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Filling in socio-ecological knowledge gaps to support marine spatial planning in data-scarce areas: Example from Zanzibar

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Abstract

Marine spatial planning (MSP) is one of the most important tools for ensuring sustainable use of marine areas. Although MSP is a well-established method, its adoption in rapidly developing countries is a challenge. One of the main concerns is data adequacy, as the MSP process typically requires a large amount of spatial data on human activities, biodiversity, and socio-ecological interactions within the planning area. Drawing from an institutional cooperation project in Zanzibar, Tanzania, we share our experience and demonstrate how to fill in socio-ecological data gaps to support the development of MSP in areas with limited data availability. We developed a rapid and cost-effective system for collecting biological data, which, together with remote sensing and place-based participatory mapping, helped formulate the first pilot ecologically informed MSP for Zanzibar. By sharing our results and experiences, we aim to provide best practices, lessons learned, and recommendations for future projects with a similar ecological setting and socio-economic context.

KEYWORDS

community mapping, marine conservation, marine spatial planning, PGIS, public engagement, remote sensing

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1 | INTRODUCTION

Marine ecosystems face multiple threats, such as overfishing, habitat degradation and pollution (Halpern et al., 2007). The unsustainable use of marine resources and the growth of ocean economies underscore the need for improved marine governance. One of the widely recognized approaches is marine spatial planning (MSP), which allocates areas for maritime activities by integrating sectoral, conservation-oriented, and societal aspects into spatial planning (Douvere, 2008; Ehler & Douvere, 2009). MSP aims to ensure the sustainable use of marine areas, while aiming to minimize adverse effects of human activities on marine ecosystems (Gilliland & Laffoley, 2008). An integral part of sustainable planning of marine areas is also coastal management, which in many parts of the world can be seen as important as MSP in sustainable use of marine resources, as the coastal zone is closely intertwined with marine areas (Eger et al., 2021).

While MSP is a widely used and globally well-established tool for ecosystem-based management of coastal and marine resources, there are fundamental constraints for MSP adoption in rapidly developing countries with little local participation, weak ocean governance and data limitations (Eger et al., 2021; Lombard et al., 2019; Santos et al., 2018). Coastal areas and island communities that have multiple inter-connected development challenges, such as population growth, urbanization, tourism and unsustainable resource use, struggle to sustainably manage marine areas and enforce conservation (Barange et al., 2014; Sale et al., 2014). Tropical coastal areas and island communities would particularly benefit from MSP and coastal management, as their socio-economic development is closely linked to healthy coastal and marine environments and capacities for these ecosystems to generate livelihoods and multiple well-being services for people (Keen et al., 2018; Lange & Jiddawi, 2009; Singh et al., 2021). Marine ecosystems play a vital role in ensuring food security and generating income for coastal communities, primarily through artisanal fishing and seafood collection (Sale et al., 2014; Stiepani et al., 2023; Sulu et al., 2015). Additionally, tourism is heavily focused on coastal areas and marine activities, forming a large part of island economies (Klein et al., 2004; Spalding et al., 2017). Projected impacts of climate change on marine resources may also challenge coastal communities´ livelihoods, calling for adaptation measures and sustainable management of marine areas (Lam et al., 2020; Makame et al., 2023; Queirós et al., 2024).

A central component of MSP process is the collection of comprehensive, up-to-date spatial data on marine ecosystems to facilitate decisions about where to allocate or limit human activities to ensure the delivery of ecosystem services (Ehler & Douvere, 2009; Kyriazi et al., 2013). Understanding how human activities potentially impact ecologically sensitive areas is important for delivering effective MSP and improved management of marine resources (Cowx et al., 2010). Ecosystem-based MSP should be rooted in ecological principles, which highlights the need for ecologically relevant data (Foley et al., 2010). Initiatives are for example key biodiversity areas or ecologically significant areas, which can be adopted at various spatial scales to support marine spatial planning (Dunstan et al., 2016; Harris et al., 2022; Kuismanen et al., 2023). Both approaches are data-greedy and require extensive biological data over broad geographical areas, although expert-knowledge can be used to supplement missing data (Harris et al., 2022). While novel concepts and data collection methods are increasingly developed to advance MSP, such as genetic diversity (Kershaw et al., 2021) and environmental DNA approaches (Huerlimann et al., 2020), baseline marine data are still in many parts of the world missing. Comprehensive biological inventories or monitoring the state of marine ecosystems are lacking, and in many cases data collection for MSP need to be developed from the scratch. In rapidly developing areas, the challenge may not only be data adequacy, but also the challenging situation to develop MSP, as available resources are under increasing pressure. Rapid, reproducible, robust and scalable methods to collect and produce data are needed (Sarker & Failler, 2023; Wen et al., 2022).

The effectiveness of MSP requires also data on the social dimension, and of its ecological linkages, which often are lacking in MSP initiatives (Santos et al., 2018). Incorporating local perceptions and place-based values enhances the identification of ecosystem services and socio-ecological interactions in marine ecosystems (Käyhkö et al., 2019; Scully-Engelmeyer et al., 2021; Strickland-Munro et al., 2016). Local knowledge can also provide valuable information about species and ecosystems (Drew, 2005). Participatory mapping methods (PGIS/PPGIS, see e.g., Burnett, 2023) are widely used in spatial planning, and in the context of MSP, they are particularly valuable for capturing the perspectives of multiple stakeholders, mapping local livelihoods, people–nature interactions, or resolving conflicting interests of stakeholders (Calado et al., 2022; Johnson et al., 2020; Moore et al., 2017). Community approaches play a crucial role in identifying key opportunities for successful MSP, and participatory mapping methods can improve engagement of local communities through the collection of their place-based local knowledge on coastal and marine areas (Blake et al., 2017; Klain & Chan, 2012;

Strickland-Munro et al., 2016). They may also empower local communities to use their knowledge in the protection and maintenance of valuable ecosystems (Scully-Engelmeyer et al., 2021). When communities are engaged in the planning process from the very beginning, there are better chances of them supporting implementation of the plans (Ferse et al., 2010).

Here, we provide an example on how to collect and analyze relevant spatial data to support coastal zone management, marine conservation, and ecosystem-based marine spatial planning. Our work concentrates on Zanzibar Islands, Tanzania, a rapidly developing area with multiple challenges in sustainable use of marine areas. Our work includes the following components: (i) development of a cost-effective, practical approach to collect and analyze biological field data, (ii) habitat classification based on remote sensing and collected field data, and (iii) collection of place-based socio-economic data by participatory approaches. We also briefly outline the steps needed to support marine spatial planning initiatives in areas where marine governance is not yet fully established. By sharing our results and experiences, we aim to provide best practices, lessons learned, and recommendations for future planning processes with similar ecological and socio-political contexts.

