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ESTIMATING THE RESPONSE OF MANGROVE ECOSYSTEMS IN HIGHLY PROTECTED BAY ENVIRONMENTS IN URBAN AREAS TO SEA LEVEL RISE: CASE FROM INNER AMBON BAY, AMBON ISLAND, INDONESIA

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Abstract

Inner Ambon Bay (IAB) is a small bay with an elongated shape, with a maximum length of about 5.1km and a maximum width of about 2.6km, and is located within the administrative area of Ambon City, the capital of Maluku Province. The waters of the bay are highly protected. There is a fairly extensive mangrove ecosystem on the northeast side of this bay which is used for various purposes, including educational and research activities. The increase in the population of Ambon City has caused residential areas to develop by expanding the mangrove area from the land side. Meanwhile, it is estimated that by 2100, the sea level will rise to a height of around 1.1m above the current sea level. Because of its benefits and to maintain the natural conditions of IAB, the existence of mangroves in the bay needs to be maintained. It is essential to examine the future of the mangrove ecosystem concerning sea level rise (SLR) to determine effective methods for preserving its presence in the bay. This study examines the possibilities in the mangrove ecosystem if the sea level rises to 1.1m above the present sea level. The results of this study show that the opportunity for mangroves in IAB to adapt to SLR is through recruitment in the population by mangrove species that are tolerant of SLR (Rhizophora). The opportunity can be increased by preventing residential areas from expanding into mangrove areas and by building permeable dams to encourage mud deposition and artificial shelter for propagule to help natural colonization.

***Keywords**: Mangrove; SLR; Coastal developed environment; Semi-enclosed sea; Ambon Bay*

Introduction

Mangroves are vegetation in tidal zones in the tropics to subtropics whose habitat is limited to low-energy coastal waters, associated with tidal zones with gentle slopes, sedimentation areas, and relatively stable sea levels [1]. The presence of mangroves in coastal areas provides various ecosystem services that contribute to human welfare, such as (i) supporting traditional fisheries and becoming a collecting ground (such as fish, crabs, wood and various other natural resources), (ii) a source of nutrients for the surrounding ecosystem such as seagrass and coral reef, (iii) breeding, feeding and nursery ground for fish and various types of land and marine biota, (iv) being a filter for anthropogenic pollutants from surface water flows from the coastal land, (v) as a sediment trap that can protect water quality and reduce sediment loads for nearby ecosystems such as seagrass and coral reefs and promote sedimentation, (vi) as a natural coastal defense that stabilizes coast, reduces wind and waves and protects the coast from extreme weather, (vii) supports tourism activities in coastal areas, (viii) support sustainable livelihoods for residents around them [2, 3].

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While the mangrove ecosystem offers numerous benefits to human life, various human activities, along with natural factors, can lead to its degradation. In general, various human activities that can cause damage to the mangrove ecosystem are (i) development activities in coastal areas (such as building roads, bridges, residential areas, tourist areas and others), (ii) agricultural and aquaculture activities, (iii) pollution, (iv) extractive activities in mangrove areas (cutting of mangroves for firewood and building materials, harvesting of mangrove fauna and other forest products), (v) construction activities on land that cause changes in hydrological conditions, (vi) sea-level rise as a result of the impact of climate change due to human activities [2].

SLR has an immediate and direct impact on coastal ecosystems in the tidal zone, including affecting the mangrove ecosystem, due to the reduced influence of land origin processes and the increased influence of marine origin processes [3]. As coastal vegetation grows in tidal zones in the tropics and subtropics, mangroves must withstand high temperatures, high salinity, and hypoxic conditions. There are six impacts of SLR on low-elevation coasts, namely: (i) permanent inundation of coastal land, (ii) more frequent and more intensive flooding, (iii) increased coastal erosion, (iv) loss and change in coastal ecosystems, (v) increasing the salinity of the soil, groundwater and surface water, (vi) inhibiting drainage or river flow and (vii) changing the rate of sediment deposition [4, 5].

SLR is putting a lot of pressure on mangrove communities [6]. Each mangrove species has a specific tolerance range that allows mangroves to adapt to different ecosystem zones, especially concerning geomorphological and environmental conditions [5]. Some mangroves tend to grow on the seaside and others some mangroves tend to grow on the landside [6, 7]. Therefore, SLR can cause changes in position, area, species composition, and dominance of mangrove areas and the health of the mangrove community [5, 6], which allows expansion of the distribution of tolerant species and suppress less tolerant species, especially in places with low sedimentation rates [5, 7].

