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ASSESSMENT OF SEAWATER LEVEL, INUNDATION DURATION AND SUBSTRATE ELEVATION FOR MANGROVE REHABILITATION PROGRAM IN THE SPERMONDE ARCHIPELAGO SOUTH SULAWESI INDONESIA

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Abstract

Assessments of seawater level, substrate elevation, and inundation duration are known to contribute to the success of mangrove rehabilitation programs. However, the majority of such programs have disregarded the need for these assessments. The objectives of this study are to assess seawater level and inundation duration, and subsequently determine suitable substrate elevation ranges for specific mangrove species used at a mangrove rehabilitation program in the Sagara Island of Spermonde Archipelago, South Sulawesi, Indonesia. During field surveys, substrate elevation and seawater levels were measured, and inundation patterns observed for 24 hours. The mangrove species found at each elevation level were identified. To predict seawater levels during 2016, tidal prediction data for the area were obtained from the Hydro-Oceanographic Department (DISHIDROS) of the Indonesian Navy. The seawater inundation frequency varied between once and twice a day, with the highest inundation duration (21-24 hours) at the Mean Lower Low Water Spring (MLLWS) level. The appropriate planting range for most mangrove species concerning seawater level and seaward to landward substrate elevation, were between Mean Lower Low Water Spring (MLLWS) and Mean Highest High Water Spring (MHHWS) tidal levels.
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***Keywords**: Mangrove rehabilitation; Hydrological conditions; Substrate elevation; Spermonde Archipelago*

Introduction

Mangrove forests are found in many coastal areas of tropical and subtropical countries situated between 30°N and 30°S latitude [1]. These forests are frequently affected by the tides, adapted to fluctuating salinity regimes, and dominated by trees, shrubs, palms, epiphytes, and ferns [2]. Mangroves provide a wide range of benefits, including protecting coastlines from wave and wind energy, storm, and abrasion, preventing seawater intrusion, carbon sequestration, providing spawning, nursery and feeding and grounds for marine biota, acting as a nutrient source for neighbouring ecosystems, and providing habitat for wildlife such as birds, reptiles and primates. Mangroves also support a number of economic resources and benefits, including forestry products (firewood, charcoal, and housing materials), fisheries products (fish, crabs, shrimps, and molluscs), medicinal products, and ecotourism [3 - 6].

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The most recent worldwide extent of mangrove forests was estimated at 16.4 million hectares in 2014 [7], distributed around the coast of 118-124 countries [1]. However, mangroves are mainly concentrated in 15 countries [1] with the largest mangrove forest areas found in Indonesia [1, 3, 8]. Unfortunately, over-exploitation of forest products for commercial purposes and conversion of these forests to other land uses (mainly brackish-water aquaculture ponds) resulted in the deforestation and degradation of 3.6 million hectares between 1980 and 2005 [9].

Many mangrove protection and rehabilitation programs have been implemented by government agencies and NGOs in Indonesia and other Southeast Asia countries in recent decades. However, the drivers of mangrove forest loss have rarely been addressed effectively or eliminated, and most of the mangrove rehabilitation programs have been unsuccessful. One common reason for failure has been a concentration on seedling production and planting, without proper regard to the selection of planting sites to ensure they are appropriate for the establishment and growth of the mangrove species planted, in particular in terms of seawater levels and substrate elevation [10 – 17]. One reason why these parameters are often ignored is that they can be difficult to quantify in practice [16]. In addition, most programs use a monospecific planting approach, or low species diversity [18 – 20], and low survival rates are common [15, 17]. For example, the survival rate of mangroves planted under rehabilitation programs in Aceh after the 2004 Tsunami disaster ranged between 15% and 60% [21]. In the Philippines, the survival rate estimated over an 11 period was only 17% to 32% [11].