2 | METHODS

2.1 | Study area

Zanzibar archipelago is a semiautonomous country within the United Republic of Tanzania, located in the tropical Western Indian Ocean. The archipelago is composed of two main islands, Unguja and Pemba, and over 50 smaller islands. Our study focuses on the northeastern section of Unguja island, where the pilot area for MSP was located (hereafter: Zanzibar) (Figure 1).

The marine ecosystem of Zanzibar can be characterized as a typical tropical seascape: a fringing coral reef surrounds the islands, and the interplay between sandy seafloors and seagrasses create a mosaic of habitats which dominate the intertidal and subtidal zones (Short et al., 2007). Zanzibar has a high average population density of 808 inhabitants/km^2 and a population of about 1.35 million (NBS, 2022), most living within 1 km from the coastline. Artisanal fishing and seafood collection are the main livelihood options for these coastal communities (Barrowclift et al., 2017; Käyhkö et al., 2019; Pike et al., 2024). Rapid population growth combined with the development of mass-tourism have created conflicts with traditional ways of living, and imposed risks to the fragile marine environment (Khamis et al., 2017). For example, the use of destructive fishing gear, such as bottom-set, dragnets, spear guns and small mesh size nets, have become more common (Rehren et al., 2018; Temple et al., 2019). Seaweed aquaculture is a prominent livelihood in Zanzibar (Charisiadou et al., 2022; Hedberg et al., 2018), especially for women who comprise over 80% of the workforce. However, the industry has its challenges: health issues are a common concern (Fröcklin et al., 2012), as are climate change and conflicts with the hotel industry. Furthermore, seaweed is cultivated within seagrass meadows, causing degradation of these habitats (Hedberg et al., 2018; Moreira-Saporiti et al., 2021).

The coastal landscape of Zanzibar has changed drastically, from traditional fishing villages to a tourism-driven society that now dominates most of the coastline. This shift has resulted in the confinement of villages to narrow coastal stretches or even pushed them further inland, distancing them from direct proximity to the sea (Khamis et al., 2017, 2019; Tobisson, 2013). As a result, local communities' access to shore and marine resources, as well as their possibilities to own land for housing or agriculture close to shoreline have become limited (Khamis et al., 2017; Lange, 2015).

2.2 | Piloting the coastal and marine spatial planning process in Zanzibar

Starting the MSP process requires a number of essential steps, ranging from developing a vision and objectives for the plan, to drafting or amending existing legislations, and establishing a governance structure that supports the formulation and implementation of MSP (Ehler & Douvere, 2009). To facilitate the transition to high-value industries and services, Zanzibar has recently prioritized blue economy strategies as a driver for societal development (Revolutionary Government of Zanzibar, 2020). However, the sustainable implementation of MSP and the growth of the blue economy sector require careful consideration of potential conflicts among sectors and stakeholders, as well as accounting for the additional pressures posed by climate change on coastal communities and marine ecosystems. Zanzibar's Blue Economy Policy strongly emphasizes the development and implementation of MSP and ocean governance has been identified among the important pillars of blue economy in Zanzibar (Semboja, 2021).

In 2014, the Zanzibar government developed the National Spatial Development Strategy (NSDS) to ensure sustainable, people-centred management of growth of urban and rural areas of the island. Under this strategy, regional and local land-use plans were adopted (DoURP, 2015), but marine areas were omitted. The

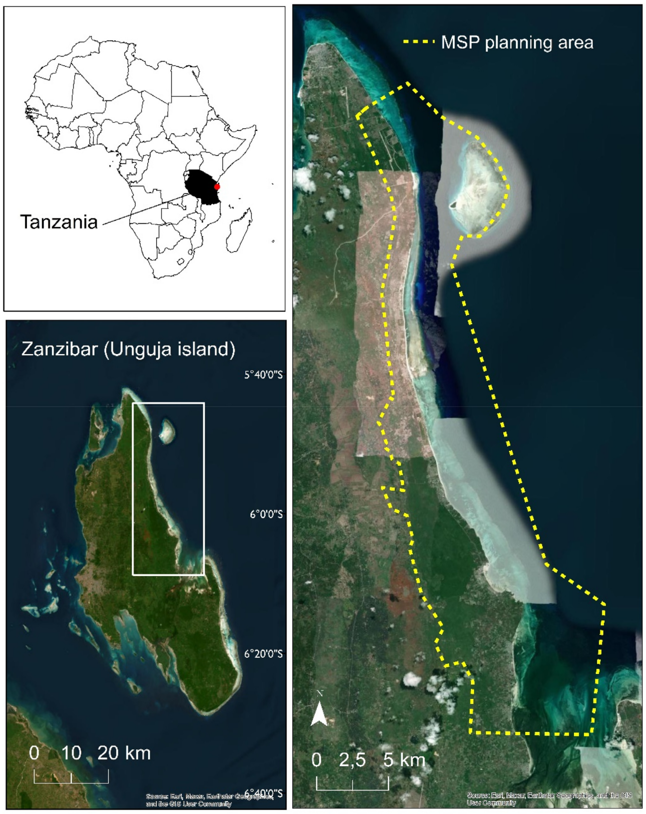

FIGURE 1 Location of Zanzibar Island off Tanzania, and the pilot marine spatial planning area in the northeastern part of Zanzibar.

incompleteness of the NSDS spurred discussions around the development of integrated coastal and marine spatial plans, leading to the creation of 'Special Area Plans'.

In 2016, institutional cooperation project was initiated between the Zanzibari and Finnish governments, "ZAN-SDI—National Spatial Data Infrastructure for Integrated Coastal and Marine Spatial Planning", to support the development of integrated coastal and marine spatial plan for the north-eastern parts of Zanzibar. The collaboration was started between Zanzibari officials with the mandate for MSP, mainly the Commission of Lands and Department of Fisheries Development, and Finnish experts who had previous experience in providing scientific decision-support for the MSP process in Finland. This pilot coastal and marine "North-East Special Area Plan", NESAP, was the first land use plan, which covered also marine areas (Figure 1), and hence it holds a unique position within the spatial planning hierarchy of Zanzibar, between NSDS and local plans. The coastal terrestrial part of the plan has been previously published in Käyhkö et al. (2019), but the marine part is presented in this paper. In the following sections we describe the process of collecting and analyzing data from coastal and marine areas, to support the formulation of pilot MSP for Zanzibar, the NESAP.