For mangroves that grow at low elevation coast, SLR can cause the following:

1) Mangroves can adapt to SLR if the rate of SLR is slow. There is a limit to the rate of SLR at which mangroves can survive. If the rate of SLR is higher than that limit, the mangroves will die [2, 3, 5, 8-10].
2) Mangrove species vary in their tolerance to seawater inundation; those that can withstand it are likely to survive SLR, while intolerant species are at risk of dying [5, 8, 10-12].
3) Mangroves that are tolerant of changes that occur due to SLR will be able to withstand the impact of SLR in a mangrove area by retreating towards the mainland [2, 3, 5, 8, 10-13]. There are mangrove species that can quickly form new colonies in newly formed habitats due to SLR and some take longer [10]. Whether or not mangroves can retreat to the mainland is determined by the presence or absence of obstacles behind the mangrove area or the availability of sufficient space for expansion [5, 10]. Naturally, obstacles can be present because of the morphological conditions of the coast. Human activities behind mangrove areas can be a barrier for mangroves to retreat [8, 10].
4) Erosion of mangrove coasts, known as mangrove die-back, occurs due to changes in sea level and the resulting alterations in water hydrodynamics caused by SLR [2, 6, 8, 10, 11]. If the rate of SLR exceeds sedimentation in the mangrove area, the substrate will erode, leading to mangrove die-back. Changes in hydrodynamic conditions that occur due to increased inundation can cause the mangrove substrate to erode and cause the mangrove root structure to weaken which causes the mangrove to fall. Changes in salinity and the frequency, duration, and depth of inundation cause intolerant mangroves to die [10]. Changes in hydrodynamic conditions in the mangrove area affect the transportation and deposition of mud in the mangrove area. If the mud in the mangrove area erodes, the mangrove will be damaged, while if the mud expands, the mangrove

will develop [14]. This situation shows that the sediment supply into the mangrove area is crucial for the survival of mangroves against SLR [6].

Ambon Bay is the largest bay on Ambon Island which is shaped like "V" which is elongated and oriented northeast and southwest. Based on coastline configuration, the bay is divided into IAB and Outer Ambon Bay (OAB). IAB is connected to the OAB by a narrow sill about 250m wide. The depth of the gap is about 12m [15,16]. OAB which has a length of about 22km and a mouth width of about 11km is directly connected to the Banda Sea (Fig. 1). With very isolated conditions as mentioned above, the waters of IAB are very protected and its hydrodynamic conditions are only influenced by tides and currents in the waters of this bay are tidal currents [17]. In IAB there are ecosystems of mangroves, seagrass, and coral reefs which are scattered throughout.

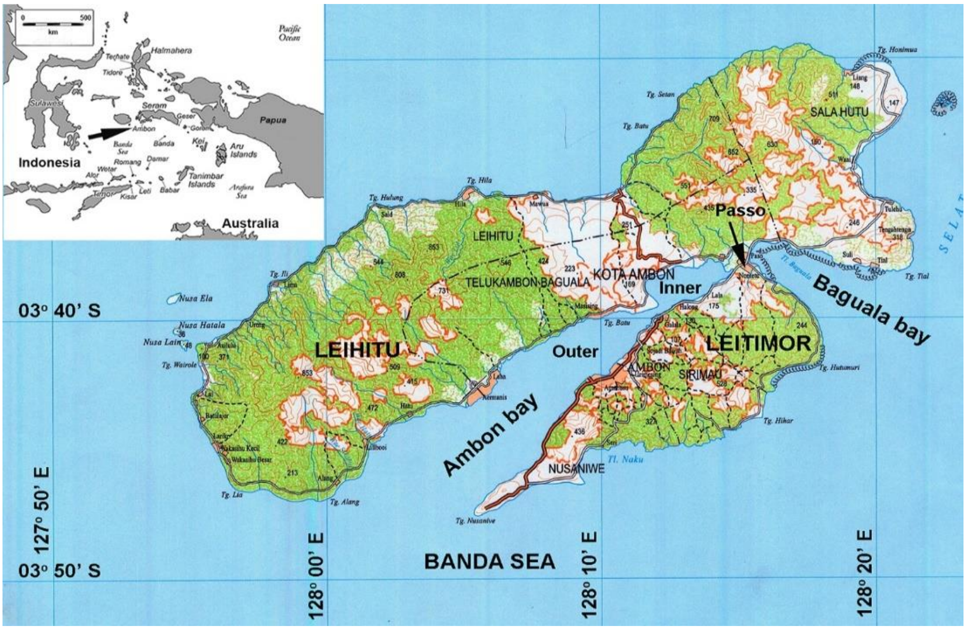

Fig. 1. Topographic Map of Ambon Island. Excerpted with modifications from the map of Peta Rupabumi Lembar Ambon from Bakosurtanal [16]. The administrative area of Ambon City covers all of Leitimor and part of Leihitu (Telukambonbaguala).

