro-invertebrates	Abundance and diversity of macro-invertebrates are ecological indicators of water-level fluctuations and human pressures. Taxonomic composition, abundance, species richness, community structure and diversity indexes are key parameters
	Fish	Fish community composition (diversity and structure), abundance and seasonality are the key parameters used to characterize fish communities in lagoons. Changes in these parameters are indicators of environmental change and anthropogenic impact
Physico-chemical	Salinity	Salinity patterns provide information about the vertical and horizontal stratification of water in the lagoon, tidal patterns and the rate of saline and fresh water ingress-egress
	Temperature	Temperature measurements provide information about the temporal and spatial variation patterns in the lagoon and the occurrence of thermoclines. It also provides information about the influence of insolation and evaporation processes
	pH	An indicator of acidification and algal activity
	Oxygen	Oxygenation levels in lagoons are an indication of primary production and general organic matter consumption
	Hydromorphological	Tidal range
Hydrology		Hydrological characterization focuses on quantifying existing hydrological processes within lagoons. These include evaporation, insolation, internal circulation (saline and freshwater ingress-egress, groundwater), groundwater input and mixing processes, amongst others
Morphology		Quantity, structure and substrate of the bed, depth variation and continuity and structure of the intertidal zone are key morphological parameters. More detailed characterizations look at the properties of the barrier, backbarrier stratigraphy, absence/presence of tidal inlet [16] and detailed bathymetry

Table 1.
 Key parameters used for lagoon characterization based on the water framework directive [1].

The aim of this chapter is to review applications of recent technological advances within the context of lagoon environmental monitoring and define the implications for future remote sensing-based monitoring of these environments and the associated management strategies. In particular, this chapter reviews reported uses of robotics and autonomous systems for the characterization of lagoon ecosystems. It also highlights future applications of such technology and interprets the findings within the context of lagoon management and protection. The first section highlights how unmanned aerial vehicles, autonomous underwater vehicles and autonomous on-water platforms have been used to enhance existing lagoon environment monitoring practices. The second section describes the implications of the use of such technology for survey design, their potential to provide continuous information in time and space and the need for tailored data processing methods. The last section identifies some of the advantages and limitations of these remote sensing monitoring methods within the context of environmental management and current practice.

2. Robots and autonomous systems

2.1 Background

In the last decade, the uptake of robotics and autonomous systems (RAS) for environmental monitoring has increased significantly. The low cost and availability of some of the technologies in the market have facilitated the integration of RAS solutions within the environmental sector. Perhaps the most significant uptake of RAS relates to unmanned aerial vehicles (UAVs) and autonomous underwater vehicles (AUVs). UAVs are small aircraft controlled remotely (i.e. with no human pilot on board). When equipped with specific sensors, they enable on-demand and generally high-resolution data collection. This overcomes some of the limitations of more traditional remote sensing methods such as satellites. Their capabilities also enable the collection of information under low cloud cover, thus increasing the operational window for environmental monitoring.

A wide range of sensors are currently available in the market for integration on existing off-the-shelf platforms (**Figure 2**). These sensors include multispectral, thermal, hyper-spectral and high-resolution red, green and blue (RGB) cameras and water quality probes. RGB cameras are the most accessible and therefore currently the most used sensor for environmental monitoring. However, recent advances in sensor miniaturization (e.g. [17]) facilitate the integration of combined sensors on a single platform, enabling RGB imagery to be coupled with other sources of information.

2.2 Unmanned aerial vehicles

Within the context of lagoon characterization, UAVs have been used to assess the preferred locations and distribution at a fine scale of blacktip reef sharks and pink whiprays within a coral lagoon and reef systems off French Polynesia (Morea) [11]. This study focused on the assessment of the differences in species presence along reef habitats such as fringing, channels and sandflats. Density estimates of both species were estimated from the video footage recorded with a GoPro Hero 3+ Silver Edition camera fitted to a DJI Phantom II UAV quadcopter. The study highlighted the usefulness of UAVs to detect statistically significant differences in species densities across lagoon habitats [11].