2.3 | Marine habitat inventories

While several biological inventories have been carried out in Zanzibar, including studies on fish species, corals, seagrasses, and mangroves (Dorenbosch et al., 2005; Jahnke et al., 2019; Lugendo et al., 2005; Mbije et al., 2002; Msangameno et al., 2017; Rehren et al., 2022), most of these inventories are limited to a certain bay or cover only a fraction of the habitats present. Comprehensive overview of ecologically valuable areas is missing, even though this would be essential information for the MSP process. We developed a rapid and cost-effective drop-video camera system that could be used for mapping marine habitats and conducting biological surveys. The system consists of a GoPro camera attached to a camera rig, equipped with high-quality video lights. The camera can be operated by hand from any small vessel and is complemented with an onboard screen for viewing the camera image or navigating to the planned inventory site. The system can function as both a video recording device and a still camera, and it can operate in depths of up to 60 m (depending on the length of the underwater cable). As the system also saves video recordings, it is useful for monitoring purposes (e.g., changes in habitat composition), and for checking information not necessarily captured at first viewing (e.g., species identities). A portable GPS tracker and an echosounder were also used in the boat for positioning and depth sounding (for more details, see Appendix S1).

To map marine habitats, we developed a simple protocol based on the National Oceanic and Atmospheric Administration (NOAA) classification scheme (Monaco et al., 2012) which uses a hierarchical system of "tiers" to categorize data collection. Tier 1 is considered the minimum information necessary to characterize habitats, while Tiers 2 and 3 include additional survey metrics, such as biological and abiotic measures. The data accuracy required by the MSP, and the resources and capacity available, largely define how the collected data should be interpreted. The system developed by NOAA serves as a useful baseline for various purposes, and it is easily adaptable. We developed a simplified version of the NOAA scheme, since only certain sized species are identifiable from videos, and as we needed data to classify habitats based on satellite imagery. The classification system includes macroalga, corals, seagrasses, and bare sand (see Appendix S2). The method mirrors the one routinely used by the Inventory Programme for Underwater Marine Diversity (Velmu) for mapping the Finnish marine area and developing the network of marine protected areas (Virtanen et al., 2018). Detailed description of the Velmu methods and data can be found in Forsblom et al. (2024).

In March 2017, we collected data on marine habitats in the NESAP marine area, up to 60 m depth (the length of camera cable). The field work followed a depth-stratified random sampling protocol, where the sites to be visited ($n = 500$) were randomly assigned based on the color of the ocean from aerial images (Google maps). The color spectrum ranged from the shallow, sandy areas (light beige) to deeper parts of the ocean (dark blue). However, the actual sites visited were determined based on the wind and wave conditions, and some of the sites assigned to darker blue areas were too deep or too far at the sea. At each inventory site, the drop-camera system was lowered down from a boat (one drop at each site), and habitats were recorded for 1 min. The minimum mapping unit obtained from the videos was approximately 20 m^2. Videos were then visually interpreted, and the spatial distribution of substrates and biological features were assessed as a percentage of the total area covered (ranging from 0% to 100%).

2.4 | Marine habitat classification based on earth observation and in situ data

To gain information on the distribution of marine habitats in the area, we combined Sentinel-2 (S2) scenes with in situ video observations to classify habitats. Various studies have used Sentinel-2 for habitat classification, including Poursanidis et al. (2021) who mapped corals, seagrasses, and sand in Mozambique, and Traganos and Reinartz (2018) who identified Mediterranean seagrasses. Huber et al. (2021) achieved relatively high accuracy in mapping underwater vegetation in optically demanding waters of Sweden, and Kulha et al. (2024) in mapping bathymetry in complex archipelago of Finland.

We obtained cloud-free Level-1C S2-scenes captured in November and December 2016 from the Sentinel Scientific Data Hub (https://scihub.copernicus.eu/). Although there was a three-month lag between the image and field work, we do not consider this problematic for habitat mapping purposes at this resolution (100 m^2), because habitats are likely to have remained unchanged during this time. While we chose the best possible scenes (i.e., no clouds or waves), the selected images had some sunglint, especially in the open ocean with higher waves. Following Hedley et al. (2005), we reduced the sunglint effect separately for each band used in the habitat classification using a formula:

$$R_n = R_{in} - b_i(R_{\mathrm{NIR}} - \mathrm{Med}_{\mathrm{NIR}})$$

where R_n is the corrected reflectance for band n, R_i is the uncorrected reflectance for band n, b_i is the regression line slope, R_{NIR} is the corresponding reflectance value in NIR band, and $\mathrm{Med}_{\mathrm{NIR}}$ is the median value of the NIR band that exist in the sample. We calculated the regression line slope and median NIR from a set of pixels located in the deep-water area that was considered homogeneous if sunglint was not present. We removed sunglint using functions from the R (R Core Team, 2020) packages sen2r (Ranghetti et al., 2020) and raster (Hijmans & van Etten, 2012).

To classify habitats, we used a gradient boosting machine (GBM) (Breiman, 2017), based on the collected field data: corals, macroalga, sand, and seagrasses. Interpreting fragmented, vegetated areas especially in deeper waters remains a challenge, and for this reason we present the probability of a pixel belonging to a particular habitat class. We expect this approach to be relevant for patchy habitats, where corals, sand, and submerged vegetation co-occur and form mixed habitats within the 10 × 10 m pixel of S2 scenes (Poursanidis et al., 2021). We used hyperparameter tuning to select optimal parameters for the classification problem and varied the interaction depth (2–4), shrinkage (0.01, 0.001) and number of trees (1:20 × 60), with the number of training samples in a node set to 10. We selected the final model for classification based on the classification accuracy across 10 cross-validation iterations, and we repeated the models 100 times. We calculated kappa values to test how well the algorithm identified each habitat. Additionally, we calculated confusion matrices for each habitat classification as percentual average cell count across the 100 resamples, as kappa values may be highly dependent on the prevalence of the studied objects (Foody, 2020). We classified habitats in R (R Core Team, 2020) with the caret package (Kuhn, 2020).

2.5 | Participatory mapping of maritime activities and ecological values

We organized two participatory mapping campaigns and workshops for local communities and stakeholders within the NESAP planning area. In these workshops, we gathered local knowledge of the ecologically valuable areas, human activities, and potential conflicts within the planning area.

The first campaign consisted of nine mapping workshops, one in each coastal village along the northeastern coast of Zanzibar. The campaign focused on collecting economic, social, cultural, and ecological activities and values of the communities related to coastal and marine areas. Workshop participants identified and delineated various land- and sea-based activities, then placed these onto high-resolution Google satellite and drone image print outs with stickers and marker pens. The resulting sketch maps were digitized to analyze intensities and spatial distribution of local communities′ values and activities along the coast. Details of the mapping campaigns and their results are described in Käyhkö et al. (2019).

