Decadal Remote Sensing Analysis of Seagrass Changes in Palu Bay, Central Sulawesi

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Abstract *Seagrass meadows provide a variety of material, non-material and regulatory coastal ecosystem service; however, the distribution of seagrass beds changes over time due to both anthropogenic activities and natural factors, so it is important to monitor changes in seagrass condition. The aim of this study was to detect changes in seagrass distribution over a 10-year period from 2012 to 2022 and changes in land use over approximately a decade through the use of remote sensing technology. Changes in seagrass meadows were analyzed using data from a 2012 Landsat 7 Satellite Data Acquisition and a 2022 Landsat 8 Satellite Data Acquisition. Water column correction was implemented using the Lyzenga Algorithm. The results showed significant changes over a decade in the distribution of coastal seagrass meadows around Palu Bay. Seagrass meadows in 2012 and 2022 covered 127.08 Ha and 87.79 Ha, respectively, indicating a decrease of 43.29 Ha in seagrass extent. The accuracy of the satellite data classification results obtained was 80%, meaning that the results are acceptable.*

Key words: Seagrass meadows, satellite imagery, anthropogenic activities

Abstrak *Lamun menyediakan berbagai layanan ekosistem pesisir, baik secara material, nonmaterial maupun regulasi; namun sebaran padang lamun mengalami perubahan dari waktu ke waktu oleh aktivitas antropogenik dan faktor alami, sehingga penting untuk melakukan pemantauan terkait perubahan kondisi padang lamun. Penelitian ini bertujuan untuk mendeteksi perubahan sebaran lamun dalam kurun waktu 10 tahun yaitu dari Tahun 2012 hingga Tahun 2022 dan perubahan tata guna lahan selama kurang lebih satu dekade dengan memanfaatkan teknologi penginderaan jauh. Analisis perubahan lamun menggunakan data Citra Landsat 7 Akuisisi Tahun 2012 dan Citra Landsat 8 Akuisisi Tahun 2022. Tahapan koreksi kolom perairan dilakukan dengan menggunakan Algoritma Lyzenga. Hasil penelitian menunjukkan telah terjadi perubahan sebaran lamun yang signifikan di pesisir Teluk Palu selama satu dekade. Luasan lamun pada Tahun 2012 dan Tahun 2022 berturut-turut sebesar, 127,08 Ha dan 87,79 Ha, terjadi penurunan luasan lamun sebesar 43,29 Ha. Nilai akurasi hasil klasifikasi citra yang di peroleh sebesar 80 % sehingga layak diterima.*

Kata kunci *: Padang lamun, citra satelit,, aktivitas antropogenik.*

1. Introduction

Seagrass meadows are coastal ecosystems that provide important ecosystem services (Mazarrasa et al., 2018; Wahyudi et al., 2020). These ecosystem services include fishing grounds that are important for the welfare of the global community (Nordlund et al., 2018), mariculture areas, recreational areas, research sites, sources of inspiration in the fields of art, architecture and advertising, serving as a source of food for humans (McKenzie et al., 2021) and associated organisms (Nordlund et al., 2016). Some seagrasses are also important in the pharmaceutical field, including medicines used to treat diarrhea (UNEP, 2004). Regulatory services of seagrass meadows include their roles in reducing ocean acidification, in stabilizing sediments and coastal protection (McKenzie et al., 2021), and as carbon sinks (Gullström et al., 2018; Marbà et al., 2015; McKenzie et al., 2021; Potouroglou et al., 2021; Serrano et al., 2018).

Seagrass ecosystem services are very complex, making this ecosystem vulnerable to change. Changes in seagrass ecosystem condition and extent can occur over time, due to anthropogenic activities (Unsworth et al., 2018) or natural factors (Rahmawati et al., 2017). Across the Indonesian Archipelago, human utilization of coastal areas has tended to increase in line with the rising human population, leading to ongoing coastal development (Unsworth et al., 2018). The site chosen for this research was Palu Bay in the Indonesian province of Central Sulawesi. The Palu Bay coast spans two administrative regions, namely Palu City and Donggala Regency. In both of these jurisdictions, some of the steep hills surrounding the Bay are mined for open-cast mining of aggregate materials (*galian* C in the Indonesian mining classification), while several coastal areas are used for crushing and/or stockpiling the aggregate as well as the construction of ports or jetties for loading ships and barges with the mined material. While mining activities and associated development are one potential threat to the seagrass ecosystems around Palu Bay. Natural phenomena in this tectonically active region such as the 2018 earthquake and tsunami (Omira et al., 2019; Patria & Putra, 2020) also have the potential to cause change and affect the seagrass meadows in Palu Bay (Ndobe et al., 2021). Based on these conditions, monitoring of seagrass beds in Palu Bay needs to be carried out.

The scale of the benefits provided by seagrass beds means that monitoring of these valuable resources is badly needed to support their management (BIG, 2014). Seagrass monitoring has been carried out in several areas across Indonesia such as the Thousand Islands (Kawaroe et al., 2010), Banten Bay (Setiawan et al., 2012), the eastern waters of Bintan Island, Riau Islands (Supriyadi et al., 2018) and around Bonebatang Island, Spermonde Archipelago (Mashoreng et al., 2020). These studies have shown changes in seagrass meadow extent, with a general trend of decreasing seagrass area over time.

