Geomorphological and hydrological changes play a critical role in mangrove forest degradation in a rapidly shrinking lagoon in Indonesia

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Abstract. Coastal lagoons are important geographic features because they provide various natural resources. Exploitative resource use and mismanagement may cause irreversible damage to the environment. This paper aims to review research and management based on the available spatial dataset in Segara Anakan, a rapidly shrinking lagoon in Indonesia, which is expected to disappear completely soon. We summarize knowledge from the earliest available publication in the 19th century (Dutch colonial time) to current times. There are three extreme patterns of changes: geomorphological, vegetation cover, and hydrological changes. These changes are basically interconnected. For example, the lagoon is continuing to shrink, while freshwater supply is higher than seawater supply, decreasing soil salinity. With this lesser saline environment, the understory mangrove species occupy and grow quick in the degraded mangrove area. Thus, mangrove seedlings have difficulty in surviving in competition with the understory plants. From this insight, a conceptual model was developed, and could be used in the management of the area. The available (spatial) data can be used to obtain more knowledge about the mangrove forest in the area.
Key Words: conceptual model, environmental changes, geomorphology, hydrology, Segara Anakan, understory.

Introduction. Coastal lagoons are attractive places because they provide various resources and ecosystem services. Coastal lagoons are brackish or marine shallow waters having depths that are rarely more than 2 m, mainly separated from the ocean, but still connected to it by at least one canal (Kjerfve 1994). Salt marshes and mangroves occupy the embankment soil of lagoons in subtropical and tropical regions. The continuum between aquatic and terrestrial systems provides various habitats, like open dry land, vegetated habitats, submerged aquatic vegetation, mudflats, and open waters. It becomes a home for many species of marine and terrestrial biota. Coastal lagoons serve marine species for nursery, feeding, and as refuge areas, so they are highly productive fishing grounds. Agriculture also starts to grow around lagoons with spreading settlements.

Many cities worldwide occupy coastal lagoons and the surrounding area, transforming natural land cover and the water body, and increasing stressors to the environment (Kennish & Paerl 2010). Kennish et al (2008) classified the stressors into two categories based on their damage levels. Irreversible damage includes habitat loss, eutrophication, wastewater, solid waste, overfishing, and sea level rise. These stressors can completely alter the structure and function of lagoons. Chemical contaminants and river diversion may be moderate in damage, shifting the community structures of aquatic biota, including aquatic plants. Invasive species introduction, land subsidence, and sedimentation can have a moderate effect, but could also cause severe damage to the lagoons and even be irreversible.

Irreversible damage in a lagoon because of heavy sedimentation has been presented by the Segara Anakan Lagoon (SAL), Central Java, Indonesia, although it is not an urban area. Lukas (2017) demonstrated the changes of SAL from 1857/60 to 2013, showing a dramatic decrease in the water surface area of the lagoon. Ironically, sedimentation has been detected since the 19^{th} century, and much research has been conducted. Moreover, the mangrove forest occupying three-quarters of SAL has experienced great loss, as 17090 ha in 1978 decreased to 9597 ha in 2003 (Ardli & Wolff 2008). Understory of mangroves replaced the mangrove tree stands. Understory occupied the bare land due to timber extraction or abandoned fishponds. Many studies considered this invasion as a mangrove forest degradation (Hinrichs et al 2009; Nordhaus et al 2019; Ardli & Yani 2020). Therefore, this lagoon has become a global concern, for example, through the USAID-funded Citanduy II project, the ASEAN/US Coastal Resources Management Project, and the ADB-funded Segara Anakan Conservation and Development Project.

The situation is aggravated by many stressors, including agriculture expansion, fisheries overexploitation, and oil pollution. Therefore, this lagoon has become a further interest for researchers. Studies in the lagoon include subjects such as botany (Sukardjo & Yamada 1992; Hinrichs et al 2009), marine zoology (Geist et al 2012), ecology (Yuwono et al 2007; Syakti et al 2015), oceanography (Holtermann et al 2009), geology (Hadisumarno 1979; Hapsari et al 2020), geography (Ardli & Wolff 2009; Lukas 2014), fisheries (Suwarso & Wasilun 1991; Máñez 2010), agriculture (Ferichani & Prasetya 2017), environmental management (Dharmawan et al 2017), and political ecology (Reichel et al 2009; Dharmawan et al 2016). An integrative study has also been conducted and provides a strong message for SAL conservation and management, which says that the district government interest was not reached as researchers could not obtain the correct picture of the situation, and that the district government preferred a conservationist approach in developing regulations (Dharmawan et al 2017). These causes also produce changes and environmental stresses in SAL, particularly causing the shrinking of the lagoon.

Presenting a correct image of the situation in SAL to the government and public is a great challenge. Much research on SAL is present in the form of project reports, scientific papers and books, making it difficult to access and be understood by the public and policymakers. Therefore, data integration and translation into implementable knowledge are urgently needed. Presenting the summarized knowledge in a map or a simple spatial model may help to deliver it to the government and the public.

This paper aims to gather available (especially spatial) data and knowledge on the mangrove degradation in SAL and generate a new integrative perspective of the SAL environmental changes, presented in an easy-access format that is understandable and applicable. Firstly, an overview of available spatial and non-spatial datasets relating to SAL is provided, including geomorphology, vegetation, hydrology, environment, and management. Secondly, knowledge patterns are presented, such as geomorphological changes, land-use/land-cover changes, and others. Thirdly, a conceptual model is proposed as a platform to integrate the available data and predict ecosystem shifting, particularly vegetation (mangrove) shifting. Finally, some future research directions are suggested in this paper.