Mangroves in IAB have a relatively small area and fragmentary distribution. Administratively, the bay area is within Ambon City's administrative area, the capital of Maluku Province (Fig. 1). The city's population growth has led to the expansion of residential areas into mangrove regions, resulting in a decline in the quality of the mangrove ecosystem [18]. Mangroves in IAB are used by various parties in Ambon City, such as Pattimura University which uses it for education, and BRIN (National Research and Innovation Agency) which was previously named LIPI (Indonesian Institute of Sciences) which uses it for scientific research activities. Waiheru Village has utilized the mangrove area as a tourism area. The bay waters are also supporting fisheries and transportation activities [15]. In a highly protected system with various kinds of human activities in it, such as in the IAB, the pressure on the mangrove ecosystem is increasingly high. The Intergovernmental Panel on Climate Change (IPCC) is an authoritative source of information about future sea levels [19]. The IPCC's estimate of SLR with medium confidence illustrates of the worst scenario where SLR can reach a height of about 1.1m above the 2000 sea level and this situation will occur in 2100 [4]. Although there is still uncertainty about the future SLR and its associated impacts on a coastal area, we can provide initial predictions of the effects of SLR on that coastal area [20].

If the SLR scenario from IPCC occurs in IAB, the pressure experienced by mangroves in the bay will come from two directions. Because of its benefits and to maintain the natural conditions of IAB, the existence of mangroves in IAB needs to be preserved, therefore it is necessary to study the potential impact of SLR on IAB coastal areas in the future, especially on the mangrove ecosystem, so that appropriate methods can be determined to maintain the presence of the mangrove ecosystem in the bay. This paper provides an overview of the current condition of the mangrove ecosystem in IAB and predicts of what will happen to the ecosystem if the sea level rises as high as 1.1m in 2100. This is an example of the impact of SLR on mangrove ecosystems which are in a very closed environment and surrounded by built-up coastal land.

Materials and Methods

Satellite imagery from Google Earth dated 20 October 2018 and 28 October 2022, was analyzed visually on computer monitors in this study to obtain data on the distribution of mangrove areas and built-up areas in the coastal zone of IAB. Data on mangrove species in IAB (from Waiheru and Passo) and its Importance Value Index (IVI) were obtained from Suyadi [21]. Data on mangrove species in Passo was also obtained from Wakano and Ukaratalo [22]. The IVI value of a species indicates the ecological importance of that species in a community [23]. This value is obtained by adding the percentage values of relative frequency, relative density, and relative dominance [21, 23-26]. Furthermore, this value measures how dominant a species is in an ecosystem [25] and the level of adaptation of a species to high pressure from various disturbances, natural and environmental factors, and local community effects [27].

Tidal-type data was obtained from *G.G. Salamena et al*. [28], *S. Nurfitri and M.R. Putri* [29], *J.A.E. van Oostenbrugge* [30], and tidal current data from *H.G. Saiya et al* [15], *M.S. Hamzah and L.F. Wenno* [17]. A topographic map of Ambon Island from Bakosurtanal [16] was used to analyze the morphology of Ambon Island. Bathymetry data of IAB was obtained from *G.A. Rahmawan et al* [31].

The data was then combined with coastal geomorphological data and human activities in the coastal lowland obtained from field observations in March 2022 in the coastal area of IAB, especially in the mangrove ecosystem at Waiheru and Passo (Fig. 2).

Fig. 2. IAB, surrounded by developed land mainly a residential area.
Note: m – mangrove. Image from Google Earth, dated Oct. 28, 2018. Image axis: 3°38’48.88” S; 128°13’21.27” E

Analysis of the impact of SLR on mangrove areas is carried out qualitatively using the following analytical approaches: (i) the possibility of changes in hydrodynamic conditions. Changes in hydrodynamic conditions are important in studying changes in ecological habitat conditions in coastal environments due to SLR [32]; (ii) the possibility of mangrove responses to the rate of SLR, (iii) the possibility of mangrove species surviving against SLR and (iv) the possibility of mangroves ecosystem retreat towards the land.

Results

Coastal geomorphology of IAB

The waters of Ambon Bay are flanked by two high relief hills that extend and are oriented northeast-southwest and both hills are predominantly composed of Pre-Tertiary volcanic rocks and have elevations of more than 1000m (Leihitu) and more than 600m (Leitimor) (Fig. 1). These hills have a dominant slope of more than 45 degrees [15]. To the northeast of IAB, there is the Passo lowland which is composed of alluvial deposits. The lowlands separate the IAB and the Bay of Baguala which are oriented northwest-southeast. To the southwest of IAB, there is the Poka-Rumahtiga Plain which is also composed of alluvial deposits. The plain separates the IAB and the OAB. On the north side, there is the Waiheru lowland (Fig. 2).