Several methods have been used for seagrass mapping, including lightweight drone and consumer grade cameras (Duffy et al., 2018), sidescan and underwater video (Vandermeulen, 2014), remote sensing (Fauzan & Wicaksono, 2019; Fauzan et al., 2017; Nguyen et al., 2021; Thalib et al., 2018; Topouzelis et al., 2018; Traganos et al., 2018) and field survey (Short et al., 2006). The use of remote sensing technology is one approach that has become widely used for monitoring changes shallow marine habitats because it is effective and efficient, including for detecting changes in seagrass condition and extent (BIG, 2014; Giofandi et al., 2020; Mumby et al., 1999). In addition, remote sensing has the ability to cover a wide area (Topouzelis et al., 2018). Seagrass mapping and monitoring are important for coastal area management planning, assisting coastal conservation and ultimately climate change mitigation (Traganos et al., 2018). With respect to managing Indonesia's valuable but threatened seagrass beds (Unsworth et al., 2018), collaboration between stakeholders is needed to maintain the seagrass ecosystems and their functions, including monitoring to inform management. However, such data are missing for many seagrass meadows, including those in Palu Bay.

Therefore, the purpose of this research was to fulfill the need for data on the changes in seagrass condition in Palu Bay, Central Sulawesi, over the past ten years (2012–2022) as well as changes in land-use over the past decade, including the extent of changes in seagrass beds and land use, the location of changes in seagrass beds and land use and to analyze the causes of changes in seagrass beds and land use. Observations of the percentage of seagrass cover also need to be carried out to determine the current status of seagrasses as an initial step in assessing the overall condition of seagrass in the future. The scientific information obtained will be used to inform the process of producing comprehensive coastal zone management plans and policies for Palu Bay. This research applied remote sensing technology, analyzing Landsat 7 and Landsat 8 satellite data to detect changes in seagrass meadow extent over the study period, and is the first study of its kind in Palu Bay, Central Sulawesi, Indonesia.

2. The Methods

2.1. Study site and materials

This research comprised three main stages: preliminary analysis of the satellite data, field survey/ground-truthing, and data analysis. The study site was the coastal waters of Palu Bay in Central Sulawesi Province, Indonesia (Figure 1). The field work was completed during August 2022. The satellite data used comprised a Landsat 7 acquisition from 2012 and a Landsat 8 acquisition from 2022.

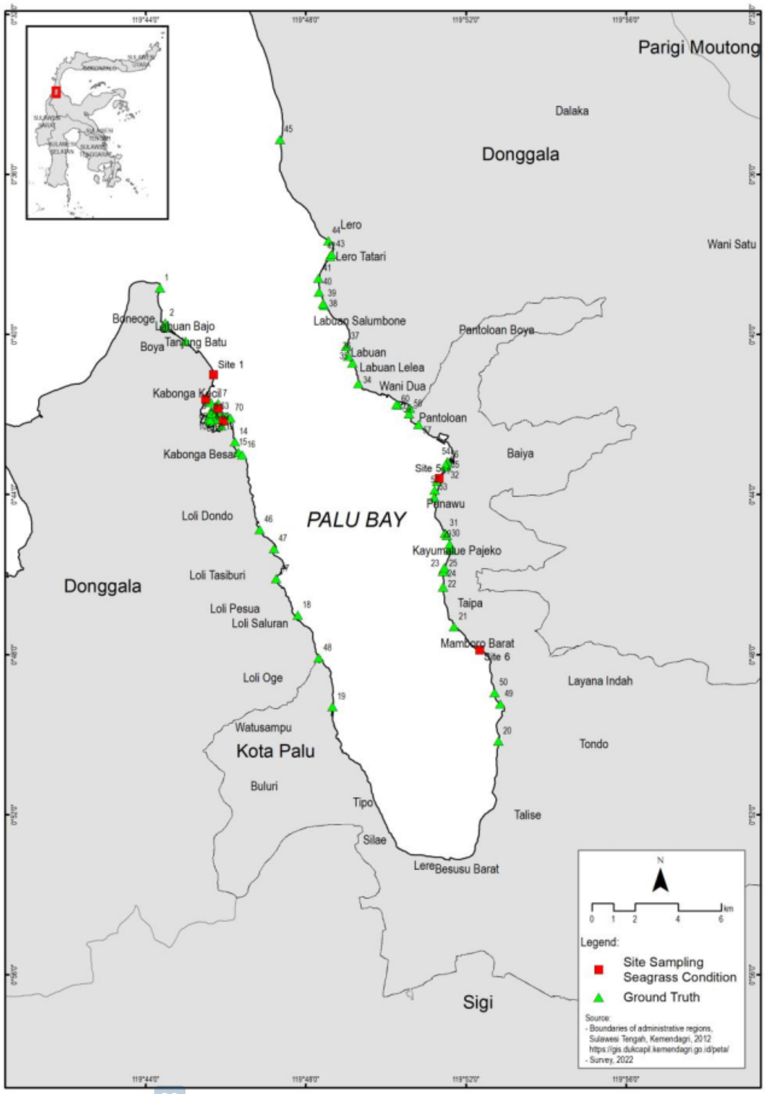

Figure 1. Map of Palu Bay showing the field sites

2.2. Preliminary processing and unsupervised classification of the satellite data

Preliminary processing of the satellite data comprised several stages, following the manual from the Indonesian Geospatial Agency (BIG, 2014). The first stage was pre-processing to improve image quality. The second stage was the correction of the water column using the Lizenga method. The next stage was classification using unsupervised classification, implemented in ENVI 5.1 and ArcGis 10.8. The Lyzenga method applies the following equation:

$$DII = \ln(\text{band } i) + [(ki/kj).\ln(\text{band } 2)] \quad (1)$$

2.3. Ground-truthing

The ground-truthing survey was conducted following Rahmawati et al. (2019) to collect information on basic aquatic habitat types as a reference for satellite image interpretation and to be used as a sample for testing the accuracy of the classification. The coordinates of 70 randomly selected ground-truthing points were determined based on the results of the unsupervised classification of the satellite imagery. A GPS (Global Positioning System) was used to find these coordinates in the field in order to collect data on the underwater objects present at these points in the coastal waters of Palu Bay.

2.4. Seagrass survey

Seagrass observation stations were determined to represent areas with varied field conditions based on the unsupervised classification and different location characteristics. The survey site was divided into 2 zones: western Palu Bay with four observation stations and eastern Palu Bay with two observation stations (see supplementary material for site descriptions). The percentage seagrass cover was measured using a systematic sampling method. At each station three 100m line transects were laid perpendicular to the shoreline around 50 m apart. The start (0 m) point was determined by measuring a distance of 5 m seawards from the first spot at which seagrass was found. A 50 cm x 50 cm quadrat was used to observe seagrass cover at 10 m intervals along each transect, giving a total of 33 quadrat plots for each station (Rahmawati et al., 2017). Percentage seagrass cover in each quadrat was estimated based on photographs of the quadrats using the Seagrass Watch method standards (Mckenzie et al., 2003). Seagrass species were identified using the Seagrass Watch manual (Mckenzie et al., 2003) and the COREMAP-LIPI manual (Rahmawati et al., 2017).

2.5. Participatory Rural Appraisal (PRA)

The aim of the Participatory rural appraisal (PRA) mapping was to obtain information related to the changes that had occurred in the coastal area of Palu Bay. According to (Chambers, 1994), PRA is a method of approaching local communities with the aim of providing opportunities for them to share information and participate in natural resource management, poverty alleviation programs, food security and health care initiatives. The PRA was conducted by involving the local communities living around Palu Bay. Information was obtained on several aspects including the type of changes that had occurred, where change had occurred, and the impact of these changes on people as well as on the coastal ecosystems (seagrass meadows, mangroves and coral reefs). The data from the PRA was used to validate the classification of the 2012 satellite data as well as to provide complementary information to support the interpretation of the results of the satellite data analysis.

2.6. Satellite data analysis

The analysis of seagrass ecosystem change based on the satellite imagery included estimating seagrass area in 2012 and in 2022, and then calculating the change in the extent of seagrass beds by overlaying the two classified images. To test the accuracy of the data obtained from this process, the satellite data classification results for 2022 were compared with actual conditions in the field. The level of accuracy K was calculated using the following equation (BIG, 2014):

$$K = (\text{Number of correctly interpreted sample pixels} / \text{number of tested sample pixels}) \times 100 \quad (2)$$

2.7. Land-use change

Land-use changes in the area around Palu Bay were evaluated based on data from 2010 and 2021. Data on land-use/land cover in 2010 with a resolution of 300 m were sourced from the European Space Agency (ESA) GlobCover Land Cover Map repository (http://due.esrin.esa.int/page_globcover.php). Data on land-use/land cover in 2021 with a resolution of 10 m were sourced from the Copernicus Sentinel-2 mission via the ESRI ARCGIS portal (https://www.arcgis.com/apps/instant/media/index.html?appid=fc92d38533d440078f17678ebc20e8e2). The area boundary used was the Palu Bay watershed area shapefile, sourced from the geoportal of the Indonesian Ministry of the Environment and Forestry (https://sigap.menlhk.go.id/sigap/peta-interaktif. The data were analyzed in Arcgis 10.8.

3. Results and Discussion

3.1. Distribution of seagrass meadows in Palu Bay

The satellite image classifications for 2012 and 2022 (Figure 2) show changes in the distribution and extent of the seagrass meadows in Palu Bay. In 2012 (Figure 2a), seagrass meadows were scattered along the coasts of Palu Bay, extending seawards at several sites (Kabonga Kecil, Kabonga Besar, Panau and Baiya), with most other seagrass meadows forming a narrow fringe along the shore. The distributions shown for 2012 are consonant with the information obtained from the PRA.

Figure 2. Distribution of seagrass meadows in Palu Bay based on classification of satellite data from 2012 (Landsat 7) and 2022 (Landsat 8).

Participatory rural appraisal (PRA) activities (see supplementary material) conducted during this study applied a participatory mapping mechanism to obtain information from coastal community members regarding the changes that have occurred along the coast of Palu Bay in recent years. In addition, PRA activities used have been carried out to validate the results of the 2012 satellite image interpretation.