Low survival rates have occurred due to failure in site and species selection in programs where these parameters were not considered [11, 12, 17]. In particular, *R.R. Lewis* [22] found that, although mangrove plantation activities are not particularly inexpensive, most mangrove rehabilitation programs were not successful due to ignoring the physiological tolerance of mangroves to tidal inundation. It is increasingly clear that it is extremely important to assess seawater levels, inundation patterns, and substrate elevation before undertaking the rehabilitation of disturbed or degraded mangrove areas. These factors play key roles in controlling natural mangrove establishment and regeneration, forest structure and species distribution patterns, and subsequent long-term stability [16, 23, 24] and hence the success of mangrove rehabilitation programs [13]. As stated by *S. Munandar et al*. [15] and proven at mangrove rehabilitation sites in many countries, such as those reported by [25 – 27], tidal inundation patterns and substrate elevation tend to be the leading factors determining mangrove growth.

The objectives of this study are to assess seawater levels, inundation duration, and subsequently determine substrate elevation ranges suitable for the establishment and growth of several mangrove species at a specific mangrove rehabilitation program site. Sagara Island was selected for this case study. This small island is situated in the Spermonde Archipelago, Indonesia. Like many other small islands in the Archipelago, the mangroves around Sagara Island have been heavily exploited, and many were converted to aquaculture ponds. However, most of these ponds have become degraded due to poor maintenance by the farmers, and in recent years many have been abandoned. There were no previous studies on this site that could support the development of mangrove rehabilitation.

Experimental

Study Area

Sagara Island is located in the inner zone of the Spermonde Archipelago, at approximately 4°42'9" latitude and 119°27'18" longitude, about 47km from Makassar City, the capital of South Sulawesi Province, Indonesia. Administratively, the island forms part of the North Liukang Tupabbiring District in the Pangkep Regency. The land area of Sagara Island is 33.015ha, while the coastal waters around the island extend for approximately 16.6km^2.

Mangrove forests originally characterized the Island and surrounded by extensive seagrass meadows and coral reefs [28].

Mangroves originally covered 17.209ha, extending all around the coast of Sagara island. The widest mangrove belt, extending up to 160 meters from the shoreline, was on the western coast, and comprised the majority (10.33 ha) of the mangrove forest area [28]. However, since the island was settled, the majority of the mangroves been cleared and converted to aquaculture ponds [28] (Fig. 1). These ponds were mainly used for semi-intensive culture [29]. Over the period 1990-2015, around 10.08ha of mangrove cover was lost due to overharvesting of wood and the development of aquaculture ponds [28].