The second participatory mapping campaign targeted sectoral and marine ecosystem experts from government institutions, non-governmental organizations, and universities. They provided expertise on spatial planning, environment, ecology, fisheries, forestry, and environmental monitoring aspects related to NESAP (Appendix S3). The mapping was carried out with the online citizen engagement platform Maptionnaire (https://maptionnaire.com/). The experts were asked to map ecologically valuable areas and their view of the place-based activities at sea (as points). Additionally, they were asked to provide free-form commentary about their chosen activities, and to elaborate on the potential conflicts between maritime activities and ecologically important areas. Both mapping campaigns were preceded by a short introduction of the NESAP process and a general discussion about the NESAP area and its characteristics.

3 | RESULTS

3.1 | Marine habitats based on video observations

Video observations were collected from 256 sites, ranging from 0.5 to 44 m (Figure 2). Sand was the most common substrate, found at 52% of sites, followed by rubble (39%), boulders (21%), and rock (11%). The southern part of the research area was dominated by seagrasses and macroalgae, while the northern part was less rich in habitat. The Mnemba atoll in the northern part of the study area had a relatively low abundance of habitats, with sand and coral rag dominating the seascape. Coral rag is cemented, rubbly limestone composed largely of fragments of coral-reef deposits. Macroalgae were found from 36% of sites, seagrasses from 29% of sites, and corals from 37% of sites (of which 28% hard and 9% soft corals). Seagrasses had the highest average coverage, exceeding 75% at various sites, followed by macroalga with 50%–75% coverage. Only few sites had high coverage of hard corals, and none of soft corals (<10%).

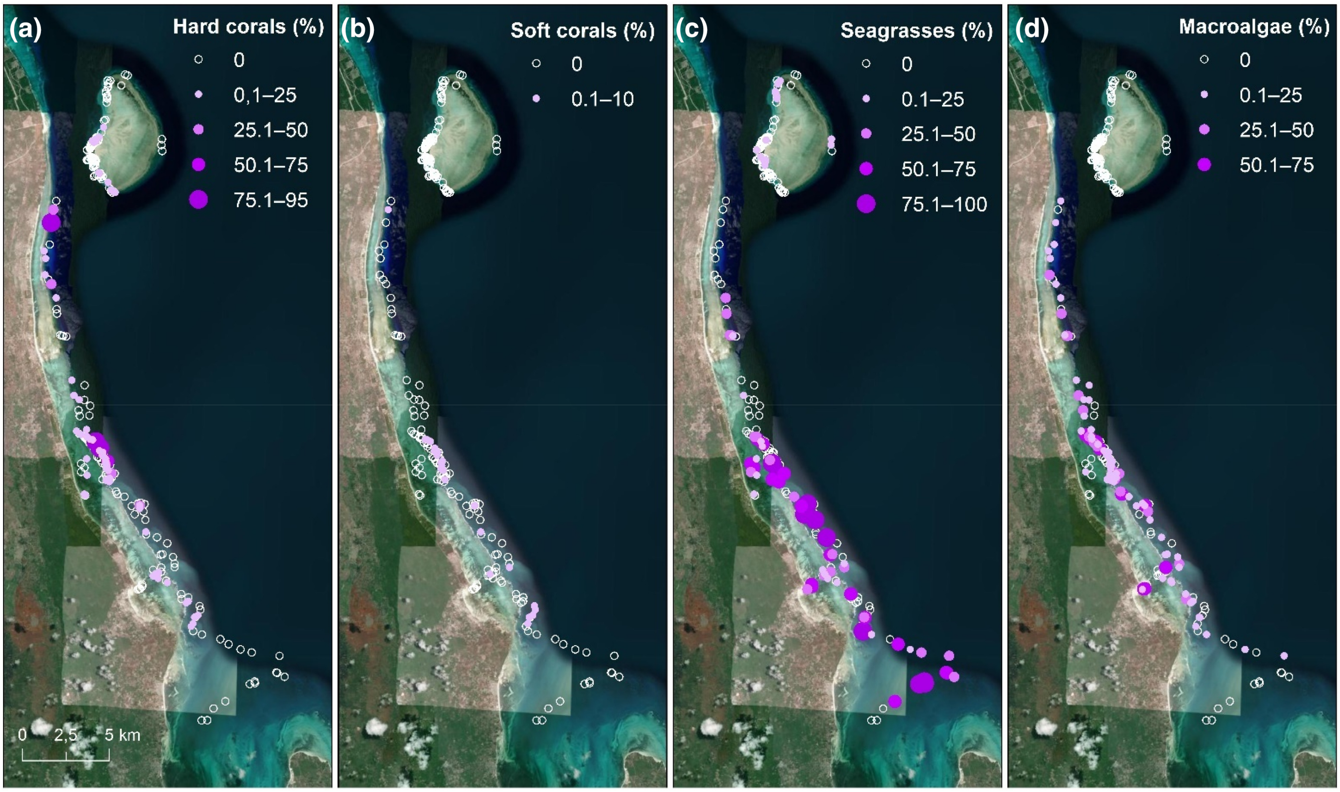

FIGURE 2 Marine habitat mapping results from the field surveys. Panels (a)–(d) show percentage coverage (%) of hard and soft corals, seagrasses, and macroalga, respectively.

3.2 | Classification of marine habitats

The highest accuracy rates were achieved for macroalgae and seagrasses, with a median of 76% (mean 74.8% ± 6.3%) and 76% (mean 74.3% ± 6.1%), respectively, across 100 model runs. The classification of S2 scenes for corals and sand performed also well, with median accuracy rates of 72% (mean 70.8% ± 4.9%) and 69.2% (mean 70.3% ± 7.1%), respectively (Figure 3a). Based on the kappa coefficients (Figure 3b), the classification agreement was moderate for macroalgae (median 0.42), fair for seagrasses (median 0.28), but almost negligible for sand and corals, with median kappa values of 0.16 and 0.09, respectively. Based on the confusion matrix (Appendix S4), the predictions across model runs underestimated the true occurrence of the habitats. The classification of corals is shown in Figure 3c for the entire study area and for an example area in the north, the Mnemba atoll, with the probability (%) of habitat being coral. Based on ground-truthing, the areas with corals were identified correctly, but some were confused with coral rag. Several patches of seagrasses were missed during the habitat classification, while macroalgae and seagrass habitats were mixed up.