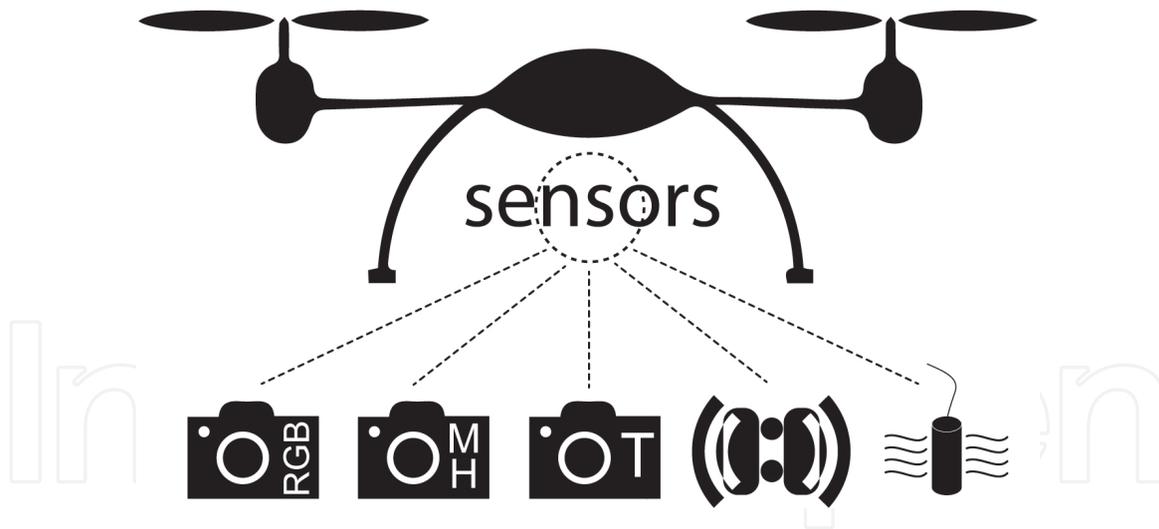


Figure 2.
Schematic diagram showing an array of sensors that can be integrated to drone platforms [i.e. red, green and blue (RGB) camera, multispectral camera, thermal camera, hyper-spectral camera, laser scanner, conductivity-temperature-depth probe].

UAVs have also been used to make water surface elevation (i.e. orthometric water height above mean sea level) and bathymetry observations in lagoons of the Yucatan Peninsula (Mexico) [18]. In Ref. [18], the authors used a DJI hexacopter Spreading Wings S900 UAV equipped with an RGB high-resolution camera (Sony DSC-RX100) and lower-resolution fish-eye lens Eken H9 camera to characterize water surface elevation. The UAV was enabled to control a tethered sonar sensor (Deeper Smart Sonar PRO + Deeper, UAB, Vilnius, Lithuania) able to map the bathymetry of the lagoons. The information thus gathered enabled the estimation of water depth. The authors reported the technology to be accurate and fit for purpose, with errors less than 7 cm for water surface elevation estimation and less than 3.8% of the actual water depth. The study also highlighted the flexibility and low cost of the technology and its capacity to monitor remote areas that are difficult to access by human operators.

Lally et al. [19] reviewed the latest advances in UAV technology (platforms, payload and probe integration) for water sample capture and physico-chemical analysis. The potential of UAVs to gather water samples in lagoons is still unexplored. To date and to the authors' knowledge, only a few examples exist of this application of the technology [19] but none within lagoon environments. Multiple limitations still curtail the uptake of the technology and include water samples are too small to be representative, restrictive drone technology, low rate of sample collection and low reliability [19]. For the technology to be transferable and cost-effective for lagoon characterization, a range of enhancements are required such as increased payload capability, increased battery endurance, beyond visual line of sight operation and real-time physico-chemical measurement [19].

2.3 Autonomous underwater vehicles, ROVs and on-water platforms

It is evident that the use of the technology for water sample collection would be of benefit to managers and conservationists alike, especially within a regulatory context where water quality assessment of such ecosystems is required on a regular basis. In England, for example, there are 52 coastal saline lagoons defined in Special Protection Areas or Special Areas of Conservation, with an additional 28 lagoonal water bodies identified under the Water Framework Directive [6]. All these lagoons and lagoonal water bodies require monitoring, assessment and reporting of the

ecological quality. The use of autonomous or semi-autonomous UAVs to gather water samples could de-risk the overall activity, provide samples from inaccessible locations (increased representativeness) and increase the cost-effectiveness of the monitoring programme.