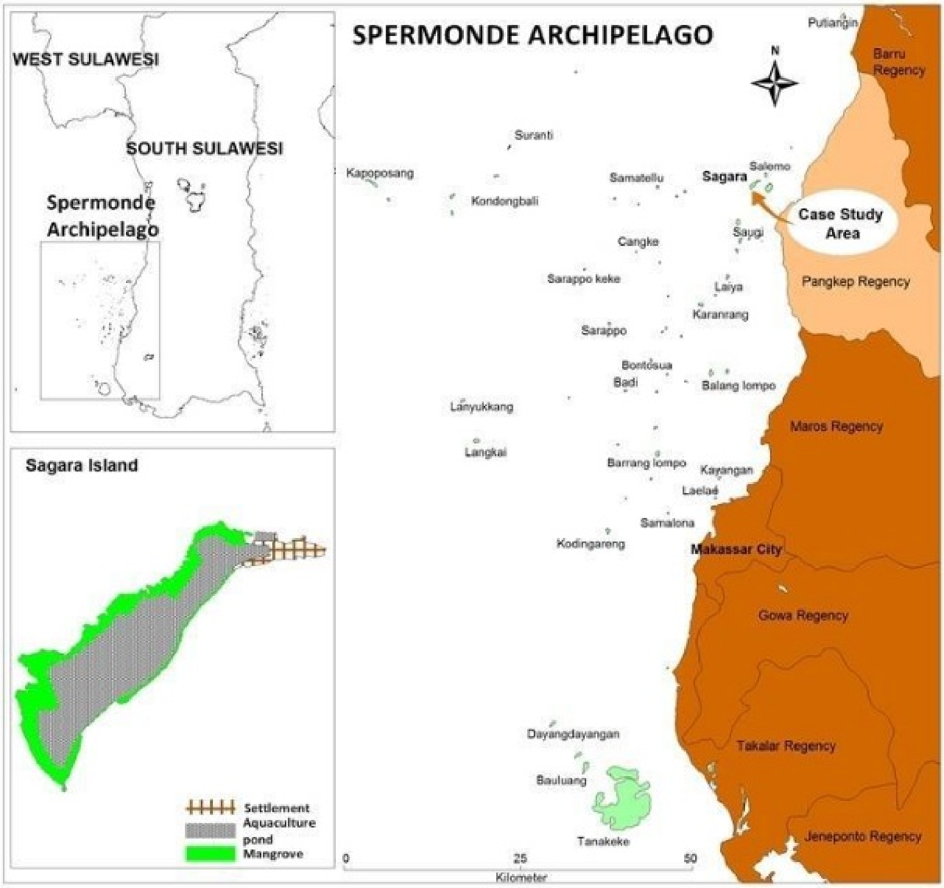

Fig. 1. Sagara Island in the Spermonde Archipelago, Pangkep Regency, South Sulawesi Province, Indonesia

Data Collection

Secondary data was used in this study comprised of tidal height prediction data for 2016. This data was gathered from the Naval Hydro-Oceanographic Department (DISHIDROS) of the Republic of Indonesia.

Primary data were collected on seawater level, substrate elevation, and mangrove species composition. These data were collected for seven days in July 2016. Seawater levels were recorded over 24 hours using a Hobo Water Logger. These data were used to verify the tidal prediction data from DISHIDROS and to predict water levels. These data were also used as a reference for calculating substrate elevations in mangrove areas using an Autolevel device supported by a Global Positioning System (GPS) unit, watch, and scaling poles (Fig. 2).

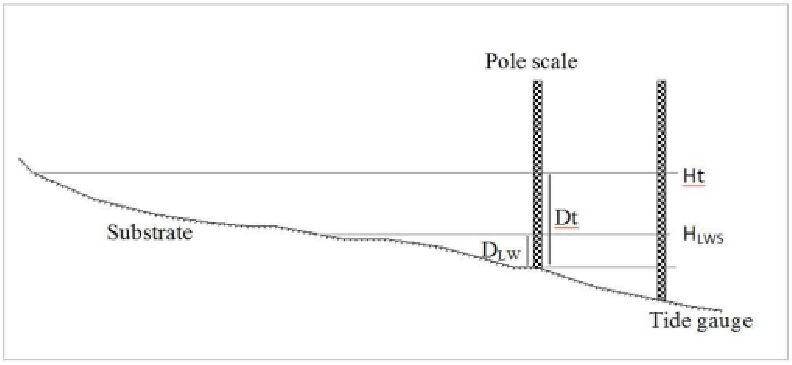

Fig. 2. Measurement of seawater depth relative to mean low water spring tide (LWS) level (adapted from Baharuddin, 2006 [33])

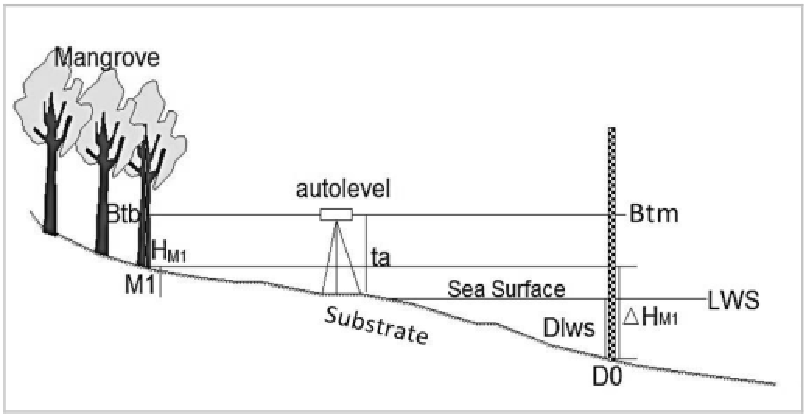

Fig. 3. Measurement of mangrove substrate elevation relative to mean low water spring tide seawater level (LWS) using a reference point (D0) and an Autolevel (adapted from Frick, 1984 [30]; USAID, 2005 [31])