Available Datasets. The datasets regarding SAL were collected from many scientific papers, project reports, and books from various databases (Table 1). This study emphasizes only references that produce spatial data or information related to the change of mangrove cover in SAL.

The results of data analysis on these datasets depict rapid changes in the SAL due to anthropogenic and natural disturbances that have been affecting it for two centuries. The datasets are categorized into 3 main topics relevant to ecosystem shifting:

geomorphological changes, land-use/land-cover, and hydrological changes. Geomorphological change is the most obvious in the SAL and has been mentioned in many papers, where the water surface area is rapidly shrinking. Land-use/land-cover change is similarly apparent. The hydrological condition of the SAL could be a cause or a result of ecosystem shifting. Other environmental conditions do not show a straightforward pattern. The details of these changes are in the following sub-sections.

Table 1

The availability of spatial data of Segara Anakan Lagoon in the literature

Dataset	*Description*	*Year*	*Scale/ Resolution*	*Thematic Class*	*Method*	*Reference*
Geo-morphology	Sea chart drawn by Cornelius Coops in 1698 as the result of expedition voyage of United (Dutch) East India Company.	1689	1:140000	-	Hand drawing	Lukas (2014)
	Sea chart drawn by Jan Theunis Busscher in 1809, known as the first detailed map of the lagoon.	1809	1:76000	-	Hand drawing	Lukas (2014)
	Topographic map, produced in 1813 and 1815 as part of the first systematic topographic large-scale mapping of Java.	1813, 1815	1:114000	-	Field survey	Lukas (2014)
	Topographic map, based on field survey.	1857-1860	1:100000	-	Field survey	Lukas (2014)
	Topographic map produced by the Topographical Service of the Netherlands East Indies based on field survey.	1897-1901	1:100000	-	Field survey	Lukas (2014)
	Topographic map produced by the Topographical Service of the Netherlands East Indies based on survey.	1924-1926	1:50000	-	Field survey	Lukas (2014)
	Bathymetry map generated from the model based on ADCP measurement, sea chart data, and SPOT imagery.	2005	-	-	Hydro-dynamics model	Holtermann et al (2009)
	Coastline map for the study of land accretion in the SAL.	2003	-	-	Field survey	Lugra & Setiady (2012)
	Sediment map of the distribution of surficial sediment over the western part of SAL.	2003	-	4 types of sediment	Field survey	Lugra & Setiady (2012)
	Map of the future projection of lagoon and land areas.	1987	-	2 classes: waters and land	-	ASEAN/US CRMP & DGF (1992)
Geo-morphology and mangrove vegetation	Map of the land accretion and the changes of mangrove areas in the western part of SAL.	1903-1986	-	6 classes of land use	Manual delineation	ASEAN/US CRMP & DGF (1992)

Table 1

The availability of spatial data of Segara Anakan Lagoon in the literature (continuation)

Dataset	*Description*	*Year*	*Scale/ Resolution*	*Thematic Class*	*Method*	*Reference*
Land use/Land cover (mangrove vegetation)	Land use map generated from SPOT XS satellite imagery by using supervised classification.	1987, 1995, 2004, 2006	20x20 m, 10x10 m	10 land use classes	Digital image processing	Ardli & Wolff (2009)
	Multi-temporal land use maps generated from Landsat series and ASTER GDEM data as input for supervised classification.	1978, 1991, 2001, 2014	60x60 m, 30x30 m	14 land use classes	Digital image processing	Farda (2017)
	Multi-temporal maps of mangroves generated from the combination of NDVI produced by Landsat 8 OLI and Proba-V ESA.	2015 (1 year multi-temporal)	30x30 m	-	Geo-statistics and remote sensing	Arjasakusuma et al (2020)
	Health map of mangroves generated from Sentinel-2 satellite imagery based on NDVI.	2017-2020	20x20 m	4 classes of mangrove health	Digital image processing	Akbar et al (2020)
	Map of the canopy density of mangroves based on NDVI generated from Landsat-8 satellite imagery.	2016	30x30 m	3 levels of canopy density	Digital image processing	Ismail et al (2018)
	Mangrove map generated from Landsat-8 OLI processed by Principal Polar Spectral indices.	2014	30x30 m	3 classes of undefined species	Digital image processing	Ramdani et al (2018)
	Multi-temporal land use map generated from SPOT-1, Landsat-ETM, and Landsat-OLI.	1987, 2003, 2016	20x20 m, 30x30 m	8 classes of land use	-	Supriatna et al (2018)
	Multi-temporal land use maps generated from SPOT-XS data and supervised classification methods.	1987, 1995	20x20 m	7 land use classes	Digital image processing	Olive (1997)
	Map of the distribution of land use and several distinct mangrove areas.	1992	-	6classes of land use and 5 classes of mangrove	Manual delineation	ASEAN/US CRMP & DGF (1992)
	Map of the mangrove forest areas, state-owned plantations, and other land use according to PERHUTANI (state-owned plantation company).	1989	-	2 classes of mangrove areas, 3 classes of plantation areas, and 5 other land use	Manual delineation	ASEAN/US CRMP & DGF (1992)
	Map of the damage level mangrove forest in SAL generated from Landsat-8 OLI.	2013	30x30 m	4 classes of the mangrove cover level	Digital image processing	Winarso & Purwanto (2014)
	Maps of the change of mangrove cover at life form classification level. Maps generated from the multi-temporal Landsat images.	1990, 2000, 2010, 2019	30x30 m	3 classes of life form	Digital image processing	Prayudha et al (2021)
Hydrology	Salinity map generated from the three-dimensional General Estuarine Transport Model.	2005-2006	80x80 m	-	Hydro-dynamics model	Holtermann et al (2009)
	Salinity map produced by Surface Water System (SMS) model.	2018	-	-	Hydro-dynamics model	Hariati et al (2019)
	Chlorophyll-a map generated from the empirical model using Landsat-8 OLI data and field data.	2016	30x30 m	-	Empirical model	Dewi et al (2018)
	Phytoplankton map generated from field measurement.	2016	-	-	Field survey	Dewi et al (2019)
	Total suspended solid map generated from SPOT-6 satellite and field data.	2016	6x6 m	-	Empirical model	Dhannahisvara et al (2018)