A faster route to achieve autonomous water sampling capability is the use of autonomous or semi-autonomous on-water platforms (**Figure 3**). Small boats with autonomous capability will overcome some of the limitations highlighted for UAV technology. In addition to water quality parameters, the capability of on-water platforms could be expanded to include factors such as water depth, bathymetry mapping, underwater habitat and emergent/submerged vegetation assessment. This would facilitate the temporal and spatial collocation of sampling for multiple variables. Recent studies have looked at their use within the context of freshwater ecosystem monitoring [20]. For example, Vandrol et al. [20] presented a structure-from-motion-based approach for the characterization of habitat and morphology in rivers for small boats capable of navigating autonomously along rivers. The methodology presented could also be transferred to lagoon environment characterization. Fornai [21] presented the small-size autonomous surface vessel (ASV) able to perform water column monitoring with a bespoke sampling probe (**Figure 3**). The autonomous solar-powered vessel “BUSCAMOS-RobObs” equipped with side scan sonar, sub-bottom sonar, laser systems, ultrasound sonar, depth metres, a multi-parametric probe and a GPS for collecting georeferenced oceanic data has been tested at the coastal lagoon system of Mar Menor (Spain) [22] (**Figure 3**). Low-budget and portable autonomous vessels have also been proved to be efficient with the collection of bathymetry and other variables in remote and dangerous coastal areas [23] (**Figure 3**).

Characterization of the euphotic and epipelagic zones can be achieved with both autonomous underwater vehicles (AUV) and remotely operated underwater vehicles (ROVs) (**Figure 4**). AUVs are robots able to travel underwater at different depths without the need of input from an operator. Remotely operated underwater vehicles (ROVs) are a variant of this type of robot. ROVs are directed by an operator via a remote control or an umbilical. Both AUVs and ROVs have been used for lagoon environment monitoring. For example, AUVs have been used in the Mar Menor (Murcia, Spain) coastal lagoon in different studies. The Mar Menor lagoon is separated from the Mediterranean Sea by a 20 km long dune cord that acts as a barrier to seawater ingress and ensures the protection of

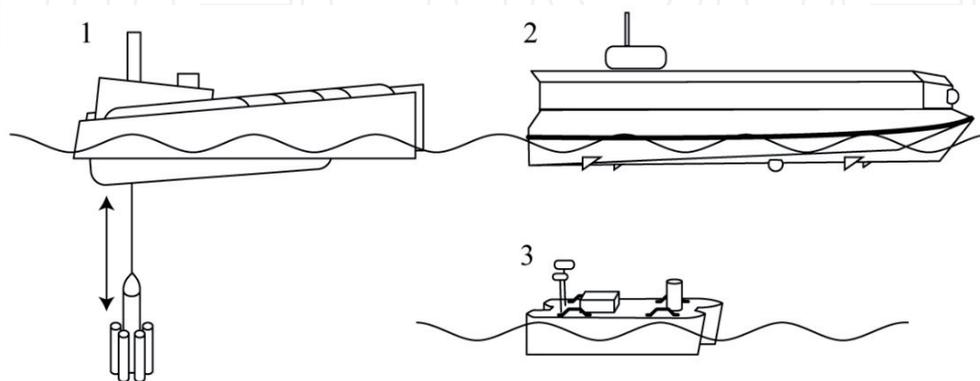


Figure 3. Schematic diagram showing multiple autonomous surface vessels (ASV) used in coastal areas and lagoon systems. (1) ASV equipped with a winch system for autonomous water column sampling [21]; (2) the solar-powered ASV equipped with a large range of sensors is able of self-mooring [22]; (3) the affordable and portable size ASV used in coastal surveys in Greenland [23].