Satellite imagery recorded on 28 October 2018 (Fig. 2) shows that the IAB has a relatively narrow tidal zone with a width ranging from around 30 to 250m. The deeper parts of the IAB are elongated in the waters close to Leitimor and the deepest parts are near the sill that connects this bay to the OAB (Fig. 3) [31].

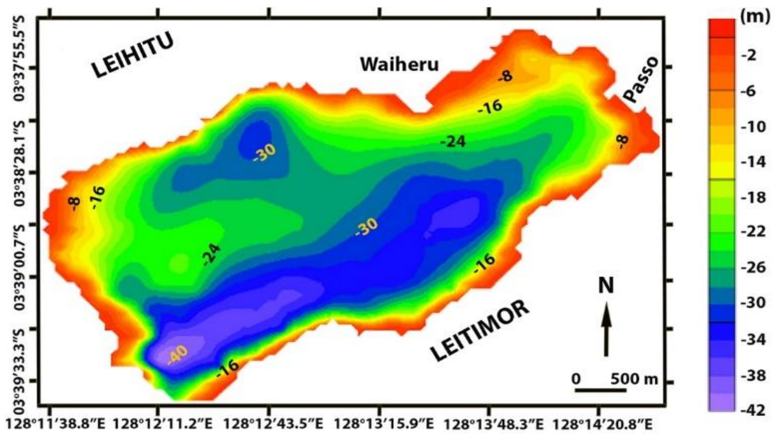

Fig. 3. Bathymetry of IAB. Source: *G.A. Rahmawan et al* [31] with modification

The rivers that flow into the waters of IAB mainly come from Leihitu. The Waitonahitu and Waiheru watershed systems are the two watershed systems (Fig. 4) that have the largest watersheds [15] and form coastal lowlands, where the coast is overgrown with mangroves. Based on the physical appearance seen in satellite images (Fig. 2) and the genesis of its formation from deposition by river flows in the river mouth area, it is concluded that the two lowlands are small deltas with a relatively low supply of sediment loads from river flows.

Human activities in the IAB coastal land

As previously stated, the IAB area is administratively entirely within the Ambon City area, which is the capital of Maluku Province. Most of the coastal land around the waters of this bay is a built-up area, most of which are residential areas. Additionally, there are offices, military facilities, and educational areas located around the bay. In the Passo and Waiheru areas, residential areas have been developed by expanding into mangrove areas (Figs. 2 and 5), and at the edge of the residential complex adjacent to the mangrove area, a seawall was built to protect the area from seawater at high tide (Fig. 6).

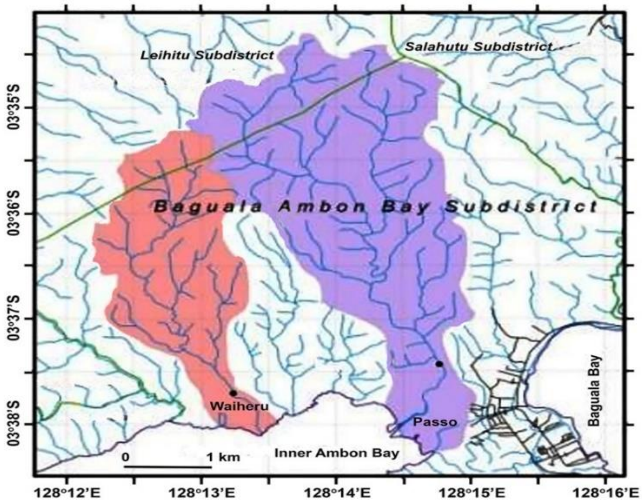

Fig. 4. The drainage system of Waitonahitu (purple) and Waiheru (red).
Source: *H.G. Saiya et al* [15] with modification

a. 

b. 