Geomorphological Changes. The decrease in the water surface of the lagoon has been described in numerous studies. These studies recorded the gradual changes in the SAL water surface over the past two centuries (Figure 1).

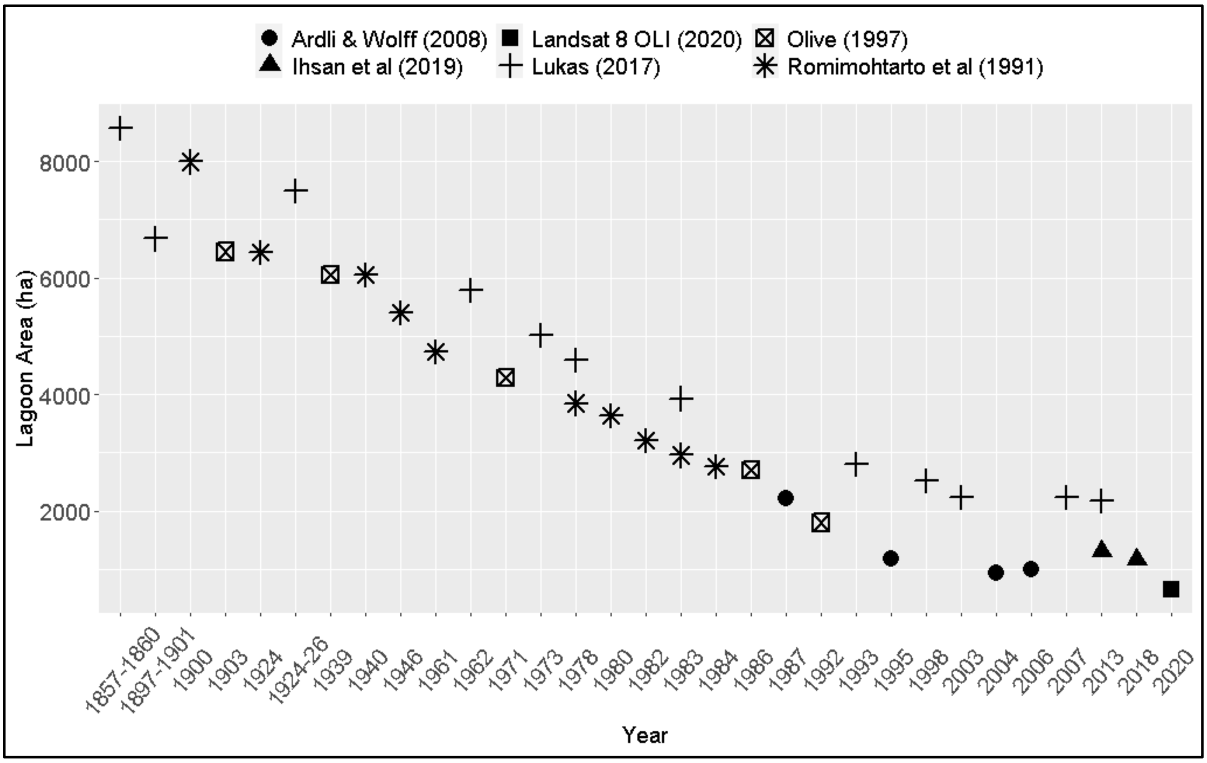

Figure 1. The changes of lagoon area in two centuries.

The longest record of the decreases in the lagoon water surface is reported by Lukas (2017). He reconstructed the historical environment of the SAL from archive maps and satellite data between 1857/60 and 2013. He recorded the initial area of the lagoon in 1857/60 as 8579.5 ha, almost 400% greater than his last record in 2013. A dramatic change in the lagoon area occurred between 1857/60 and the 1920s. Before Lukas (2017), Romimohtarto et al (1991) reported a similar decreasing trend in the lagoon water surface area from 1897/1901 to 1984. Others also found this decreasing trend, but only a few data points were presented (Olive 1997; Ardli & Wolff 2008; Ihsan et al 2019). Here, one data point is added, calculated from Landsat (2020) using Lukas' approach, showing a smaller water surface area than the last record in 2018 (Ihsan et al 2019). These data provide strong evidence that the surface water area of SAL is continuously shrinking (Figure 2).