Substrate elevation was measured using two approaches: measurement of the depth water from the surface to the substrate, and using substrate height difference or leveling [30, 31]. The first approach was conducted when mangrove areas were inundated, whereas the second approach was applied when mangroves were not flooded, or at low tide (Fig. 3). The first stage was to measure water depth at one point, flooded with in water connected to the sea, which was marked as a depth reference point. The measurements of substrate height differences were conducted on the outer (non-flooding) edge of the mangrove area with reference to this depth reference point. The substrate height differences were measured from the seaward edge to the landward boundary of the distribution of each selected mangrove species [31]. Substrate elevation measurements were validated using an Autolevel measuring device, by measuring the depth of the substrate with a scaling pole simultaneously at one mangrove sampling point while still inundated, while the depth was validated by the tidal data measurements. Thus, the depth and elevation data obtained could be related to the mean sea level (MSL). The mangrove species found at each elevation level were recorded and considered as representative of the species present at that elevation.

Data Analysis

Seawater levels were calculated using formulas 1-7 [32, 33]:

HAT (Highest Astronomical Tide) $= LAT + 2(AK_1+AO_1+AM_2+AS_2)$ (1)
MHHWS (Mean Highest High-Water Spring) $= LAT + 2(AK_1+AO_1) + AM_2+AS_2$ (2)
MHHWN (Mean Highest High-Water Neap) $= LAT + 2(AK_1) + AM_2+AS_2$ (3)
MSL (Mean Sea Level)/So = 90 cm (adapted from DISHIDROS) (4)
MLLWN (Mean Lowest Low Water neap) $= LAT + 2(AO_1) + AM_2+AS_2$ (5)

MLLWS (Mean Lowest Low Water Spring) $= LAT + AM_2 + AS_2$ (6)

LAT (Lowest Astronomical Tides) = $MSL - (AK_1 + AO_1 + AM_2 + AS_2)$ (7)

where:

AK_1 : amplitude of lunar diurnal component (K_1);
AO_1 : amplitude of lunar declinational diurnal component (O_1);
AM_2 : amplitude of principal lunar semidiurnal component (M_2);
AS_2 : amplitude of principal solar semi-diurnal component (S_2).

The water depth at the depth reference point was calculated using formula 8 [33]:

$$D_{LWS} = D_t - (H_t - H_{LWS}) \tag{8}$$

where:

D_{LWS} : water depth at low tide (cm);
Dt : water depth at time t (cm);
Ht : water height at time t (cm) on the tide gauge;
H_{LWS} : water height at low water on the tide gauge (cm) (Fig. 2).

Calculation of tidal inundation patterns was based on the length of time between tide that passed through five water level categories (MHHWS, MHHWN, MSL, MLLWN, and MLLWS) and recede per day. The result indicates the mean daily duration of inundation within each group.

Mangrove substrate elevations were calculated using formulas 9-11 [30]:

$$H_{D0} = D_{Lws} \tag{9}$$

$$\Delta H_{M1} = Btm - Btb \tag{10}$$

$$H_{M1} = H_{D0} + \Delta H_{M1} \tag{11}$$

where:

H_{D0} : height of D0 (cm);
D_{LWS} : water depth at low tide (cm);
ΔH_{M1} : difference in elevation between substrate at point M1 and substrate at point D0;
H_{M1} : height of substrate M1;
Btm : horizontal plane for D0;
Btb : horizontal plane for M1;
ta : height of the Autolevel (cm) (Fig. 3).

Results and discussion

Composition and distribution of mangrove species

A total of 98 mangrove trees were identified. Eleven mangrove species were recorded: *Rhizophora stylosa, Rhizophora apiculata, Rhizophora mucronata*, *Bruguiera gymnorrhiza*, *Ceriops tagal*, *Sonneratia alba*, *Sonneratia caoselaris*, *Avicennia marina*, *Lumnitzera racemosa*, *Scyphiphora hydrophyllacea*, and *Excoecaria agallocha*. Nine species were found along the west coast, seven along the east coast, and five each along the north and south coasts (Table 1). *Rhizophora stylosa* was the most dominant species, followed by *Rhizophora apiculata* and *Sonneratia alba* (Table 1).