3.3 | The use of marine areas and ecological values

PGIS campaigns in coastal villages involved 218 participants from mixed-gender and livelihood sector groups. The average number of participants in each workshop was 15. The participants marked a total of 114 areas with place-based values. Fishing-related activities were

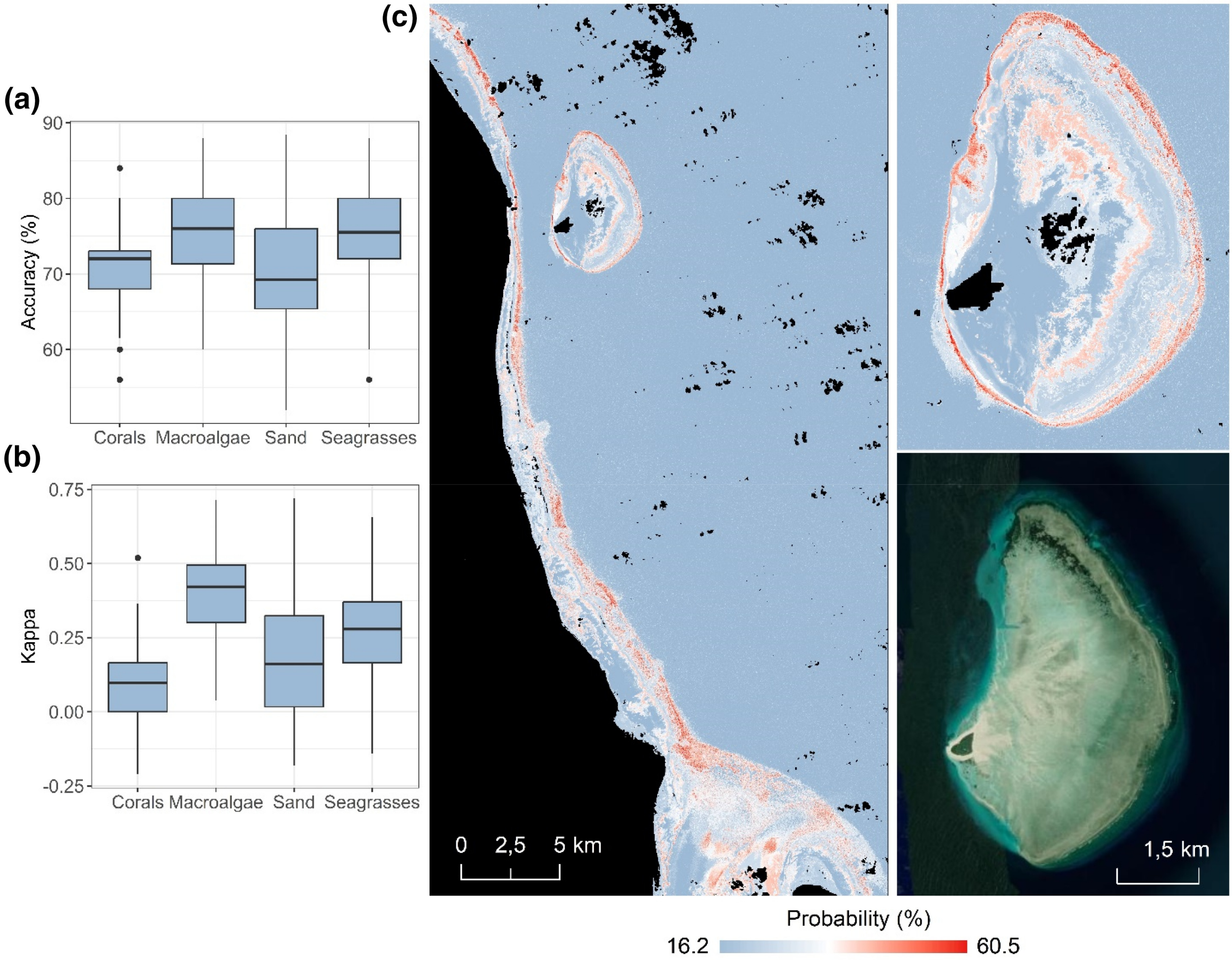

FIGURE 3 The performance of marine habitat classification across the 100 models, based on (a) accuracy (%) and (b) kappa values. (c) An example of habitat classification (probability, %) of corals in the NESAP area and a zoomed-in area of the Mnemba atoll. Land and removed clouds are shown with black.

most common in the NESAP area. Specifically, 21 fishing areas, 13 reef passages (which allow boats to cross the fringing reef), and 17 landing sites (where fishing boats land and catches are sold) were identified (Figure 4b,c). Fishing activities covered 61% of the mapped areas (Figure 5a), followed by seafood collection with 29 individual sites identified, accounting for 21% of the marked areas. Seaweed farming, although comprising a smaller proportion (4%) of the marked areas, was also recognized as an important activity in these coastal communities. In the unstructured responses, participants highlighted some areas of biodiversity importance, (corals, seagrasses) but their concerns were mostly on human activities. For instance, seagrass areas were identified within areas of seaweed farming, and corals within reef passages. Areas associated with biodiversity (corals, seagrasses, and conservation areas) represented 14% of the mapped sites. Locally managed marine areas were well-known and identified. Participants highlighted that most of the fishing activities take place around the Mnemba atoll, which is part of a marine conservation area. Detailed results of these village PGIS campaigns can be found in Käyhkö et al. (2019).

The participatory mapping campaigns for sectoral marine ecosystem experts and organizations involved 23 stakeholders and 6 marine experts. The participants mapped 638 sites, which were categorized into five groups: coastal tourism, biodiversity, fishing activities, seafood collection, and seaweed farming. Coastal tourism was the largest category of the marked sites, accounting for 39% of all mapped sites (Figure 5b). Based on the free-form answers, tourism was identified as an essential economic activity. Pristine environments, including beautiful beaches, were noted as significant attractions for tourists. However, some stakeholders expressed concerns about conflicts between the community and hoteliers, such as access to shore and landing sites, as well as the limited carrying capacity of the ecosystems due to increasing number of tourists. Additionally, some stakeholders were concerned over the decline of sea turtles due to destruction of nesting sites and the degradation of coral reefs. Beach erosion and climate change were also identified as significant challenges for coastal tourism in the region.

The second largest category of mapped sites was biodiversity, accounting for 32% of the marked sites (Figures 4e and 5b). Biodiversity included sites related to coral reefs, seagrasses, mangroves, coastal forests, and protected areas. Information regarding corals was gained from diving operators, based on their most important dive sites along the fringing reef, concentrating predominantly around the Mnemba atoll (Figure 4e).