Comparison of the seagrass distribution maps for 2012 and 2022 (Figure 2a and 2b) shows that there have been some changes in distribution, including the loss of seagrass ecosystems in some areas, but distribution patterns of other areas remained similar or did not change significantly. In both 2012 and 2022, the classification maps show distribution of seagrass within the western zone, in particular the relatively extensive seagrass meadows in front of Kabonga Kecil and Kabonga Besar villages did not change significantly. During the field survey, anthropogenic activities that could potentially threaten the existence of seagrass beds, such as rock mining and aggregate stockpiling in coastal areas, were not found at these sites. Based on the observations at Kabonga Besar Village, this site has mangrove ecosystems around the Sulawesi mainland coast and around the several small islands close to the shore. Fringing coral reef ecosystems were also found, including in the waters around Levuto Kabonga Island. The presence of these two coastal ecosystems most likely helps to support the continued presence of the seagrass ecosystems in this area. In the eastern zone of Palu Bay, the seagrass ecosystems in front of the villages from Panau to Baiya also show little change. The survey also observed mangroves and coral reef ecosystems in this area.

However, changes in seagrass distribution were visible along the coast at several sites in both the western and eastern zones of Palu Bay. In the western zone, one area where seagrass extent had been reduced and some seagrass meadows had been lost in 2022 was the coast between Kabonga Kecil Village and Boya Village. Reclamation had occurred along around 1.5 km of the coastline for the construction of a ring road as well as tourism facilities including a platform and recreational park area called an *anjungan*. At several other sites along the western coast of Palu Bay seagrass meadows had been lost due to the use of the coastal strip for stockpiling mined aggregate (sand, stones and gravel) prior to use or shipment to other areas on cargo ships or barges. This was especially prevalent from Buluri Village in Palu City to Banawa District in Donggala Regency. Another cause of the loss of seagrass beds is reclamation for the construction of a hotel (Silae Village) and the construction of breakwaters and coastal seawall embankments along a stretch of coast approximately 7 km long from Silae Village (west zone) to the salt pans in Talise Village (east zone). This is supported by Unsworth (2018) that coastal reclamation is one of the significant causes of the loss of seagrass beds in Indonesia.

Other information obtained from the community included reports that before the 2018 tsunami people often saw several dugongs on the coast between Mamboro and Taipa Village, but since the tsunami dugongs have rarely been seen and only in lower numbers. Dugongs have also been reported further north along the east coast of Palu Bay (Moore et al., 2017). Dugongs eat seagrass as their main source of food, especially small seagrass species such as *Halodule* sp. and *Halophila* sp. (Sheppard et al., 2007). This is in accordance with information from the community that in the past *Halophila* and *Halodule* was common along on the coast around Mamboro Village. During the field survey this genus was observed but only represented a small percentage of seagrass cover.

It is also interesting to note that the people of Mamboro Village expressed an interest in the ornamental Banggai cardinalfish (BCF) *Pterapogon kauderni* (local name *capungan layar*), which was introduced to the site by an ornamental fish trader in 1998. This introduced fish became established and bred successfully, providing an additional source of income for the community. The tsunami almost wiped out the BCF population, along with the seagrass, corals and other benthic organisms, leaving barren substrate strewn with debris (Moore et al., 2019, 2020). During the PRA, the people of the Mamboro village were keen to seek the reintroduction or rehabilitation of the BCF population, because the seagrass ecosystem had started to recover, as reported by a survey in 2020 (Syahril et al., 2020).

The Ministry of Marine Affairs and Fisheries of the Republic of Indonesia (MMAF) and the Central Sulawesi Provincial Marine and Fisheries Service collaborated on programs to restore the coastal ecosystems after the tsunami. These included the planting of mangroves at several sites about a year after the 2018 earthquake and tsunami, including along the coast of Mamboro Village. However, based on observations during the field survey, the mangrove restoration efforts at this site were not going to plan. One reason for this might be that all but a very few isolated mangroves in this area had been lost long before the tsunami, and the conditions may no longer be conducive to supporting mangrove ecosystems.

The PRA produced other information related to the distribution of seagrass and other aspects of coastal ecosystems in the eastern zone of Palu Bay. In particular, several years before the tsunami event, seagrass ecosystems along the coast of Mamboro Village were quite extensive and comprised several types (species). According to Nordlund et al., (2016), the loss of seagrass ecosystems can have an impact on the lives of people who use these ecosystems directly or indirectly. The respondents mentioned organisms associated with the seagrass beds including fish such as rabbitfishes (Siganidae), seahorses (*Hippocampus* sp.), dugongs, macroalgae (e.g. *Padina* sp.) and many other organisms. There are also data on other invertebrate taxa including mollusks and echinoderms (Ndobe et al., 2021). However, the seagrass meadows were quite narrow, only extending around 15-25 m seawards, because of the coastal topography which is not gently sloping but drops steeply beyond the narrow coastal shelf. Similar narrow seagrass meadows were found along the coast to the north of Mamboro, in Taipa, Kayumalue and Pantoloan villages, although in some areas the seagrass belt was more sparse or narrower. The tsunami caused severe damage to many of the seagrass beds along the east coast of Palu Bay. However, by the time of the survey in 2022 the seagrass in Mamboro Village and several other locations was showing signs of recovery.