Tidal characteristics: seawater levels and inundation patterns

Tidal characteristics contribute to the duration of seawater inundation and thus affect the mangrove species distribution at each elevation in the tidal zone [17]. The tidal analysis showed that the diurnal tide component harmonic constants (K1 and O1) had a greater influence than the semidiurnal tide components (S2 and M2) (Table 2).

The Formzhal number [34] of 1.733 indicates that the prevailing tidal regime at the study site is mixed diurnal (on some days the tidal cycle occurs only once, while on most days there are two tidal cycles, often with significantly different amplitudes). The seawater level varied between 0 and 164cm relative to LAT, and between -82 and 82cm relative to MSL. The maximum tidal range was 164cm, with a mean neap tidal range of 24cm and a mean spring tidal range of 104cm (Table 3).

Table 1. Mangrove area extent, density, and species

Site	Mangrove area (Ha)	Mangrove belt width (m)	Mangrove species											Number of species
			Rs	***Ra***	***Rm***	***Bg***	***Ct***	***Sa***	***Sc***	***Am***	***Lr***	***Sch***	***Ea***	
North	1.732	27 - 80	+	+	-	-	-	+	-	-	+	+	-	5
East	1.285	10 - 14	+	+	+	-	-	+	-	-	+	+	+	7
South	3.862	18 - 91	+	+	-	+	-	+	+	-	-	-	-	5
West	10.33	23 - 160	+	+	-	+	+	+	+	+	+	-	+	9
Sub-total			28	22	2	9	2	18	4	2	6	2	3	
Total	17.209							98						

+ Present, - not present

Rs (Rhizophora stylosa), Ra (Rhizophora apiculata), Rm (Rhizophora mucronata), Bg (Bruguiera gymnorrhiza), Ct (Ceriops tagal), Sa (Sonneratia alba), Sc (Sonneratia caoselaris), Am (Avicennia marina), Lr (Lumnitzera racemosa), Sch (Scyphiphora hydrophyllacea), and *Ea (Excoecaria agallocha).*

Table 2. Tidal harmonic constants for Sagara Island and the surrounding area

	So	**M2**	**S2**	**N2**	**K1**	**O1**	**M4**	**MS4**	**K2**	**P1**
A cm	90	13	17	5	32	20	0	1	5	10
g°		108	216	226	295	265	0	328	216	295

Table 3. Seawater levels around Sagara Island and nearby

Water level types	High water level above LAT (cm)	High water level relative to MSL (cm)	Average tidal range Neap tides (cm)	Average tidal range Spring tides (cm)	Maximum tidal range (cm)
HAT	164	82			164
MHHWS	134	52		104	
MHHWN	94	12	24		
MSL	82	0			
MLLWN	70	-12			
MLLWS	30	-52			
LAT	0	-82			

HAT: Highest Astronomical Tide; MHHWS: Mean Higher High Water Springs; MHHWN: Mean Higher High Water Neaps; MSL: Mean Sea Level; MLLWN: Mean Lower Low Water Neaps; MLLWS: Mean Lower Low Water Springs; LAT: Lowest Astronomical Tide.

Based on the mixed tidal regime, seawater inundation frequency varied between once and twice a day. The longest inundation duration (21-24 hours) occurred at the Mean Lower Low Water Springs (MLLWS) level, with a mangrove substrate elevation of -50cm relative to MSL (Fig. 4). The distribution of each mangrove species differed with respect to seawater inundation. *Rhizophora* spp. and *Sonneratia* sp. had the highest tolerance to the seawater inundation (between 0 and 24 hours) [35], followed by *Bruguiera gymnorrhiza* and *Lumnitzera racemosa* (between 0 and 21 hours) (Fig. 4).