Fig. 5. Mangrove distribution at Waiheru and Passo which is directly adjacent to developed land is mainly a residential area: a. Image axis: 3°37'56.39" S; 128°13'23.98" E; b. Image axis: 3°38'04.61" S; 128°14'34.32" E.
Note: m – mangrove. Image from Google Earth, dated 28 Oct. 2022

Fig. 6. Residential area with seawall as coastal defense structure at the back of the mangrove area at Passo (above) and Waiheru area (below). The tip of arrow A points to the sea level position at the high tide. Photo: March 2022

In 2012, the Ambon City Government issued an Ambon City Regulation concerning the 2011-2031 Ambon City Spatial Planning which contains provisions regarding the protection of the mangrove coast. This regulation determines the mangrove areas in Waiheru and Passo in the following categories: (i) scientific protected areas aimed at educational purposes, research, and preserving the diversity of endemic species, (ii) natural tourism areas and (iii) coastal protected areas as mangrove coast [33]. This regulation shows that the Ambon City Government prohibits the conversion of mangrove areas for other uses. The regulation also means that in the future there will be no development activities that will change the mangrove area into a built-up area.

Mangroves in the IAB

The relatively wide mangrove ecosystem in IAB is found in the Passo and Waiheru areas. Both are present in the small delta region of the Waiheru River (in Waiheru) and the Waitonahitu River (in Passo). Based on the pattern of their presence in the river delta area, the two mangrove ecosystems fall into the category of deltaic type [34] or river-dominated mangrove [35] (Figs. 2 and 4).

The types of mangroves found in Waiheru and Passo are presented in Table 1. In Passo, the distribution of mangroves forms zonation (Fig. 7).

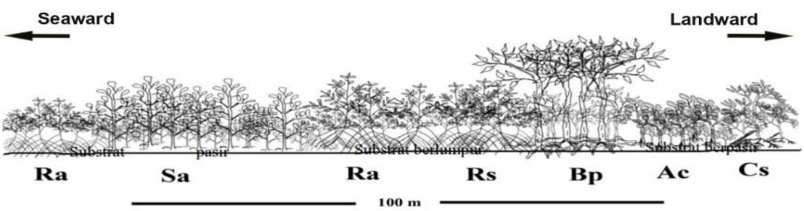

Fig. 7. Mangrove zonation at Passo, IAB. Ra: *Rhizophora apiculata*, Sa: *Sonneratia alba*, Rs: *Rhizophora stylosa*, Bp: *Bruguiera parviflora*, Ac: *Aegiceras corniculatum*, Cs: *Campostemon schultzii*. Glossary: Substrat pasir: *sand substrate*; Substrat berpasir: *sandy substrate*; Substrat berlumpur: *muddy substrate*. Source: *D. Wakano and A.M. Ukaratalo* [22] with modification.

Table 1. Mangrove species at Waiheru dan Passo delta

Waiheru	Passo	
Data from *Suyadi* [21]	Data from *Suyadi* [21]	Data from *D. Wakano and A.M. Ukaratalo* [22]
Trees • *Rhizophora apiculata* • *Sonneratia alba* • *Avicennia officinalis* • *Bruguiera cylindrica* Sapling • *Avicennia officinalis* • *Rhizophora apiculata* • *Osbornia octodonta* • *Ceriops tagal* Seedling • *Osbornia octodonta*	Trees • *Sonneratia alba* • *Rhizophora apiculata* • *Bruguiera cylindrica* Sapling • *Rhizophora apiculata* • *Bruguiera cylindrica* • *Aegiceras cornoculatum* Seedling • *Rhizophora apiculata*	Trees • *Sonneratia alba* • *Rhizophora apiculata* • *Bruguiera parviflora* • *Bruguiera cylindrica* Sapling • *Rhizophora apiculata* • *Sonneratia alba* • *Bruguiera parviflora* • *Aegiceras cornoculatum* • *Camptostemon schultzii* • *Osbornia octodonta* • *Bruguiera cylindrica* • *Hertiera littoralis* • *Excoecaria agallocha* Seedling • *Rhizophora apiculata* • *Bruguiera parviflora* • *Sonneratia alba* • *Aegiceras cornoculatum* • *Acrosticum aureum* • *Bruguiera cylindrica*

The Importance Value Index (IVI) indicates the ecological significance of species in the community, as shown in Table 2.

Table 2. The Important Value Index (IVI) of mangrove species at Waiheru and Passo

Species	Waiheru	Passo
Tree		
Bruguiera cylindrica	37.2	14.7
Rhizophora apiculata	110.3	139.2
Sonneratia alba	81.6	146.2
Avicennia officinalis	70.9	-
Sapling		
Bruguiera cylindrica	-	83.1
Ceriops tagal	14.2	-
Osbornia octodonta	44.0	-
Rhizophora apiculata	141.0	193.3
Aegiceras corniculatum	-	23.2
Avicennia officinalis	100.8	-
Seedling		
Osbornia octodonta	200.0	-
Rhizophora apiculata	-	200.0

Data from *Suyadi* [21]

The mangrove area in Passo has a tree density of 580trees/ha and a basal area of 3.74m^2/ha, a sapling density of 800 individuals/ha, and a basal area of 0.13m^2/ha; in the Waiheru area, the tree density is 420trees/ha and the basal area is 0.97m^2/ha, the sapling density 2240individu/ha and the basal area 0.10m^2/ha [21]. Based on the IVI value, the dominant mangrove type in Passo is Sonneratia alba (IVI: 146.2%), the codominant type is Rhizophora apiculata (IVI: 139.2%); in Waiheru the dominant mangrove type is Rhizophora apiculata (IVI: 110.3%) and the codominant was Sonneratia alba (IVI: 81.6%) (Table 2). Table 2 shows that the number of seedling species is the lowest, which indicates that good regeneration is not occurring in mangrove areas [36].