The participants identified encroachment, over-extraction of resources, and the disappearance of important marine species as significant threats to biodiversity. It was noted that biodiversity around the Mnemba atoll has been declining over the last 15 years. Most of the corals in the NESAP area were reported to be in poor status due to destructive fishing, overfishing, and unregulated tourism. However, stakeholders also acknowledged the potential benefits of conservation (e.g., establishment of coral conservation zones), which could contribute to increased tourism in the area. Furthermore, some emphasized the potential for developing ecotourism to safeguard the environment.

Fishing activities were the third largest category of marked sites, accounting for 16% of the mapped sites. Based on the provided free-form answers, overfishing was identified as a threat by some stakeholders, along with uncontrolled tourism activities and an increasing population. Uncontrolled waste disposal also poses a threat to fishing activities and marine life. Villages along the NESAP coast were identified as being highly dependent on fishing, underscoring the importance of sustainably managed fisheries in the area.

Seaweed farming represented 10% of the mapped sites in the PGIS campaign, and several existing sites were identified along the coast. This activity was recognized as crucial due to its socioeconomic impact and as an alternative livelihood for fishing. Finally, seafood collection accounted for 3% of the marked sites. Free-form responses revealed that, during certain periods, many fishers prioritize collecting octopus or other species, as they are important sources of food for the local community, and an additional source of income. This also highlights the seasonality of fisheries pattern in the study area.

4 | HOW THE DATA WERE USED TO DEVELOP A PILOT COASTAL AND MARINE SPATIAL PLAN—THE NESAP

The collected spatial data were used to form a pilot MSP for Zanzibar, the North-East Special Area Plan, NESAP (Figure 6). Zoning decisions were made by the spatial planners of Zanzibar government, based on the data and local expert knowledge, with support from the ZAN-SDI project. Relying on simple GIS overlay analysis, data were compiled to form a general understanding of maritime activities and ecological values (Appendix S5). NESAP delineates important areas for nature and for certain uses, to guide the development in the area (Figure 6a), as well as constraints for development, that

FIGURE 4 The upper panel (a–d) shows the results of the PGIS mapping campaign in the nine coastal villages (features drawn on paper maps), and the lower panel (e–i) the results of the stakeholder PGIS campaigns, involving sectoral and marine ecosystem experts from government institutions, non-governmental organizations and universities aggregated to 1 × 1 km grid from the Maptionnaire points. Data for panels (a)–(d) are from Käyhkö et al. (2019).

is, where human activities should be restricted or prohibited (Figure 6b) (more details of the delineations can be found from Appendix S5). The whole northeastern part of Zanzibar is part of a marine protected area that is not fully enforced. Only the Mnemba atoll is a conservation area surveilled by the authorities, but in the NESAP the whole area is set under development restrictions. NESAP also identifies areas of high conservation value in the

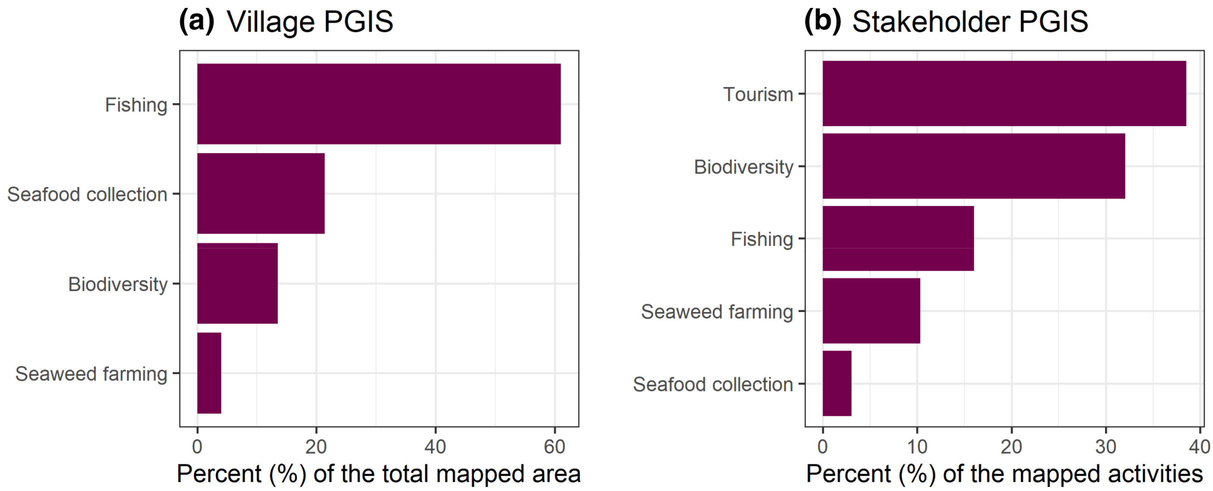

FIGURE 5 Panel (a) shows the percentage (%) of the mapped area per activity type in the coastal villages, and panel (b) the frequency (%) of mapped activities by the sectoral and marine ecosystem experts from government institutions, non-governmental organizations, and universities.