The apparent cause of the rapidly shrinking SAL is heavy sedimentation from the rivers around the lagoon (Lukas 2017). Based on data collected in the 1960s and 1970s, Napitupulu & Ramu (1982) estimated that the sediment supply rate is 17.4 million t year^{-1}, with the Citanduy river contributing the most, with 87% of the total sediment supply. A decade later, Purba (1991) found that the rate is lower than the previous estimate, accounting for 5-10 million t year^{-1}. This sedimentation supply undoubtedly causes land accretion (Olive 1997; Lugra & Setiady 2012; Sari et al 2016). Approximately 74 ha of new land formed between 1968 and 1987, and 29 ha between 1987 and 1995 (Olive 1997). Land continued to grow as several small islands have emerged in the middle of the lagoon with an accretion rate of 78.5 ha year^{-1} between 1999 and 2003 (Lugra & Setiady 2012). Thus, the islands achieved a size of 392.5 ha. In the relatively new literature, an estimated 339.7 ha of new land emerged between 2003 and 2014 (Sari et al 2016).

Figure 2. Segara Anakan Lagoon transformation between 1978 and 2020, digitized by Prayudha et al (2021) from Landsat-3 1975-1978 and Landsat-8 2020.

Sedimentation in the SAL is a complex process. Lukas (2017) found that the extensive land transformation in the upland area causes soil erosion, adding sediment loading to the rivers. It includes the development of coffee cultivation, the immigration from lowland to upland areas, the construction of railways across the watershed, timber extraction, and plantation establishment. Between the mid-twentieth century and the 1970s, the land transformation in the watershed was marked by the development of rain fed agriculture. The development of agriculture also occurred in the lowland (Ardli & Wolff 2008), where rice agriculture replaced mangrove areas by 44% between 1987 and 1995. These may contribute to sediment supply to the SAL.

There are concerns about the rapidly shrinking area of the SAL water surface. Some measures to face such a problem, for example, could be providing a model prediction and dredging the lagoon. Purba (1991) and Olive (1997) predicted that the lagoon would disappear in 2000, but their prediction was not confirmed at the time. Some efforts have been undertaken to conserve the lagoon, like tree planting and field terracing in the upland area (Lukas 2017) and dredging the lagoon (ADB 2006; Ardli & Wolff 2008). These efforts might be helpful, but the rate of sedimentation remains high. If the present data from Landsat-8 satellite imagery is included in the SAL water surface dataset and we apply a linear regression (Figure 1), it can be predicted that the lagoon will completely disappear by 2042.

Land-use/Land-cover Changes with Focus on Mangrove Vegetation. Between 1903 and 1986, there was an increase in the mangrove area of SAL due to the new land occupation by mangrove seedlings and saplings (ASEAN/US CRMP & DGF 1992). However, land-use/cover changes in the SAL were reported more complex after those years, with additional stressors from humans. The oldest dataset of land-use/cover changes in the SAL was revealed from satellite images in 1968 (Olive 1997). There have been three distinct periods of mangrove transformation in the SAL from that time until now (Figure 3). Period I occurred between 1968 and 1987, when rice field expansion into mangrove forests caused a sharp decrease in the mangrove cover. Due to this decline, conservation projects were implemented, reducing the rate of mangrove loss in Period II (1990-2006). In Period III (2006-now), the mangrove area increased slightly, but mangrove trees were still logged and used for firewood, charcoal, and as building material (Sastranegara et al 2007).