The mangrove ecosystem in these areas is threatened by residential development encroaching on their habitat. In some locations, a seawall was constructed to protect the residential area (Fig. 6).

Hydrodynamic condition of IAB

Ambon Island and the surrounding area are influenced by the monsoon which greatly influences local environmental conditions. From June to August, the Southeast Monsoon occurs, the wind blows to the northwest with a maximum daily average speed of 20-38km/h (4-5 Bf), bringing cool and humid air from the Banda Sea to Ambon Island and causing a large amount of rain and the air temperature is relatively low. From December to February the Northwest Monsoon occurs, the wind blows to the southeast with a maximum daily average speed of 12-28km/h (3-4 Bf). In this period the air temperature is high and rainfall is low. In the inter-monsoon period, wind speed is low and direction varies [30].

Tidal cycles in Ambon Bay are mixed semidiurnal [28-30] with a maximum spring tide range of 2.5m [30].

The IAB waters are almost surrounded by high hills (Fig. 1) and only have a narrow gap connecting them to the OAB directly connected to the Banda Sea waters. With the environmental conditions of the IAB being so closed, the waters of the bay are not influenced by waves or currents moving in the waters of the Banda Sea because waves and currents coming from the Banda Sea must cross the OAB and experience attenuation before they can reach the IAB. Apart from that, IAB waters are also not influenced by wind blowing from the Banda Sea because they are protected by hills so waves formed by wind cannot develop in IAB waters. Thus, only tides influence the condition of the IAB waters [17].

Tides drive surface currents in Ambon Bay [15, 17] and generate tidal upwelling at the sill of Ambon Bay [28, 37]. When the tide moves up, the surface current from the OAB moves into the IAB and conversely when the tide moves down, the surface current in the IAB moves out into the OAB [15, 17]. The average speed of the flood tides current flowing in from the OAB to the IAB when the tides are moving up is 84 cm/s, the average speed of the ebb tides current flowing out of the IAB to the OAB when the sea water is moving down is 34.7cm/s [15] and this data shows that the IAB is a bay with flood dominant tidal currents [32] which means that the sediment load from the OAB tends to move into the IAB. In expansive coastal wetland regions, dominant flood tide currents tend to move sediment loads toward land [32] and it is very possible that this condition also occurs in mangrove areas in IAB which is only a few hundred meters wide, especially during the rainy season. In the IAB, when the tide rises, surface currents rotate in a clockwise direction (Fig. 8); when the sea recedes, surface currents all move towards the sill and then move out to the OAB (Fig. 9).

Fig. 8. Tidal current in IAB during tide rises. Drawing based on data from *H.G. Saiya et al* [15]

When the tide rises, tidal upwelling occurs in the OAB and causes seawater from the OAB from the depth below the sill depth to enter the IAB by crossing the sill [36], but tidal upwelling is more frequent and more significant occurring in spring tide during the Southeast Monsoon and transitional monsoonal season [28].

Only during the Southeast Monsoon when rainfall is high, large amounts of sediment load enter the IAB waters and cause the seawater to turn light brownish. The suspension deposition rate in AIB is approximately 1.7cm/year [15]. Significant mud deposition does not occur in the mangrove area which is a tidal zone (Fig. 6) and there are no mudflats in front of the mangrove area. This indicates low sediment input from land because the large sediment input to coastal waters can be seen from the presence or absence of mud flats in the area [38, 39].

Fig. 9. Tidal current in IAB during tide move down. Drawing based on data from *H.G. Saiya et al* [15]

Discussion

Effects of SLR on hydrodynamic conditions in mangrove area

The mangrove environment is a sedimentological system. The ability of mangroves to tolerate SLR depends on the sediment dynamics that occur when sea levels increase. Generally, the sediment on the surface of the mangrove substrate is in balance with the current average sea level [13]. SLR means changing the balance in the mangrove area.