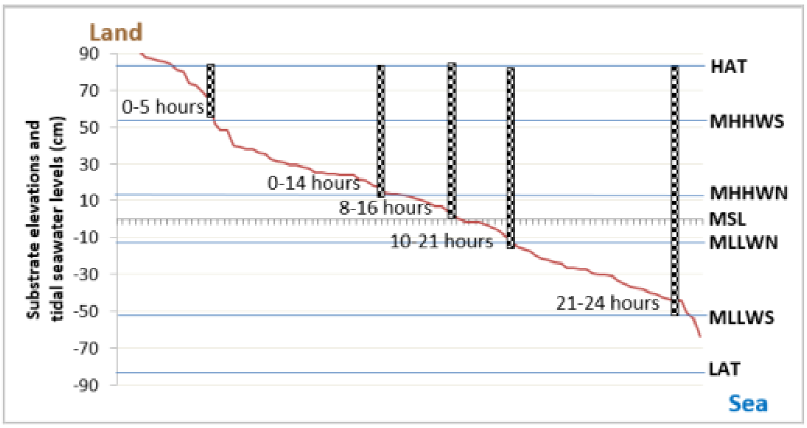

Fig. 4. Duration of daily inundation at different tidal seawater levels and mangrove substrate elevations

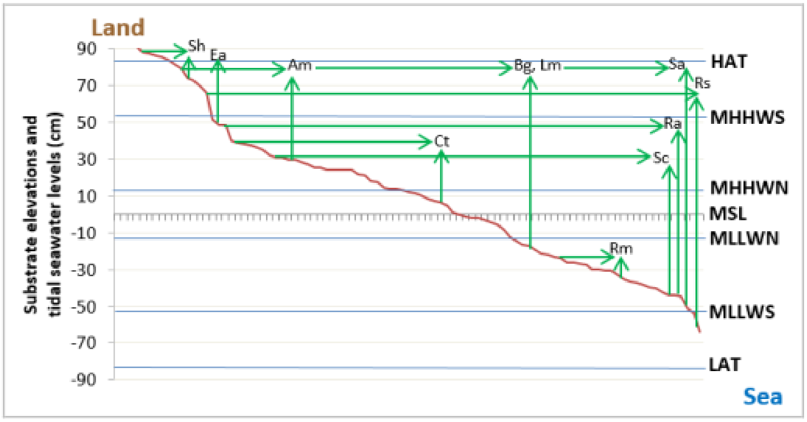

Fig. 5. Mangrove species distribution is relative to substrate elevation and water level. Vertical and horizontal arrows indicate the range of each species. *Rs (Rhizophora stylosa), Ra (Rhizophora apiculata), Rm (Rhizophora mucronata), Bg (Bruguiera gymnorrhiza), Ct (Ceriops tagal), Sa (Sonneratia alba), Sc (Sonneratia caseolaris), Am (Avicennia marina), Lr (Lumnitzera racemosa), Sch (Scyphiphora hydrophyllacea)* and *Ea (Excoecaria agallocha)*

Mangrove substrate elevation

Substrate elevation ranges of the various mangrove species in relation to seawater levels are shown in figure 5. The greatest expanse of the dry substrate was exposed at the lowest astronomical low tide (LAT), with flood tides rising slowly to the highest level (HAT). The width of the intertidal area and the swiftness of the water flows depend on substrate elevation [36]. Thus, substrate elevations above the HAT (> 90 cm) were no longer regularly flooded with seawater due to tidal cycles. In the study area, the majority of the mangrove species were growing in the zone between the MLLWS and MHHWS. This is different from the coast of Sumatra, where most mangroves species still grow above the average water level [10]. *Rhizophora stylosa* was the most abundant species in this area, followed by *Rhizophora apiculata* and *Sonneratia alba* (Fig. 4, Table 1). Although the majority of specimens of these species were found between the MLLWS and MHHWS (between -50 and 50cm relative to MSL), two *Rhizophora stylosa* trees were found below the MLLWS and one above the MHHWS. Other mangrove species found between these substrate elevations included *Rhizophora apiculata*, *Rhizophora mucronata*, *Sonneratia alba,* and *Sonneratia caoselaris*. The root systems of these species enable them to be highly tolerant of seawater salinity, and the suitable substrate type (sandy mud) was also most likely a factor promoting their survival in this elevation range [37].