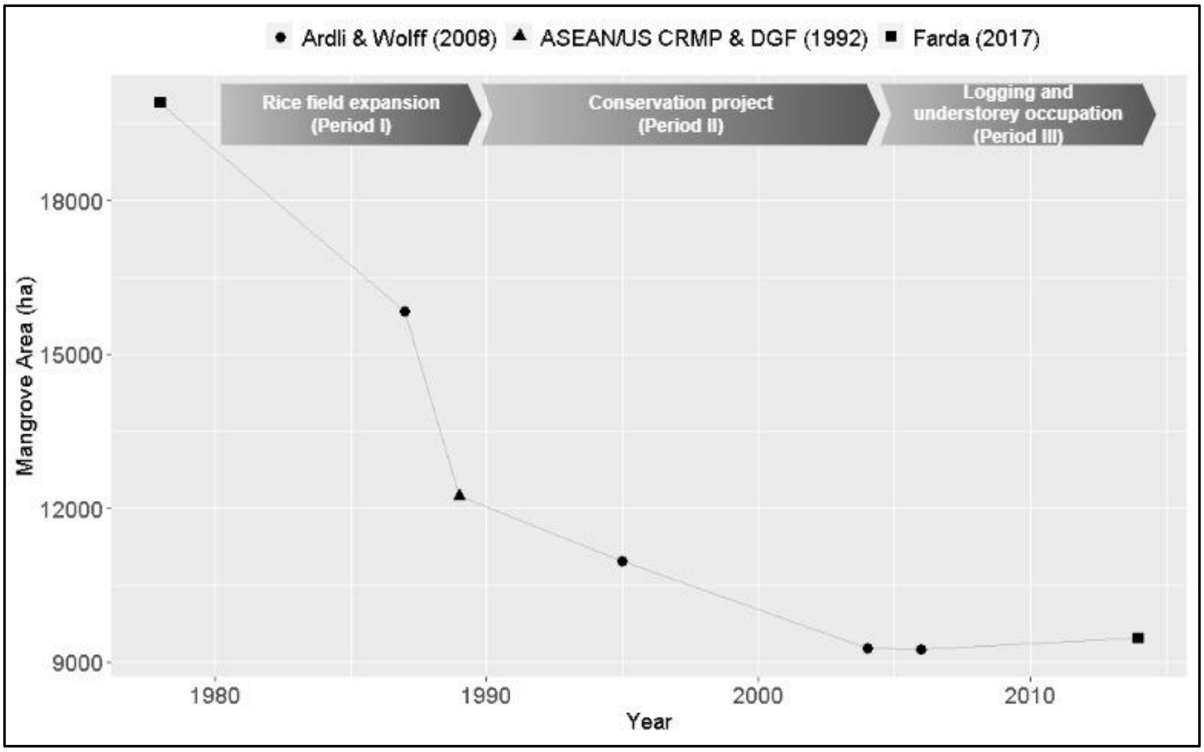

Figure 3. The trend of mangrove area within Segara Anakan Lagoon.

In Period I, along with the occupation of the new land formed by sedimentation, rain-fed rice fields replaced the mangrove forests (Olive 1997). Afterward, many studies confirmed the cause-and-effect relationship between the rice field expansion in the 1980s and the decline of mangrove cover (Ardli & Wolff 2008; Farda 2017). The establishment of rice fields is evident, while the fisheries resources decline due to the lagoon shrinking and the new land uprising (Olive 1997). Rice agriculture in the SAL is strongly supported by the village head (Kepala Desa), who tries to solve the economic problem of the area. The villagers prefer working in the rice fields rather than joining a transmigration program. As a result, the area of rice fields is extensive along the northwest shoreline of the lagoon.

Conservation projects had successfully decelerated the rate of mangrove loss between 1990 and 2005, during Period II. The internationally funded projects in the SAL had succeeded in extending the mangrove area to 1125 ha through rehabilitation activities and simultaneously conserved 5000 ha of mangrove forest from 1996 to 2006 (ADB 2006).

In Period III, the mangrove area in the SAL increased slightly. However, based on observations, understory plants (*Acanthus* spp. and *Derris trifoliata*) become dominant formations in the central part of the SAL (Figure 4).

These plants occupy forest gaps (Hinrichs et al 2009; Nordhaus et al 2019) formed by logging activities and timber utilization by local communities. Under certain conditions, *Acanthus* spp. and *D. trifoliata* are invasive and may inhibit the growth of mangrove trees (Giessen et al 2007; Tomlinson 2016). Nordhaus et al (2019) found a decline of mangrove tree biomass in the central part of SAL, as *Acanthus* spp. and *D. trifoliata* replaced mangroves. *Aegiceras corniculatum* and *Avicennia alba* experienced a tremendous loss in that area between 2005 and 2015.