SLR means increasing the depth of the water column and changing the hydrodynamic conditions of the waters in the mangrove area and tidal inlet. In a mangrove coastal environment open to wave activity, SLR increases wave energy and currents in the mangrove area. In IAB which is very sheltered only tides are dominant and no waves are formed in the waters of the bay, SLR does not cause an increase in wave energy so there is no erosion of the mangrove coast due to increased wave energy. In Ambon Bay, the narrow gap or sill connecting the IAB and OAB functions as a tidal channel. Rising sea levels cause the gap to deepen and the surface to expand. Under these conditions, the average speed of tidal currents crossing it increases [40]. In a study in Jakarta Bay, it was stated that in the SLR scenarios of 0.25 and 0.50m, SLR does not change the pattern of tidal currents, but increases the speed of tidal currents near the coast with a tendency that the higher the SLR, the greater the increase in current speed [41]. Considering the morphological conditions of the IAB coast, this situation is projected to apply to the IAB in a SLR scenario of up to 1.1 meters. An increase in tidal current speed due to SLR was also mentioned by Passeri [32] based on the results of his study conducted in The Great Bay Estuary, Northern Gulf of Mexico.

The impact of SLR on mangrove areas at IAB can also be analyzed based on the condition of the rear of the mangrove area which borders the residential area (Fig. 6). In this study, data on the elevation of the coastal plain (residential area) from direct measurement have not been obtain, so the land elevation to sea level has not yet been known measurably. However, the results of field observation and photograph analysis of the coast (Fig. 6) provide a relative picture that if there is an SLR of 1.1m from the current sea level in 2100, the coastal plain at the rear of the mangrove area will be inundated by seawater and become a tidal zone (Fig. 10). The illustration shows that under current conditions, mangroves grow in tidal and subtidal zones. By the year 2100, mangroves will only be found growing in the subtidal zone.

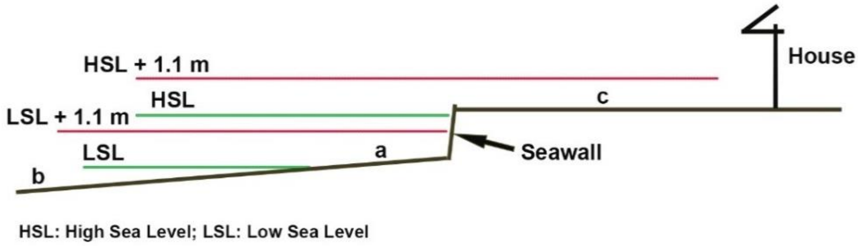

Fig. 10. An illustration of changes in coastal environmental conditions due to sea level rise in Passo and Waiheru. HSL and LSL: current sea level; HSL + 1.1m and LSL + 1.1m: sea level in 2100. Present: a - tidal zone; b - subtidal zone; c - coastal plain (residential area). In 2100: a & b - subtidal zone, c - tidal zone. Under current conditions, mangroves grow in tidal and subtidal zones. In 2100, mangroves will only grow in the subtidal zone.

In IAB, mangroves dominantly grow in the tidal zone. Therefore, the SLR in the bay also affects the height of the water column in the mangrove area. If the SLR cannot be offset by mud deposition in the mangrove area, then inundation occurs. Inundation of mangrove areas in IAB is very likely to occur. The possibility of inundation due to a lack of sediment supply from land is highly possible in the IAB area because the watershed from Waiheru that flows to the coast of Waiheru and Waitonahitu that flows to the coast of Passo is relatively small. After all, Ambon Island is a small island. In such conditions, mangrove species that are tolerant of seawater inundation will be able to withstand SLR. In IAB, the possibility of a mangrove retreat is blocked by a residential area behind the mangrove area.

Mangrove adaptation to SLR

Environmental factors that will naturally affect the response of mangroves to SLR are coastal geomorphological conditions. If mangroves grow on the coast with a low-elevation coastal plain as a background, SLR will inundate the lowlands. The flooded coastal lowland become new habitat for mangrove and allows the mangroves to retreat toward the mainland [8, 10, 13]. Based on geomorphological conditions, the coastal areas in the Waiheru and Passo areas in IAB are coastal lowlands that allow mangroves to retreat or expand towards the mainland if there is a SLR, in actual conditions now, mangroves can't retreat towards the mainland because behind it has developed a residential area (Fig. 2).

SLR affects the distribution of mangrove species in a mangrove area. This is determined by the tolerance of mangrove species to the rate of SLR. Sonneratia and Avicennia cannot survive the high rate of SLR because the pneumatophore cannot keep up with the high rate of SLR. Meanwhile, Rhizophora can survive because its stilt or aerial root can be above sea level [5]. Rhizophora species such as *Rhizophora apiculata* are known as "front mangroves" or mangroves that grow in the proximal zome or frontmost zone which experiences regular sea tides and is continuously submerged [42]. A root system with aerial roots allows this type of mangrove to grow in tidal zones and its roots can remain continuously below the water surface except when the sea recedes very low [5, 43].