Meanwhile, along the coasts of Talise and Tondo Villages, the extent of seagrass meadows had already begun to decrease before the tsunami due to the direct and indirect impacts of reclamation activities, and more were lost during the tsunami. The field observations indicated that several other areas along the east coast of Palu Bay, such as in Talise Village, are no longer suitable for the post-tsunami growth and recovery of seagrass ecosystems, due to reclamation projects, the construction of seawalls and embankments, and the high turbidity of the waters close to the Palu River estuary. Seagrass recovery is also likely to be difficult or even impossible in some areas of Tondo Village due to reclamation for housing construction along approximately 700 m of the coastline.

In the western zone, the community also reported that several years ago seagrass meadows with associated organisms such as shellfish, rabbitfishes and dugongs were also found along the coastal from Silae Village in the south to Watusampu Village in the north. Seaweed farming was also common along the coast from Buluri Village to Watusapu before the rock mining became prevalent. As rock mining extended along the east coast of Palu Bay from Buluri Village in Palu City to Banawa District, in Donggala Regency, along with stockpiling aggregate and the construction of docks for the ships and barges, this seaweed farming had to stop. Rock mining activities also have an impact on seaweed cultivation in the western zone of the bay. The impact of mining on seaweed cultivation is reflected in the report, published in the online news media (antarasulteng.com) on 23 October 2015, that the government of Palu City stopped the seaweed development program in 2015 due to these anthropogenic activities. Seaweed farming on the east coast of Palu Bay had failed a few years earlier due to thermal pollution from cooling water discharged by a coal-fired power station at Panau.

As pointed out by Nordlund et al. (2018), nearshore seagrass fisheries are important for the livelihoods and well-being of coastal communities in developing countries. According to the fishing community, the income of fishermen and shellfish gleaners in Palu Bay has decreased drastically due to the impact of mining and the 2018 earthquake and tsunami. For example, previously shellfish gleaners could collect an average of 50 kg of shellfish per day, but in 2022 they could only collect less than 10 kg per day. The catch of finfish such as snapper, grouper and rabbitfishes had also declined sharply, and these fishes were now very difficult to obtain.

Based on information from the community (PRA) and direct observations made in the field, most of the changes in or loss of seagrass meadows along much of the western coast of Palu Bay were caused by mining and construction related activities, including stockpiling for hotel construction, aggregate storage, docks/jetties and seawall construction. The tsunami caused some direct damage but also exacerbated these processes, so that the rate of seagrass ecosystem loss has accelerated since the 2018 earthquake and tsunami. Meanwhile along the eastern coast of Palu Bay, the tsunami and earthquake events played a greater role in seagrass change, although seagrass ecosystems in this zone are also affected by anthropogenic activities such as coastal reclamation and aggregate mining in the Labuan River, both of which raise the level of turbidity and sedimentation.

Generally, based on the PRA, most people around the coast of Palu Bay are not aware of the direct benefits or ecosystem service provided by seagrass ecosystems. However, some people did understand the function of seagrass as a habitat for marine organisms such as rabbitfishes and shellfish. One habit of Palu Bay fishermen which can be seen as positive with respect to seagrass conservation is that they do not generally anchor their boats in the seagrass ecosystem but keep them at the top of the beach, so the potential for damage due to boat anchors is relatively low.

Based on the 2012 seagrass distribution map and the 2022 seagrass distribution map, it can be said that there have been changes in coastal conditions that have occurred several years ago until now. The cause is strongly suspected by the existence of anthropogenic activities such as rock mining in conjunction with coastal stockpiling activities (Figure 6), rock mining in rivers and natural factors such as earthquakes and tsunamis that are aggravating the condition of coastal ecosystems including seagrass ecosystems. Based on observations during the survey that some parts of the coast of Palu Bay such as in some parts of Buluri Village experienced subsided beach to a depth of about 4 m (see supplementary material). Patria & Putra (2020) also reported that part of the coast of the Silae sub-district had experienced the same thing at a depth of about 1.5 m (see supplementary material). The part of the coast that experiences subsided beach is the Palu-Koro fault line.

Rock mining activities in Ulujadi District (west zone) are accompanied by beach stockpiling activities for the construction of a barge dock for transporting mining products in the form of sand, gravel and rocks to be transported outside the area. Another activity that accompanies this mining activity is the activity of barges going back and forth in Palu Bay. Based on the information gathered from the community and the map of the distribution of seagrass in 2012 and 2022, it can be concluded that in addition to natural factors, this anthropogenic activity is strongly suspected of causing ecosystem damage on the coast of Palu Bay, including seagrass ecosystems, especially in the coastal area of Ulujadi District (western zone).

Issues related to rock mining (*galian* C) and reclamation along the coast of Palu Bay and their impact on the environment including coastal ecosystems have been hotly discussed in recent years by various elements of society through various discussion forums and reported through local and national media. Rock mining in the hills occurs from Buluri Village, Palu City to Banawa District (west bay zone), in addition, rock mining activities occur in Labuan River (east bay zone). Meanwhile, the reclamation of the Palu Bay coast is carried out with various purposes, such as docks for ships transporting rock mining products, housing, and hotels and others.

The accuracy test compared the 2022 satellite image classification with the results of the ground-truth survey using a confusion matrix (see supplementary material). The accuracy level K obtained was 80%, which meets the standard established by the Indonesia Geospatial Agency (BIG, 2014), which is a K value of 60% or greater.