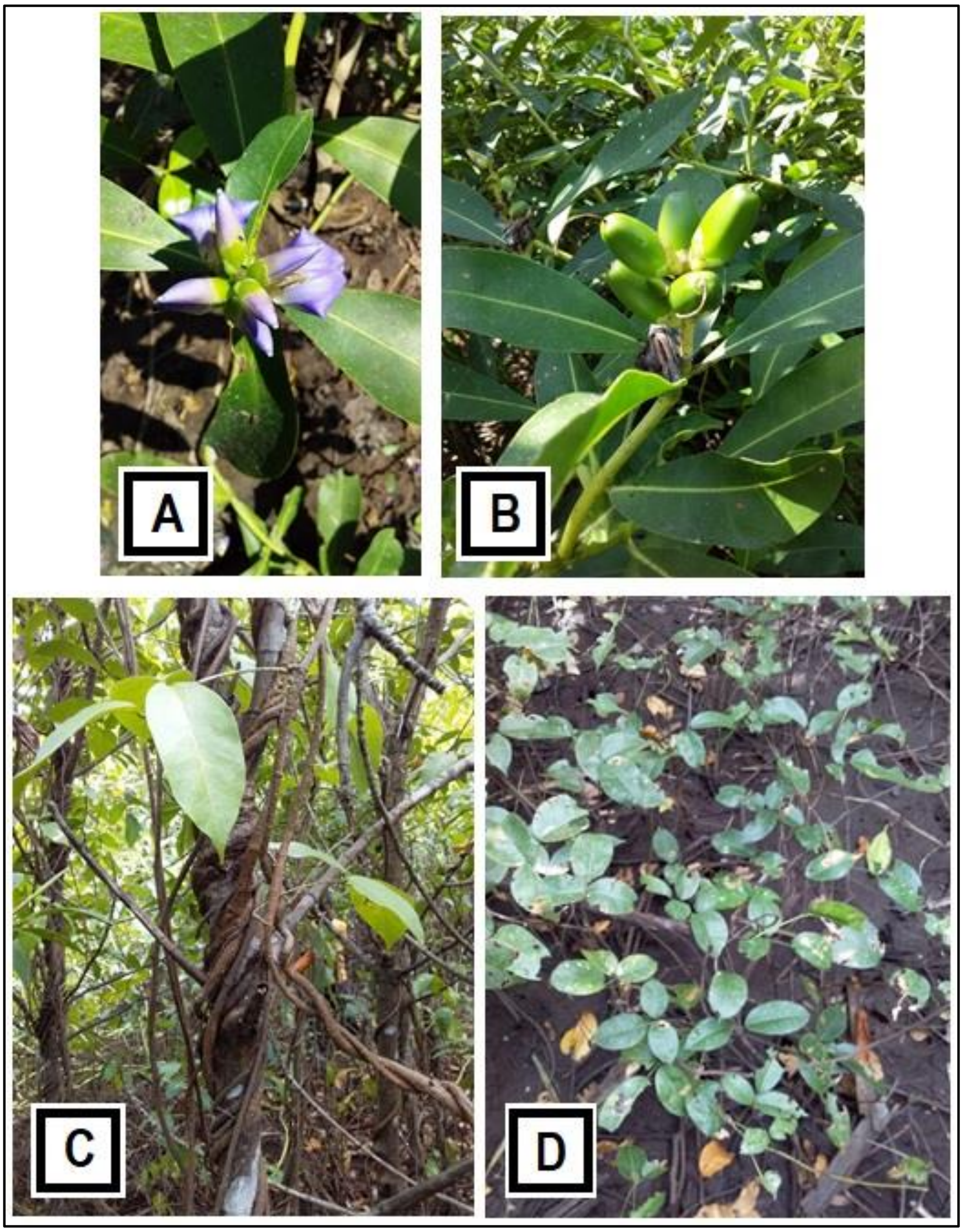

Figure 4. Understory plants; A - flowers of *Acanthus* sp.; B - fruits of *Acanthus* sp.; C - *D. trifoliata* strangles mangrove trees; D - *Derris trifoliata* on the forest floor.

Acanthus spp. and *D. trifoliata* have not been presented well in the most available mangrove maps generated from satellite imagery (Ismail et al 2018; Akbar et al 2020). The maps generally show only the existence of mangrove cover with canopy density classes. Moreover, there is a severe error in the image analysis results due to the coverage of *Acanthus* spp. and *D. trifoliata* (Winarso & Purwanto 2014). The coverage of these plants is considered to have a higher canopy density than mangrove forests (Ismail et al 2018; Arjasakusuma et al 2020). *Acanthus* spp. and *D. trifoliata* form a dense ground cover, which looks like a dense tree canopy from top view (Figure 5). As a result, an area with *Acanthus* spp. and *D. trifoliata* coverage is classified as dense mangrove forest if the satellite imagery is interpreted without field verification.