In an environment that does not receive sediment input from outside, such as in a coral-reef island environment, mangrove ecosystems can survive at an SLR rate of 8-9cm/100 years and experience stress at an SLR rate of 9-12cm/year [3]. The worst-case scenario predicts a global SLR of about 1.1m by 2100, compared to present levels [4]. That means the average rate of SLR is around 11mm/year. If the condition of the SLR rate occurs in the environment of coral reef islands without allochtone sediment input, the mangroves on these islands will become extinct. This situation illustrates the vulnerability of mangroves on reef islands and the importance of sediment or mud deposition in the mangrove environment which can offset the rate of SLR. The rate of sedimentation in the mangrove environment in IAB is not yet known, so it cannot be estimated how the mangroves will respond if the SLR scenario of IPCC [4] occurs.

In the mangrove area in IAB, there are Bruguiera, Sonneratia, Avicennia, and as Rhizophora. Table 2 shows that based on the IVI *Rhizophora apiculata* is present and dominant in Waiheru and Passo. Figure 7 shows that *Rhizophora apiculata* grows on the seaside and towards land in intersperses with *Sonneratia alba*. The presence of *Rhizophora apiculata* in IAB shows an opportunity for mangroves to adapt to SLR even though they currently show low natural regeneration.

In the 110cm/100-year SLR scenario, Bruguiera, Sonneratia, and Avicennia will likely disappear, and Rhizophora has the chance to survive [5, 41, 42]. A long-term study of past mangrove ecosystems based on pollen analysis shows that SLR causes Rhizophora which tends to grow on the seaside to expand inland by expanding the Bruguiera zone which tends to grow on the land side [6, 7].

The adaptive response of mangrove areas to SLR can occur as migration or expansion of mangrove areas towards the land. This migration can occur through mangrove zone migration or landward recruitment at the back of the mangrove area and recruitment within the mangrove population that shifts inland [13]. In IAB, the mangrove area is directly adjacent to the developing residential area behind it. This situation prevents the mangrove area from expanding landward. Thus, the opportunity for mangroves to adapt to SLR can occur through recruitment in mangrove populations that are tolerant of SLR.

Chance of mangroves to survive in IAB

Mangroves in IAB are under strong pressure from residential areas that develop behind them, which closes the opportunity for mangroves to expand inland in the event of SLR. This situation causes the opportunity for mangroves to survive only by recruitment in the population. The mangrove's likelihood of survival is low due to the narrow width of the mangrove area and the low sedimentation rate of mud. Therefore, the intervention of the local government to maintain the existence of mangroves in IAB is very important.

For residential areas, to deal with this environmental change problem related to SLR there are two adaptation options. The first option is to build a coastal defense structure to protect the residential areas from inundation by seawater. The second option is to move residents to areas that are predicted to be free of inundation in the event of SLR. The first option means preventing mangroves from developing landward. In the second option, the potential for mangroves to expand inland is challenging, as converting developed areas into suitable habitats for mangrove growth requires human intervention. From the perspective of financial and social costs, the first option is cheaper than the second option. Therefore, the first option to build coastal defense structures in the face of SLR is more reasonable.

As a consequence of the above choices, actions need to be taken to increase the chances of mangroves surviving in the event of SLR to stop the expansion of settlements into mangrove areas and to build a coastal structure in front of the mangrove area which can trigger an increase in the deposition of mud on the mangrove coast, such as by building permeable dams. This method has been applied to overcome the erosion of muddy coast or mangrove coasts in various countries including Indonesia (in Demak and Gresik) that triggering mud sedimentation and mangrove growth [44]. This method can be combined with helping the natural colonization of mangroves in certain places by providing or increasing the entry of seedlings to certain locations, protecting seedlings from herbivores, and elevating the retention period of propagule with artificial shelters [45].

Conclusions

Mangroves in IAB are in a very protected environment with hydrodynamic conditions dominated by tides. Mangroves are in a deltaic environment, with a discontinuous distribution, and are adjacent to residential areas behind them. In a scenario where SLR by approximately 1.1m by 2100, the mangrove ecosystem in the IAB is under significant pressure. Adaptation of the mangrove ecosystem through landward expansion cannot occur because it has been limited by residential areas. Opportunities for adaptation to survival exist through recruitment within the population by mangrove species that are tolerant of SLR, such as Rhizophora.

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