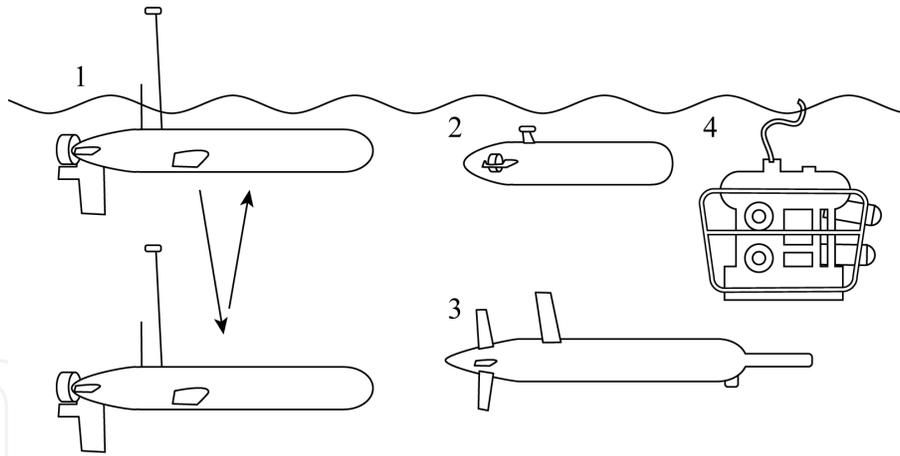


Figure 4.
Schematic diagram showing multiple autonomous underwater vehicles (AUV) and a remotely operated vehicle (ROV). (1) Guanay II [27]; (2) SPARUS [28]; (3) Seacon [26]; (4) general remotely operated vehicle (ROV).

the characteristics of both environments. In [24], the AEGIR [25], Seacon [26], Guanay II [27] and SPARUS AUV [28] were deployed in the Mar Menor lagoon to better understand the ingress-egress of marine and freshwater into the environment. The multiple AUVs were equipped with probes to capture real-time measures of salinity. Similarly, in the Indian River Lagoon (Florida, USA) [29], AUVs have been used to collect spatially dense water quality data to study the spatial variability of conditions related to algal blooms. The Indian River Lagoon extends across three estuaries for over 160 miles. Phytoplankton blooms are frequent within the lagoon and are well known to have an ecological impact on the three estuaries. The AUV was used to measure water quality parameters that provide indicators of algal activity, temperature, conductivity, pH, dissolved oxygen, turbidity, total chlorophyll and phycocyanin fluorescence. In [30], the authors developed an AUV system able to track a leopard shark tagged with an acoustic Lotek MM Series transmitter along the SeaPlane Lagoon (Los Angeles, USA). The AUV was fitted with a stereo-hydrophone and receiver system able to detect acoustic signals. Further applications of AUVs exist in marine environments [31], many of which could be transferred to lagoon environments. Predicted improvements of the technology, such as enhanced hovering capability, long endurance and rapid response capabilities [31], will facilitate further monitoring applications in lagoon environments.

2.4 Concluding remarks

The use of RAS for lagoon environmental monitoring has proved to be successful for multiple variables. The cost-effectiveness of such methods is yet unknown and needs to be understood in relation to comprehensive and more integrative monitoring programmes. The capabilities provided by RAS could further benefit lagoon environment monitoring via the integration of different platforms—e.g. UAVs, AUVs, ROVs and bespoke sensors. The technology readiness level of such approaches is still constrained by a number of factors, such as the miniaturization of sensors, but initial conceptual models have already been tested [32, 33]. Successful design of integrated solutions will require a significant degree of collaboration between experts from different disciplines, including engineers, biologists, ecologists, environmental scientists, marine scientists, data analysts and software developers. Future developments and investment should focus on further

advancing the technology towards achieving an integrated system that enables the collection of collocated spatio-temporal information of all the parameters required for lagoon characterization (**Table 1**).

3. Implications for survey design

Standardization of monitoring protocols across lagoons, although a EU regulatory requirement [34], is challenging because of the complex and varied range of conditions encountered across such environments. Identification of the best location where specific samples of water quality, habitat or phytoplankton are to be taken is usually difficult to determine due to the spatio-temporal variability present within and between lagoon environments and a priori lack of knowledge of the conditions within the lagoon. Recent studies have looked at developing statistically robust sampling protocols to address this gap in knowledge. The use of robotics and autonomous systems introduces continuous monitoring capability. This makes survey design easier by prioritizing continuous data collection over point sampling. From a statistical perspective, such approaches to data collection enables the estimation of unbiased measures of dispersion and central tendency, with less intensive requirements on determining where point sample should be taken. This is of special relevance when trying to disentangle the effects that multiple factors (e.g. management practice) have on the quality of the lagoon.