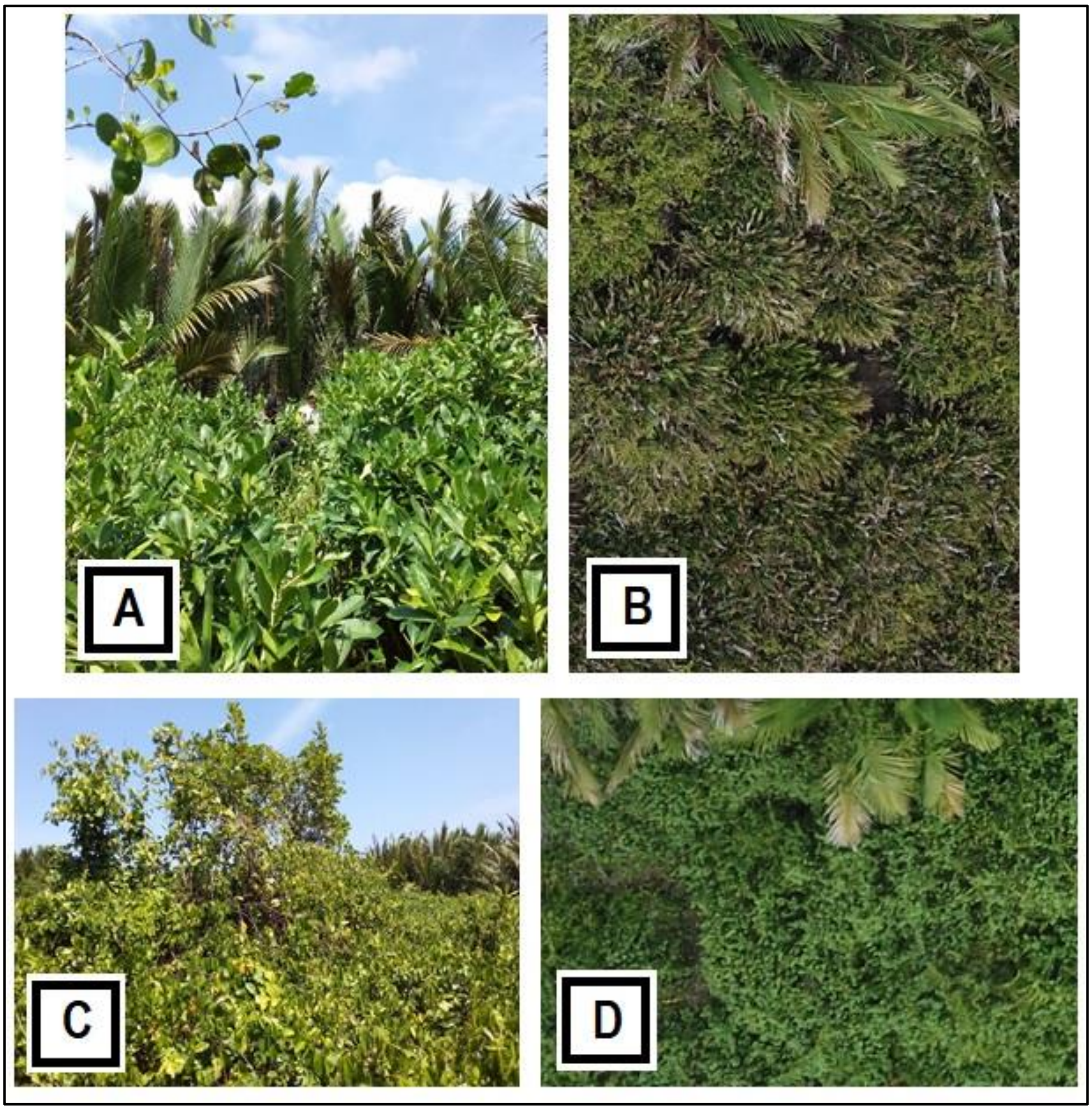

Figure 5. Coverage of *Acanthus* spp. and *Derris trifoliata*; A - *Acanthus* spp., side view with Nypa palm trees in the background;B - top view; C - *D. trifoliata*, side view with Nypa palm trees in the background; D - top view (D).

To revise mangrove maps of the SAL, Winarso & Purwanto (2014) proposed a new approach, and their results fit well with most field conditions. They also noticed that the coverage of *Acanthus* spp. and *D. trifoliata* make a misclassification in the results of satellite image analysis. In their map, an area with this coverage was classified as deforested mangroves. However, their study has no detailed information at lower classification levels, such as life forms, vegetation community, or species. In addition, to our best knowledge, there is no mangrove mapping in the SAL at such levels. The only detailed map of mangroves in SAL was presented by Prayudha et al (2021). They used the multitemporal Landsat satellite images to produce a mangroves map at the life form classification level, with an accuracy of 78.79% and kappa coefficient of 0.729. However, further research should be conducted to validate and compare it with other methods.

Hydrological and Other Changes. The environment hydrodynamics in the SAL are influenced by the discharge of surrounding rivers and tidal force from the two main outlets of the lagoon. Holtermann et al (2009) investigated the influence of those two factors on the water mass distribution throughout the lagoon. They revealed that the Citanduy river dominantly supplies freshwater into the lagoon. The lagoon is flushed with freshwater when the high discharge of Citanduy flows coincidently with the neap tide period. This process is intense in the western part and gradually limited to the central part of the SAL. Hence, there is a salinity gradient in the SAL from brackish in the western part to gradually more saline in the eastern part. In this part, there is also freshwater input from Donan river discharge. However, the discharge is not enough to lower the salinity of the lagoon water. A previous study also confirmed this salinity gradient (Hariati et al 2019).

Due to sea-level rise (SLR), the salinity pattern in the SAL waters may change dramatically in the future (Hariati et al 2019), and the SAL waters may be more saline than the current condition by 2050. In addition, the intrusion of saline water may occur up to 16 km away from the coastline by 2050.

The changes in water and soil salinity in the SAL have been detected as the cause of mangrove shifts. Nordhaus et al (2019) found that the low saline environment in the central part contributes to the growth of *Acanthus* spp. and *D. trifoliata* once it occupies the forest gaps. Conversely, these plants rarely occur in the eastern part of the SAL, where the water and soil salinity is higher than in the central part (Ardli & Yani 2020). Therefore, the fate of the surviving mangroves in the SAL would depend on what happens with the water and soil salinity in the region. Combined with heavy sedimentation, as explained before, the increase of river discharge into the SAL and its canals may cause an expansion of *Acanthus* spp. and *D. trifoliata,* replacing mangroves. Under an adverse scenario, mangroves in the SAL may be surviving when SLR occurs, as projected by Hariati et al (2019). SLR will bring more salinity into the SAL, where only mangrove plants would survive.

Besides salinity, there are other aspects of hydrology in the SAL. Most studies reported non-spatial data (Jennerjahn et al 2009; Syakti et al 2015), and only a few presented spatially explicit information, such as chlorophyll-a concentration, phytoplankton, and total suspended solids (TSS) (Dhannahisvara et al 2018). To date, it remains difficult to explain how that information relates to the shifts in mangrove communities or even the total transformation of the SAL.

Interconnectedness between Datasets. Figure 6 shows the summary of all the datasets presented in the previous section, showing the relationship between the datasets, and presenting a bigger picture of the problems in the SAL. The central issue in the SAL is sedimentation and river discharge of Citanduy, making the lagoon shrink. These changes cause mangrove community shifting and hydrological changes in the lagoon. Furthermore, all components of vegetation and hydrology may be affected, such as land cover, stand density, zonation, community, salinity, and TSS. There may be an adverse effect of vegetation and hydrology on the SAL geomorphology. However, one must bear in mind that sedimentation has been occurring due to landscape transformation in the hinterland (Lukas 2017), and climate change may have also become an additional factor causing sedimentation. According to this abstraction, we proposed a framework for developing a prediction model.