3.3. Changes in seagrass ecosystem extent

The area of seagrass based on image analysis of classification results in 2012 and 2022 was 127.08 Ha and 83.79 Ha, respectively, meaning that the seagrass area decreased by 43.29 Ha for a decade. The shrinkage of seagrass area in Palu Bay was smaller than what happened in Van Phong Bay, Vietnam (Vo et al., 2020). The images from the 2012 and 2022 classifications can then be compared by overlaying to see areas that have changed (Figure 3).

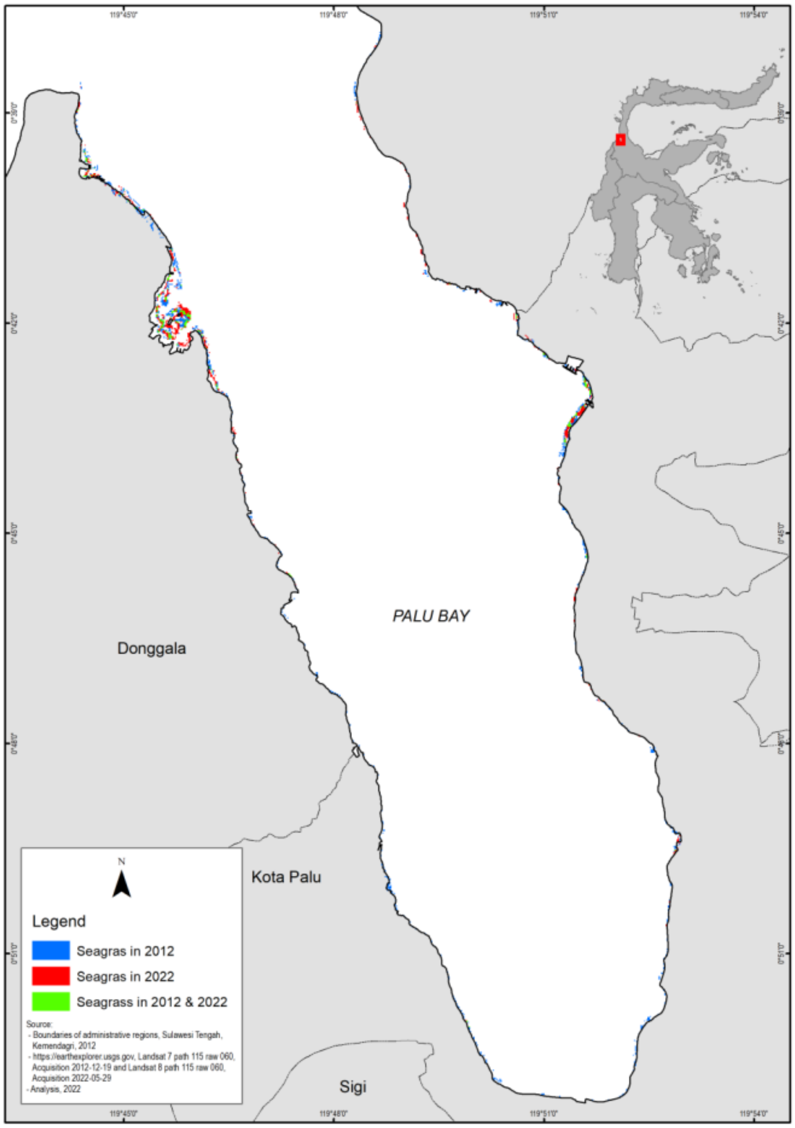

Figure 3. Overlay of seagrass ecosystems in Palu Bay in 2012 and 2022

In Indonesia, the main causes for the loss of seagrass beds are coastal development, land reclamation, sedimentation, coral and sand mining, seaweed cultivation, overuse of associated organisms, and ship activities (Unsworth et al., 2018), while natural factors include by earthquakes, strong currents, large waves, storms and tsunamis (Rahmawati et al., 2017). Changes in seagrass area in the Palu Bay Coast are most likely caused by rock mining activities, coastal reclamation, barge activities going back and forth in the waters, sedimentation, and the 2018 earthquake and tsunami. Vo et al. (2020) have also reported that natural disasters, coastal reclamation and various other human activities such as aquaculture activities have a negative impact on the distribution of seagrass beds in Vietnam.

3.4. Seagrass condition and species composition

Decree of the Minister of the Environment No. 200 of 2004 divides seagrass into the Good category (percentage cover 60% or greater) and the Degraded category (less than 60% percentage cover). The Degraded category is further subdivided into the Sparse (30-59.9% percentage cover) and Poor (less than 30% percentage cover) categories. The data on seagrass condition and species composition collected at six sites around Palu Bay (Table 1) show that five of the six sites were in the Sparse Degraded category (collective area 79.74 Ha), while just one was in the Good category (4.05 Ha). Seagrass meadows in or close to the Good category were close to mangrove and coral reef ecosystems, without direct impacts from human settlements or other anthropogenic activities that can threaten coastal ecosystems. Some were also protected by the presence of small islands near the survey sites.