Palma et al. [35] studied the effect of sampling design on coral reef characterization when collecting high-resolution (0.4 cm) RGB imagery with semi-autonomous water vehicles (**Figures 5 and 6**). The authors were interested in determining seascape metrics that would provide information about the configuration of coral reefs in Ponta do Ouro Partial Marine Reserve (Mozambique) and the morphology of the site (**Table 1**). A range of sampling scales (quadrats of size 0.5 m × 0.5 m, 2 m × 2 m, 5 m × 5 m, 7 m × 7 m) and densities (from 1 to 100 quadrats) were compared. Results showed that sampling scales equal to or coarser than 5 m × 5 m and sampling densities equal to or larger than 30 were most effective along the 1655 m² case study area. The study highlighted that special attention needs to be given to the design of coral reef monitoring programmes, with decisions being based on

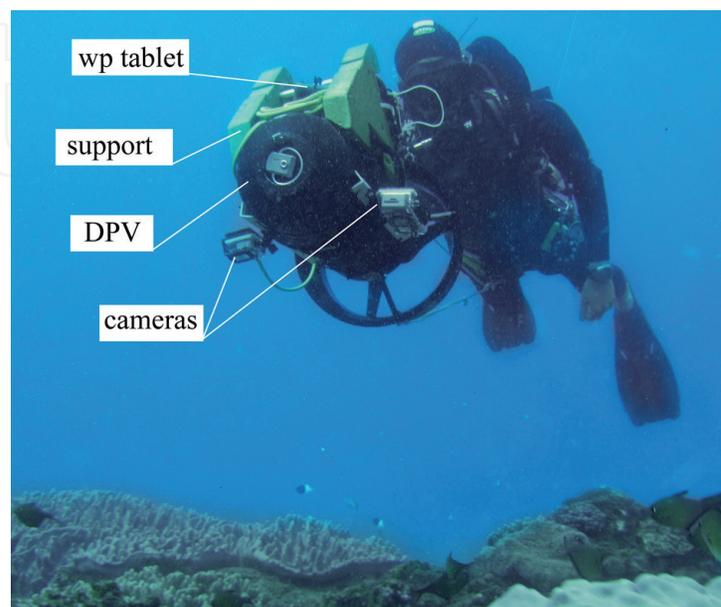


Figure 5. The driver propulsion system (DPV), a remotely operated vehicle (ROV), equipped with a waterproof (wp) tablet and cameras. The tablet is used to coordinate data collection and steer vehicle direction.