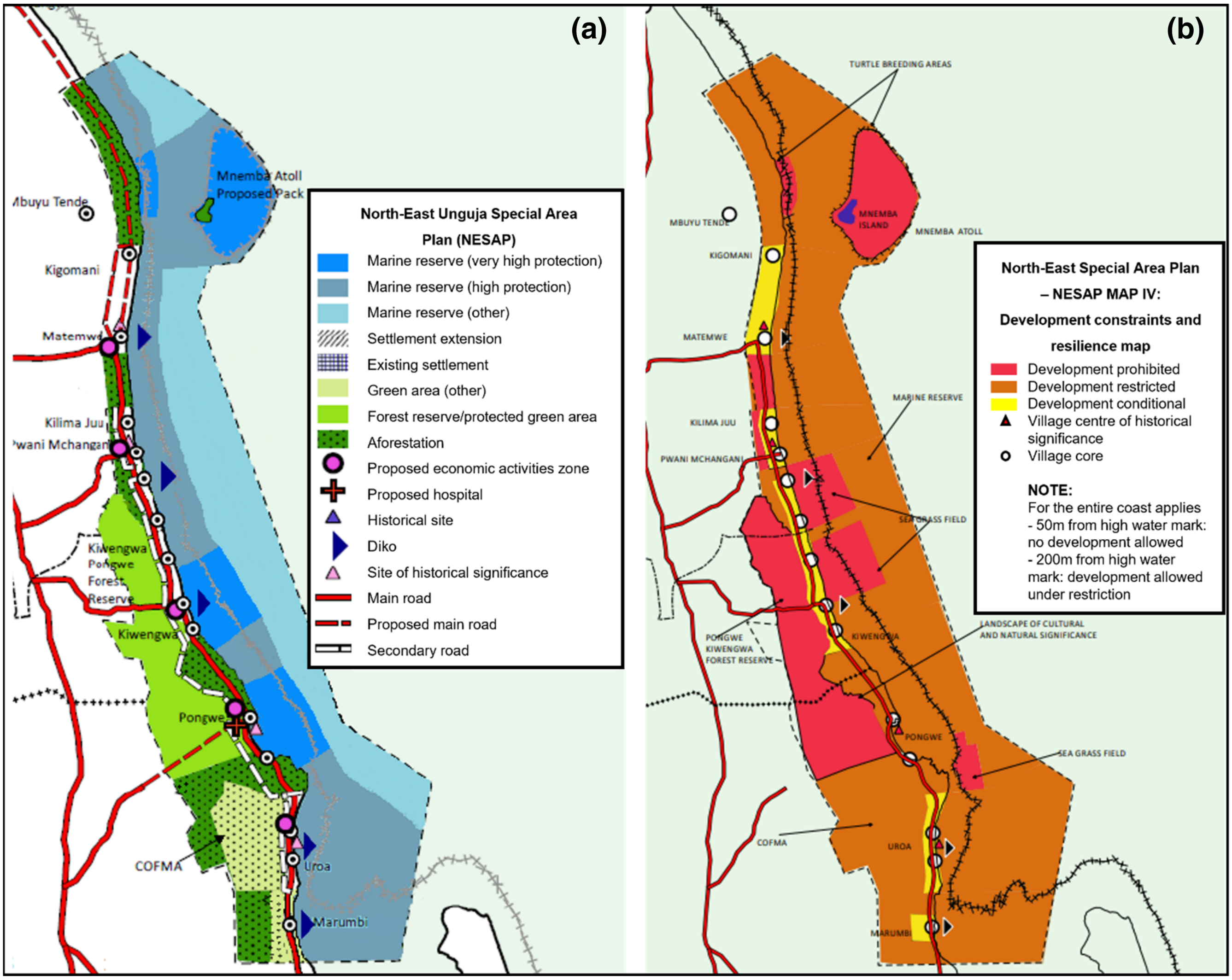

FIGURE 6 The finalized North-East Special Area Plan, NESAP (a) and potential constraints for development (b). Image courtesy: Department of Urban and Rural Planning of Revolutionary Government of Zanzibar (see details in Appendix in S5).

marine areas off Kiwengwa and Pongwe, characterized by a mixture of hard and soft corals, macroalgae, and seagrasses (Sections 3.1 and 3.2). The same areas also hold high value for the local communities, with seafood collection and seaweed farming (Section 2.5). The detected hard coral concentration (Section 3.1), which is the only one found in the area, is proposed to be designated as a restricted development zone. The other areas along the fringing reef are suggested to be given special consideration, where development should be controlled (Figure 6b). Less strict development restrictions, coupled with multi-use of marine areas, are proposed for the rest of the coastal zone, which has a longstanding tradition of seaweed farming and seafood collection. NESAP also identifies "blue corridors", the seascape delineated based on connecting the important fishing areas and routes, with reef passages and landing sites (Section 3.3). The official endorsement of NESAP is still pending (as of November 2023), due to transfer of jurisdiction mandate over MSP to a newly established Ministry of Blue Economy and Fisheries. With new policies and strategies in place to support the sustainable use of marine areas (e.g., Blue Economy policy, Zanzibar Development Vision 2050, Semboja, 2021), there are hopes that the socio-economic development of Zanzibar will be steered by better stewardship of the sea and its resources.

5 | DISCUSSION

The spatial information gathered and methods co-created during the ZAN-SDI project supported Zanzibar government in the process of making informed planning decisions for NESAP, and helped planners to formulate MSP elements into the planning instrument. Based on the experiences, we outline critical points of success, and potential solutions for challenges encountered during the process, to guide future similar work.

5.1 | Find creative and affordable ways to collect spatial marine data

Limited availability of spatial data presents a significant challenge for the development of MSP, but also for the establishment of ecological baselines, monitoring changes, and determining the effectiveness of management measures. Since Zanzibar coastal areas are under heavy use and coastal landscapes change rapidly, there is a need to identify robust, yet reliable spatial data collection and co-production methods, which allow informed mapping, monitoring and management actions on the ground. Similar challenges in obtaining ecologically relevant data were encountered during the MSP process for instance in Kenya (Tuda et al., 2014), Greece (Kostopoulou, 2022), Saint Kitts and Nevis (Agostini et al., 2015), Indonesia (Wen et al., 2022), Montserrat (Flower et al., 2020), Barbuda (Johnson et al., 2020), and Malaysia (Jumin et al., 2018; Razak et al., 2024). All used rather similar approaches to obtain data for MSP: rapid collection of ecologically relevant data, habitat classification, mapping human activities, participatory approaches to complement missing data, and finally zoning the plan with decision support tools, based on which the first drafts of MSP were formulated. In Zanzibar, the formulation of NESAP did not rely on decision support tools (e.g., Marxan, prioritizr, and Zonation), but instead on simple GIS methods, such as spatial data overlays and visual inspections of data. During any spatial planning process, the time, and resources available set the limits for acquiring relevant data. What is useful, adequate, or relevant data for MSP is case specific, determined by the socio-economic and ecological setting of the planning area in question. In ideal situations, spatially explicit, extensive biological data (preferably at the species level) would exist long before the MSP process takes place, and valuable locations to consider in MSP would already be available (e.g., Kuismanen et al., 2023). As such is rarely the case, alternative options to obtain data are warranted.

There are now global initiatives that have improved the availability of ecological data. For instance, the Allen coral atlas (https://www.allencoralatlas.org/) provides marine habitat data from the shallow areas, and useful information on bleaching events and water quality. The data could be used in conservation planning, marine monitoring, or targeting biological inventories. New methods to analyze data are also emerging, such as the integration of semantic segmentation with 3D mapping, which allows rapid, automated interpretation of underwater videos (e.g., coral reefs), reducing the resources needed for video analysis (Sauder et al., 2023). Some initiatives, such as the Global Fishing Watch (https://globalfishingwatch.org/), also provide relevant data on human activities at sea. The Global Fishing Watch maps fishing effort and the type of fishing activity based on satellite imagery (Kroodsma et al., 2018; Li et al., 2021), as well as the extent of offshore industrial activities (Paolo et al., 2024). The benefit of these data is that the temporal resolution allows monitoring of sea areas, such as the efficiency of management measures (McDermott et al., 2019), or for instance the extent of illegal fishing activities (Park et al., 2023).