Table 1. Seagrass percentage cover and species composition at six sites in Palu Bay

No	Village/Site	Station	Seagrass cover (%)	Mean cover by species (%)*					
				Cr	*Hu*	*Th*	*Ea*	*Ho*	*Si*
1	Kabonga Kecil	1	50.22	0.00	6.83	16.09	3.91	3.26	5.87
2	Kabonga Kecil	2	34.24	0.00	0.00	0.00	23.48	10.91	0.00
3	Kabonga Besar	3	57.42	1.21	0.00	36.67	14.39	4.39	0.00
4	Kabonga Besar	4	62.38	0.00	0.00	10.95	51.43	0.00	0.00
5	Baiya	5	52.14	17.32	20.71	7.50	4.46	4.46	0.00
6	Mamboro	6	31.11	12.78	1.67	1.11	14.44	1.11	0.00
	Mean		47.92	5.22	4.87	12.05	18.69	4.02	0.98

Local people around Palu Bay call all seagrasses *nambo* or *rago*. Six species of seagrass were identified at the observation sites (Table 1): *Cymodocea rotundata* (Cr), *Halodule uninervis* (Hu), *Thalassia hemprichii* (Th), *Enhalus acoroides* (Ea), *Halophila ovalis* (Ho), and *Syringodium isoetifolium* (Si). One study has reported that species such as *T. hemprichii* and *Halodule* sp. can be severely damaged by physical factors such as large waves (Sachithanandam et al., 2022), and environmental factors such as exposure to weather and/or the variation in severity of the tsunami waves in 2018 may have influenced the distribution of the six species found. The seagrass species with the highest mean percentage cover was *Enhalus acoroides* (18.69%).

3.5. Land-use change

The analysis of data on land-use/land cover shows significant change over the period 2010 to 2021 (Figure 4). In particular, the built-up area increased from around 1,564 ha in 2010 to 20,546 ha in 2021, an increase of an order of magnitude. This increase is likely an overestimate, as the low resolution of the 2010 data undoubtedly missed many smaller developments, especially ribbon development along the coastal and inland roads, and even the town of Donggala. Nonetheless, many of the newer built-up areas visible to the east and south of the Bay in 2021 (Figure 5b) clearly cover more than one 300 m squared pixel, and should therefore have appeared on the 2010 map (Figure 5a) had they been present then.

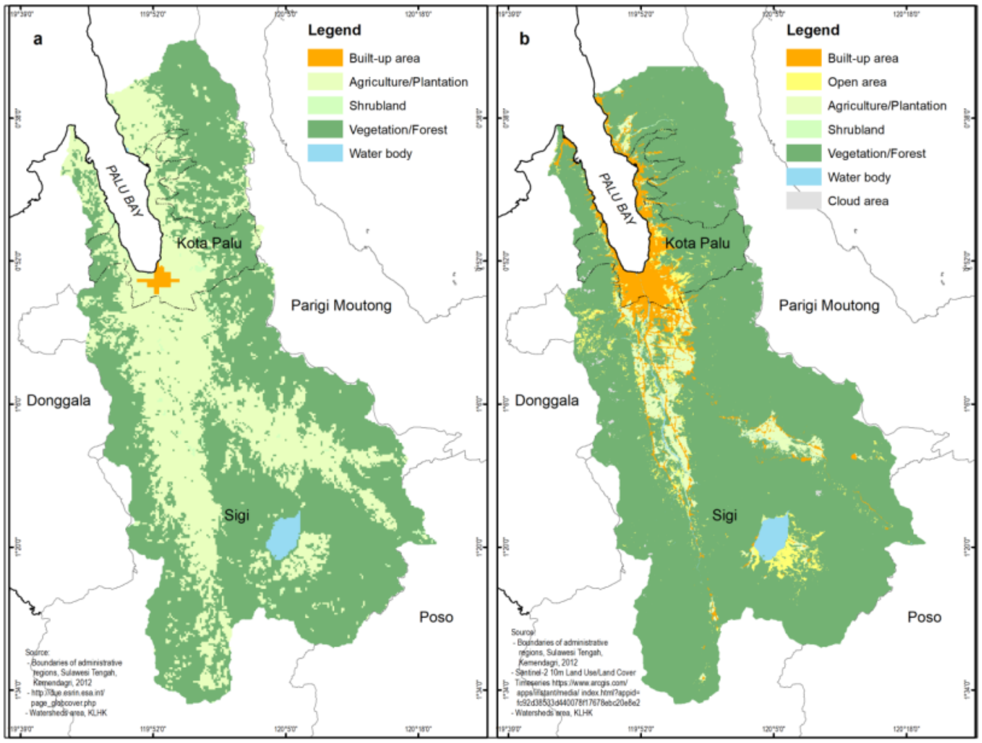

Figure 4. Land-use around Palu Bay (Palu City and Donggala Regency): a. 2010; b. 2021

Figure 4 shows that by 2021 the built-up area had expanded and spread around the coast of Palu Bay, decreasing available land for agriculture and plantations. In particular, the expansion of the already growing built-up area in Tondo Village, Mantilore District was accelerated by the construction of housing for victims of the 2018 earthquake and tsunami. Conversely, some areas previously cultivated or used for housing and other facilities have reverted to vegetated (forest or scrub) areas. This is thought to be due to the effects of the triple disaster in 2018 (Syamsidik et al., 2019), as some of the land affected by the earthquake and liquefaction has been abandoned and allowed to revert to nature (Ndobe et al., 2020; Nurdin et al., 2022).