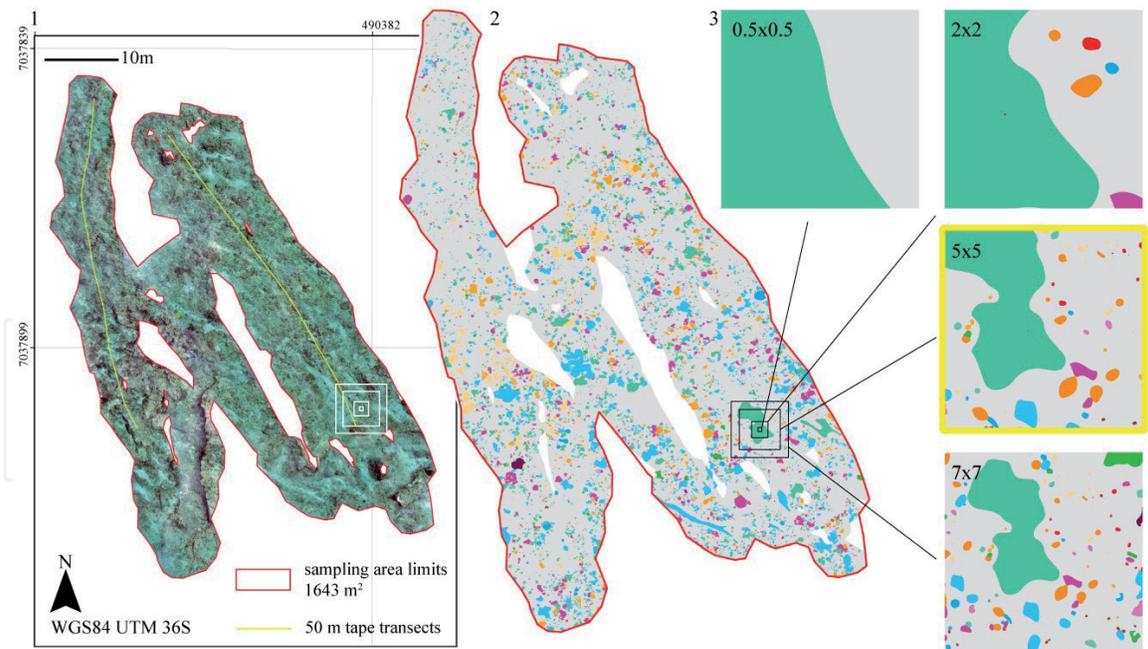


Figure 6. Coral reef area sampled at Ponta do Ouro partial Marine Reserve in Palma et al. [35]. The image shows the different sampling strategies compared in the study ($0.5\text{ m} \times 0.5\text{ m}$, $2\text{ m} \times 2\text{ m}$, $5\text{ m} \times 5\text{ m}$ and $7\text{ m} \times 7\text{ m}$). Each sampling strategy depicts a different spatial configuration of the number and coverage of species (colored polygons) present within the area.

the seascape metrics and statistics being determined. Although the Ponta do Ouro Partial Marine Reserve is not classed as lagoon, the results obtained are transferable to lagoon environments.

More recent studies, also transferable to lagoon environments, have looked at the combined use of structure-from-motion (SfM) approach and ROV to map coral reefs and reduce the need for destructive sampling. In particular, Palma et al. [36] developed a framework for wide-scale benthic monitoring which is transferable to lagoon environments. The authors estimated population structure, morphology and biomass automatically from imagery collected with a (i) a GoPro Hero4 Black Edition (Woodman Labs, Inc., San Mateo, CA, USA) recording maximal resolution still images ($4000\text{ pixels} \times 3000\text{ pixels}$) and (ii) a Sony Alpha NEX7 Digital Camera (Sony Corporation, Minato, Tokyo, Japan) recording full high-definition ($1920\text{ pixels} \times 1080\text{ pixels}$) videos mounted on a ROV—the driver propulsion system (DPV) (Figure 7). The point clouds generated with both cameras contained more than 6.5 million points. Both the point cloud and the high-resolution imagery collected enabled the estimation of coral morphometrics, such as height, width and planar surface of coral colonies. With the methodology proposed in [36], the error in coral height estimation was always $<12.6\text{ cm}$. For coral width estimation, the error was always $<14.7\text{ cm}$, whereas for the estimation of the planar surface, the error was 533 cm^2 . Palma et al. [36] were also able to develop the methodology further to estimate coral ash free dry weight (AFDW) from the imagery collected based on the planar surface estimated. AFDW is the biomass weight present within the coral after oxidation of the organic component occurs at high temperatures. Eq. (1) is specific for *Paramuricea clavata* [37]. The results provided information on the overall health of coralligenous habitats within the Marine Protected Area of Portofino (Punta del Faro, Italy). The technology enabled sampling of 52 m^2 within 6 minutes, with data analysis requiring under 10 hours of post-processing work:

$$AFDW = A \cdot 0.0047 \cdot 0.1515 \quad (1)$$

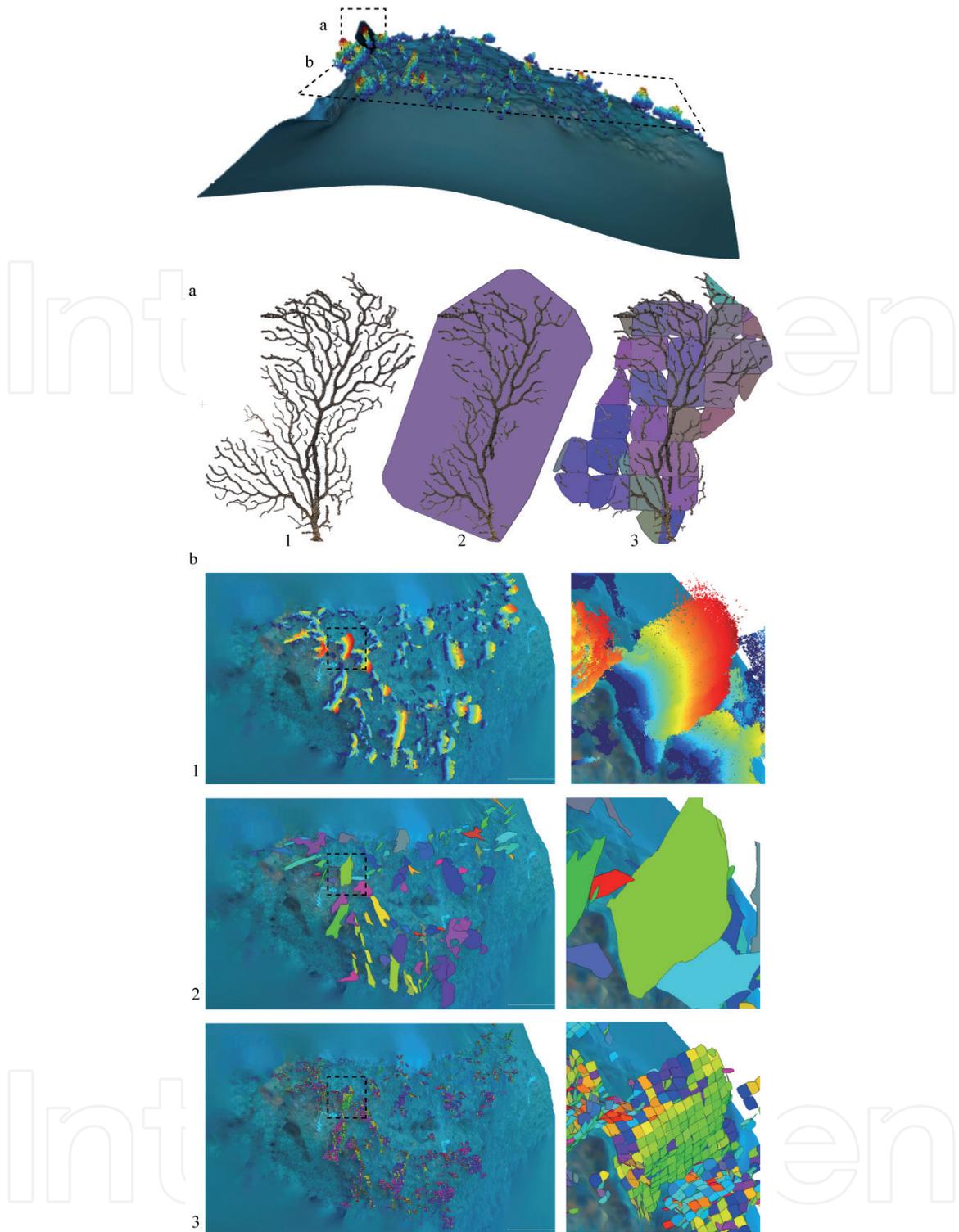


Figure 7.

Image depicting the structure-from-motion methodology developed by Palma et al. [36] to sample corals without the need for destructive sampling. Overall view of the sampled area within the marine protected area of Portofino (Punta del Faro, Italy); (a) detailed view of a scanned coral branch and the automated estimation of its surface area; (b) sequence of images showing the implementation of the estimation of the surface area of corals on-site using SfM methods: (b1) point cloud generation, (b2) delineation of outmost boundary and (b3) estimation of the coral surface area via a small set of polygons.

Technological advances in RAS and data processing algorithms enable more comprehensive data sets to be produced that facilitate more informed management decisions. The increased quality and quantity of data collected provides a robust foundation for the use of more advanced statistical methods than the estimation of measures of central tendency and dispersion.

4. Management considerations

4.1 Key challenges

Remote sensing approaches including the use of satellites, UAVs, remote-controlled boats and underwater vehicles provide the potential for significant advances in the understanding of the environmental characteristics and functioning of lagoons. They can facilitate a better understanding of the temporal and spatial variation of environmental quality parameters, of habitat extent and condition, of risks, pressures and resultant responses and of the effectiveness of mitigation measures. They can contribute to coordinating and implementing nature-related policies [2], to the standardization of monitoring programmes ([34]) and to identifying environmental management priorities. They could also be used to better understand climate change impacts.

Recent studies [2] have highlighted the need to increase research and technology development (RTD) to enhance current lagoon management practices. For example, current understanding of the functioning and ecological quality of European lagoons is currently impaired by limited and incomplete data sets [2] such as lack of water quality measurements, gauging records, climate stations or water level stations. Further data weaknesses identified included insufficient water quality data in spatial and temporal dimensions for lagoon model calibration and validation. Based on a total of four case study areas, the work by Stålnacke et al. [2] concluded that effective lagoon management critically depends on high-quality data in geospatial format. Such data can be obtained with the remote sensing RAS solutions described in previous sections. However, there are several challenges to the deployment of remote sensing approaches and their widespread uptake by those responsible for the management and oversight of lagoons. Many of the techniques are still predominately the domain of the research community. There is as yet no purpose driven overarching monitoring and surveillance protocol for lagoons into which the use of remote sensing can be easily positioned. Thought has to be given to the use that will be made of the data that will be collected. For example, is it being collected because it is now possible to collect it or it will inform and improve the management of a lagoon.