While the availability of global data provides a good basis for area-based planning, the spatial resolution may still not be adequate for MSP purposes. This limitation highlights the necessity for innovative approaches and collaborative efforts to overcome data scarcity, improve data availability, and enhance the sharing of critical information for effective marine management. Data-sharing over institutional barriers sets another critical challenge that needs to be overcome to support sustainable management of coastal and marine areas. Low-cost and robust methods to collect biological data are needed, particularly when institutions have limited resources to collect data, or they rely on external funding and work force. For instance, the low-cost drop-video camera system which we developed (Appendix S1) was an efficient way to collect data. Combined with satellite images it enabled the identification of habitats over broad geographical scales, and participatory mapping filled gaps in knowledge.

5.2 | Engage local communities in planning process and collect socio-ecological data of marine areas

Participatory mapping approaches used in this study showed how diverse and valuable local knowledge coastal communities hold on land and marine resources. Without engagement of the local village residents, NESAP process would not have direct access to information of the distribution and dynamics of human activities and practices on marine areas. The socio-ecological data gathered directly supported the identification of most valuable areas for local livelihood practices, and indirectly on potentially valuable ecological areas. PGIS campaigns also worked towards higher awareness and better engagement of the local communities in the NESAP process. Through the stakeholder mapping campaigns, NESAP planners obtained broader perspectives of the potential values and conflicts along the coastal area and were able to address these issues in the discussions with the local communities. It is increasingly acknowledged that spatial planning and zoning processes should consider bottom-up engagement of multiple stakeholders and particularly local communities (Eger et al., 2021; Singh et al., 2021). This increases sustainability of the plans, as conservation efforts can be more effectively combined with livelihood strategies of the people. Community engagement enhances local awareness of marine ecosystems, provides local residents capacities and know-how, and increases the social and cultural acceptance of MSP (Zhang & Bakar, 2017). Also, through participatory mapping, ecological knowledge is enriched with socio-ecological data of coastal and marine ecosystems (Wen et al., 2022). Because of this, residents are more likely to support and adopt the proposed strategies, and to play a role in the continued management of resources.

When integrating socio-ecological data provided by the local communities, it is important to interpret the data keeping in mind that it may not reflect knowledge of the entire community. Perspectives of different communities or community members may be under- or over-represented, or power-relations between different community groups and members may leave opinions unexpressed (Nunan et al., 2020). For example, imbalanced gender engagement and cultural norms may hinder women's active involvement in PGIS campaigns. Therefore, place-based data collection requires careful planning and facilitation. Gender differences can lead to varying opinions, particularly concerning activities at sea. In Zanzibar, for example, the seascape and associated resources are gendered: most fishers are men, while seaweed is mainly farmed by women (De la Torre-Castro et al., 2017). Therefore, it is crucial to ensure that community-based mapping campaigns have sufficient representation of different social and professional groups.

The PGIS answers reflect the participants′ attitudes, perceptions, and values attached to places at the time of mapping, and as such may change over time. Periodic mapping campaigns, regular follow-ups, or interviews to capture changing circumstances or evolving values, would be essential components of a dynamic and adaptive PGIS approach. This would allow for updates in spatial data, thus ensuring its accuracy and relevance over time. PGIS campaigns should at least be synchronized with the updates of MSP, or when monitoring the implementation of MSP.

While PGIS has demonstrated relevance and applicability in enhancing local involvement in spatial data generation and spatial planning (McCall & Dunn, 2012), the methodology is not well suited for dealing with activities that are not spatially confined, particularly in marine environments (e.g., fishing locations). The absence of prominent landmarks and the difficulty in defining locations at sea further complicate the mapping process. Observations on marine habitats and biodiversity may also be biased or spatially inaccurate, due to limited visibility. Yet, it has been concluded that for instance local ecological knowledge gained from local fishermen has a high overlap with conventional scientific knowledge (Berkström et al., 2019). Field visits and engagement of community members as "co-researchers" could allow collaborative mapping, thus contributing to more comprehensive and accurate representations of place-based activities.

6 | CONCLUSIONS

This study demonstrated an approach to data collection and collaborative planning, resulting in a pilot coastal and marine spatial plan for Zanzibar. The work emphasizes the need for creative and affordable methods to collect spatial marine data. Innovative approaches, such as the low-cost drop-video camera system, and the integration of satellite imagery, proved effective in mapping marine habitats. These cost-effective techniques are particularly valuable in resource-constrained settings, enhancing data availability to support the development of MSP. More importantly, the work showed the importance of stakeholder collaboration. Through participatory mapping and the collection of socio-ecological data, this study showed how local knowledge can enhance the identification of valuable marine areas. Stakeholder involvement not only filled data gaps but also provided diverse perspectives, essential for setting planning objectives and formulating management strategies. Incorporating views from coastal communities ensures that marine spatial plans are more accurate and relevant, and most importantly, widely accepted, fostering sustainable and adaptive management of marine resources. The developed draft MSP offers practical guidance for promoting sustainable development in the area, including environmental impact assessments for new developments and adherence to the principles of ecosystem-based marine spatial planning. The knowledge gained provides valuable inputs and strategic foundations for future work in sustainable marine management in Zanzibar.

AUTHOR CONTRIBUTIONS

Elina A. Virtanen: Conceptualization, Methodology, Data Curation, Investigation, Formal analysis, Writing—Original Draft, Writing—Review & Editing. Niina Käyhkö: Conceptualization, Methodology, Writing—Review & Editing, Funding acquisition. Zakaria Khamis: Conceptualization, Methodology, Data curation, Writing—Review & Editing. Muhammad Juma Muhammad: Conceptualization, Methodology, Writing—Review & Editing, Funding acquisition. Hashim Muumin: Conceptualization, Data curation, Writing—Review & Editing. Mohammed Habib: Conceptualization, Data curation, Writing—Review & Editing. Ville Karvinen: Methodology, Data curation, Investigation, Writing—Review & Editing. Juho Lappalainen: Methodology, Data curation, Investigation, Writing—Review & Editing. Meri Koskelainen: Data curation, Investigation, Formal analysis. Niko Kulha: Writing—Review & Editing, Investigation, Formal analysis. Markku Viitasalo: Conceptualization, Methodology, Writing—Review & Editing, Funding acquisition.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data presented in this study are archived at Zenodo https://doi.org/10.5281/zenodo.11115802.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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