Open land identified in 2021 covered an area of 11,273 Ha, and appears to include the aggregate rock mining areas along the escarpment of the mountains behind the western coast of Palu Bay as well as the Poboya gold mining area. Some of the rock mining areas to the west of Palu Bay used to be plantations, with commodities including coconut and sugar apple or srikaya (*Annona squamosa*). Meanwhile, the highly degraded Poboya gold mine area used to be the Palu Forest Park, a protected area (Ambo-Rappe & Moore, 2019; Muhammad et al., 2012). These and other land-use changes may have had negative impacts on the seagrass meadows around Palu Bay. Impacts of land clearance have caused seagrass condition to decline in the waters of eastern Bintan, Indonesia (Supriyadi et al., 2018), and a lack of integration in land use planning can lead directly to spatial problems in coastal areas (Baja et al., 2018).

The field survey found 39 ports or jetties/loading sites associated with aggregate mining around Palu Bay (Figure 5). These structures and activities have certainly had an impact on the seagrass ecosystems. The jetties have mostly been constructed by the simple expedient of tipping rock/aggregate material into the sea to form platforms reaching deep enough water for ships or barges to be loaded, a form of small-scale coastal reclamation. In addition to the direct loss of seagrass covered by this infill, the construction and operation of these facilities, including the grinding and stockpiling of aggregate close to the shore, results in heavy sediment loads. Together with sedimentation from the mining activities further inland, the increased turbidity will affect seagrass growth and could even eliminate seagrass meadows in affected coastal waters around Palu Bay.

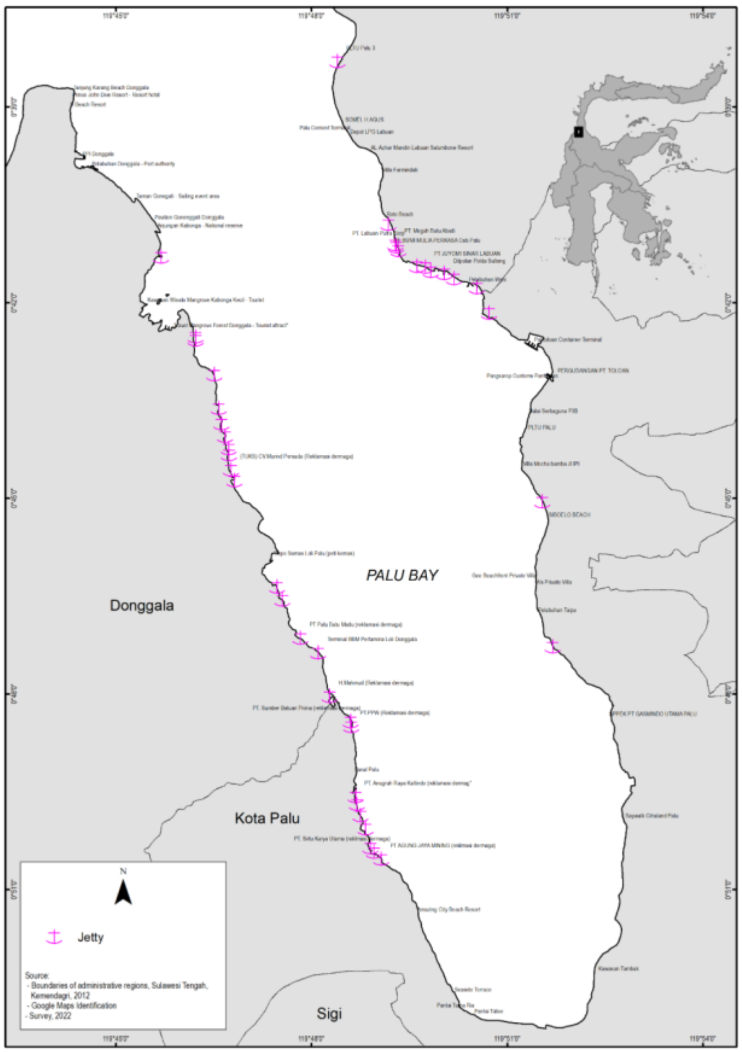

Figure 5. Ports and jetties around Palu Bay in 2022

4. Conclusion

Analysis of the seagrass meadows in Palu Bay based on satellite data was validated by ground-truthing with a classification accuracy of 80%. The results show a significant decrease in seagrass ecosystem extent over the decade from 2012 to 2022. Direct observation and participatory methods indicate that the main drivers of the decline in seagrass extent in Palu Bay are anthropogenic activities such as aggregate mining, activities associated with the shipping of mining products, and coastal reclamation. The natural disaster in 2018 also appears to have been a factor, in particular through increases in turbidity and sedimentation, which have had negative impacts on the condition of seagrass beds in Palu Bay.

The sites around Palu Bay where healthy seagrass meadows had remained healthy were mostly those where supporting ecosystems (mangroves and coral reefs) were still present and there were no observed threats from direct anthropogenic activities. Areas with environmental conditions that had allowed seagrasses to recover and develop into healthy meadows included the coastal waters of Kabonga Kecil and Kabonga Besar Villages and the waters around Levuto Island on the west coast, and from Panau Village to Baiya Village on the east coast of the Bay. Based on the results of this study, the researchers recommend as a matter of urgency the implementation of a comprehensive coastal area management plan for the coast of Palu Bay. Such a plan is needed to realize maritime-based economic development in line with the blue economy paradigm adopted by the Indonesian Ministry of Marine Affairs and Fisheries (MMAF).

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