Remote sensing approaches clearly have an important role to play in the baseline assessment of a lagoon enabling detailed characterizations of habitats, morphology and quality. They can then be used to determine how these parameters vary within and between years including the impact of climate change. In addition, they can enable a better assessment of the condition of a lagoon, the pressures, responses and effectiveness of interventions, than existing methodologies. Whether such detailed characterizations are needed for all lagoons will be for individual managers and organizations to determine.

There are few agreed protocols for the collection and interpretation of data using these techniques. This can limit their use in demonstrating compliance with legislative requirements. However, if remote sensing techniques do gain greater utilization in terms of routine monitoring including for legislative purposes, then this will significantly increase data transfer and storage capabilities and requirements. These monitoring approaches generate significant quantities of data that will have to be managed—the transfer and storage of this data could be a challenge. Agreed data collection and analysis protocols would facilitate the exchange of information and enable intercountry comparisons to be made.

These technologies produce information that has not routinely been available previously [31, 38], for example, spatial and temporal variations in a range of water

quality parameters obtained using on-water platforms with a variety of probes [39]. Such information will enable modeling outputs to be ground-truthed and better management decisions to be made. Although this information will enable a greater understanding of lagoons, it will require expenditure that previously was not required. Business cases will therefore need to be made to justify expenditure on initial characterization studies and then for routine surveillance. Such capital and revenue requirements could form a barrier to entry of these techniques into routine use. It may take a significant time before these techniques have widespread uptake by wildlife trusts, government agencies and regulatory bodies.

Some of the techniques will substantially reduce the cost of data collection and improve the health and safety of those collecting the information such as the use of small boat-mounted ACDP sensors to measure flow. However, for others it was not possible to collect the type of information that can now be gathered such as the spatial distribution of water quality parameters. To collect such information would therefore result in costs that were not previously incurred. Additional funding will therefore be necessary, and the case is made as to why such information is useful and justifies the level of expenditure proposed.

4.2 Technology acceptance

Technological uptake and integration in standard monitoring programmes will depend upon the factors highlighted in previous sections as well as the cost-effectiveness of the technology and the acceptance of the results produced by government agencies.

There could be resistance to the use of such systems because of the associated cost or initial capital investment. In addition, some people will resist the introduction of new technologies. Innovation is not always welcomed. There can be a level of conservatism in people working in a science or technical area to new approaches. It is not the way that they were taught to do things, and efficiencies can lead to some people losing their jobs or having to do something else. For example, the use of UAVs may be constrained by concerns that the technology can be used to violate individuals' privacy, their link to war-fare and the risk of collision with aircraft [40, 41]. Technological advances occur very fast within the context of RAS. However, the rate-determining step in their uptake can be the associated business and governance processes.

Technology acceptance and adoption models could be used to determine the key factors that will drive the uptake of remote sensing RAS monitoring solutions [42]. These models consider internal antecedents of behaviour-like attitudes, values and intentions, norms, incentives and institutional constraints to provide an estimate of the likelihood of technology uptake. Further research is required to better understand how the uptake of RAS-based remote sensing technology for lagoon environment monitoring can be facilitated.

4.3 Concluding remarks

Lagoons have been difficult environmental features to characterize and assess with the typically used monitoring approaches. They are extensive, and their characteristics vary spatially and temporally. Remote sensing approaches and RAS developments therefore provide new opportunities to better understand and assess lagoon environments. They also provide the means of better understanding what management approaches work in practice and assessing the effectiveness of interventions. They can also be used to inform the design of routine monitoring programmes.

However, there are real challenges in translating research and development and investigative approaches into repeatable and robust monitoring techniques that can be used on a routine and standardized basis for regulatory and compliance purposes. There will therefore need to be a concerted effort if the clear benefits that the developing remote sensing and RAS technologies provide are to be realized in the management of lagoon environments. The risk of not using such techniques and approaches is that the lagoon environments will continue to suffer environmental degradation.

Conflict of interest

The authors declare no conflict of interest.

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