The two mangrove genera *Sonneratia* and *Rhizophora* were frequently found growing adjacent to one another on the sandy mud intertidal substrates. The cone roots of *Sonneratia* sp. rise from the dense flat root system spreading horizontally away from the trunk; they can trap the propagules of *Rhizophora* spp. which are swept away or fall from the mature trees and become stuck in gaps between *Sonneratia* sp. roots, and thus these species can survive and grow together. However, two trees, one *Sonneratia alba* and one *Avicennia marina*, were found growing at the HAT and surviving on sandy substrate. Substrate distribution at this elevation is associated with sediment transport mechanisms [38]. Sandy substrates carried by the longshore currents are deposited when they meet a barrier. The root systems characteristic of *Sonneratia Alba* with their horizontal distribution can bind this sediment type [39 - 41].

At higher substrate elevations (near the MLLWN), the mangrove species found were *Bruguiera gymnorrhiza* and *Lumnitzera racemosa*. *Bruguiera gymnorrhiza* was commonly found in the mid intertidal zone, in the middle of the mangrove ecosystem range, but its range also tended to extend to the boundary with dry land or the highest limit of the intertidal zone [2, 42, 43]. This species has lower knee roots with typical pneumatophores [37]. According to [44], the knee root is a modification of cable roots. The horizontal roots, which mostly grow just below the soil surface, periodically grow vertically upwards then immediately loop downwards to resemble a bent knee. In the meanwhile, in *Lumnitzera racemosa* pneumatophores are normally absent [37], demonstrating that this species tends to tolerate restricted periodic seawater inundation. This species is often found in the upper tidal zone from mid to high intertidal zone [45], but has also been recorded along the sandy beaches [46].

In addition, four mangrove species were found growing above the MSL, including *Ceriops tagal, Avicennia Marina*, *Excoecaria agallocha* and *Scyphiphora hidropyllacea*. The distributions of these species are controlled by substrate elevation relative to the MSL [46]. However, the number of individuals of each of these species was low (around 2 - 3 individuals). The presence of *Ceriops tagal* and *Avicennia Marina* at this elevation is related to the relatively low tidal range, short period of inundation and sandy mud sediment, all of which are characteristics suitable for the growth of these species. According to [47], the genus *Ceriops* is often found in monospecies stands on well-drained sites, in mangrove areas that are only reached by tides occasionally. *Avicennia marina* tends to be prominent in low and high intertidal forests, but is rarely abundant [42]. In open estuaries, such as those found around the mainland of South-eastern Australia, they are generally distributed between the MSL and MHHWN [48, 49]. Although *Excoecaria agallocha* and *Scyphiphora hidropyllacea* were also recorded above the MSL, these species mainly inhabit the zone from the MHHWS landward, even extending above the HAT. The root systems of these species allow for inundations of short duration, which is a major factor supporting their growth and survival in this elevation range [37].

Conclusions

The assessment of seawater level, inundation regime, and mangrove substrate elevation at the study site clearly delineated the planting zones appropriate for various mangrove species. The most appropriate elevation ranges for *Rhizophora stylosa, Rhizophora mucronata, Rhizophora apiculata*, *Sonneratia Alba*, and *Sonneratia caoselaris* is between the MLLWS and

MHHWS; however, these species, especially *Rhizophora stylosa*, can also grow below the MLLWS. Although *Bruguiera gymnorrhiza, Lumnitzera racemosa, Ceriops tagal,* and *Avicennia marina* can be found between the MLLWS and MHHWS, elevations close to the MLLWN are suggested as more suitable for *Bruguiera gymnorrhiza* and *Lumnitzera racemosa*. *Ceriops tagal* does best between MSL and MHHWS, whereas *Avicennia marina* prefers elevations between MHHWN and MHHWS. While it is suggested that both *Scyhiphora hydrophyllacea* and *Excoecaria agallocha* should ideally be planted between the MHHWS and HAT, *Scyhiphora hydrophyllacea* could also be planted above the HAT.

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