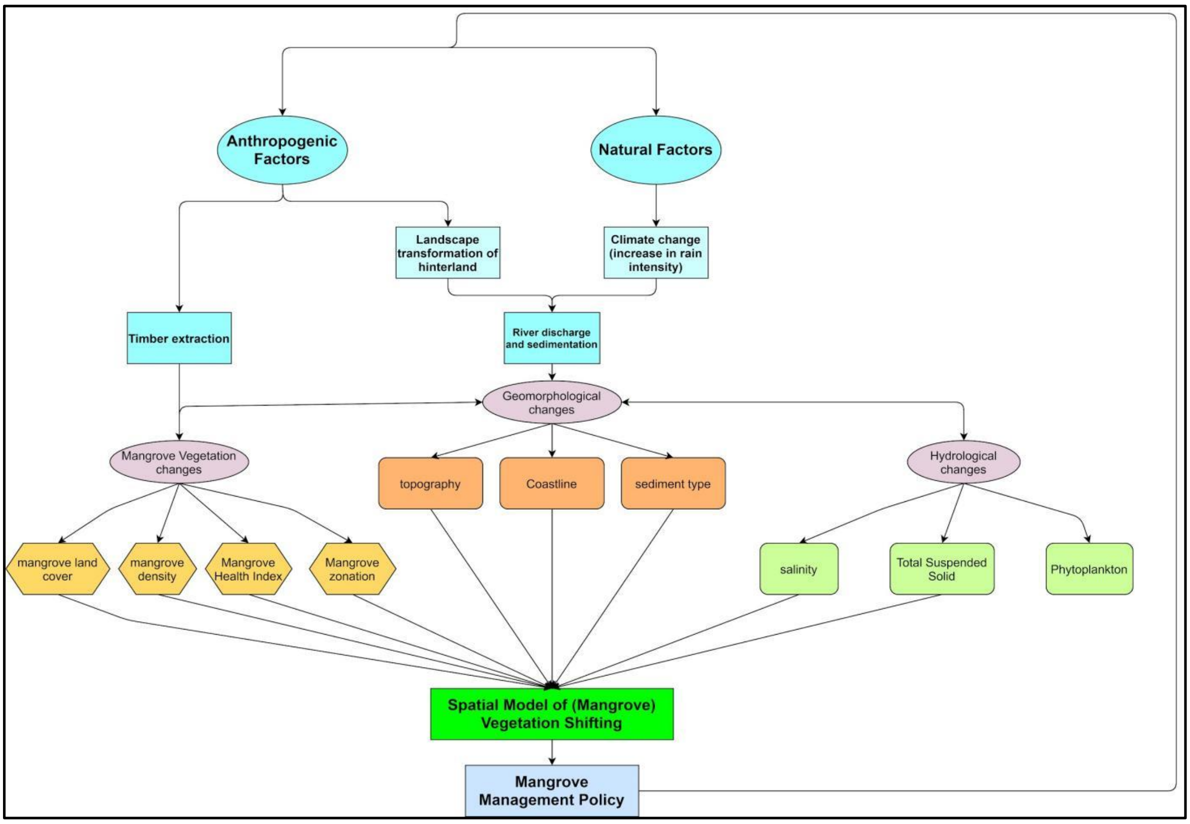

Figure 6. Interconnection between datasets regarding Segara Anakan Lagoon.

Model Development. Based on the best available data and on the relationship between datasets, a framework that can be further developed as a prediction model was created. The framework is adopted from the Land Use and Land Cover Change (LULCC) model developed by Moulds et al (2015) and Mas et al (2014). This framework is created to develop a model for studying and predicting the vegetation shifting of mangroves in the SAL (Figure 7). The model allows studying environmental changes in spatial context. Hence, it may provide a better visualization for the decision-makers or other related stakeholders, helping them understand the SAL's circumstances. The framework of the model consists of three phases: calibration, simulation and assessment.

The calibration phase aims at relating the explanatory variables with the observation data. This phase employs the statistical models for describing the relationship between variables and selects the most appropriate model for describing the actual situation. To construct and select a statistical model, observation data and explanatory variables are needed as the input. The observation data represents the mangrove vegetation shifting over the period. This information is provided from the multi-temporal maps of land cover, commonly generated from the mapping process using a remote sensing approach. In the SAL, many sources related to the observation data of mangroves are available. Most of the data are generated from a remote sensing approach through satellite technology. The long-term remote sensing satellite mission such as Landsat and SPOT supports the availability of the multi-temporal data in the SAL (Olive 1997; Ardli & Wolff 2008). Moreover, the development of cloud computing and big data storage allows exploring various remote sensing datasets and methods for generating fast and more accurate maps (Farda 2017).

There are many candidates of explanatory variables. In this case, the explanatory variables could be grouped into socio-economic, geomorphologic, and hydrologic variables. Socio-economy can be represented by the land-use pattern in the SAL and its surroundings. This approach has been used by several studies describing the change of mangrove distribution through the land-use/land-cover model. For instance, DasGupta et al (2019) and Supriatna et al (2018) used "distance to road" and "settlement" or "built-up area" as surrogates for describing the risk of human disturbances, such as timber harvest and land clearing. Geomorphology plays a vital role in the SAL transformation, which also strongly influences the distribution pattern of mangroves. The development of new land allows mangroves to grow since their elevation is still within the range of the tides. Conversely, in some parts, the elevation of the old beach rises, preventing the expansion of mangroves from within the range of the tides. The land accretion in the SAL is recorded in numerous studies (Lugra & Setiady 2012; Lukas 2017), providing the map of coastline change within the SAL. The hydrology is also influencing the distribution pattern of mangroves in the SAL. Nordhaus et al (2019) and Ardli & Yani (2020) described the salinity influencing the mangrove distribution pattern. The understory community (*Acanthus* spp. and *D. trifoliata*) tends to grow in the low saline environment, as found in SAL's western and central parts. Adversely, in the eastern part, the dense canopy cover and high water and soil salinity inhibit the understory.

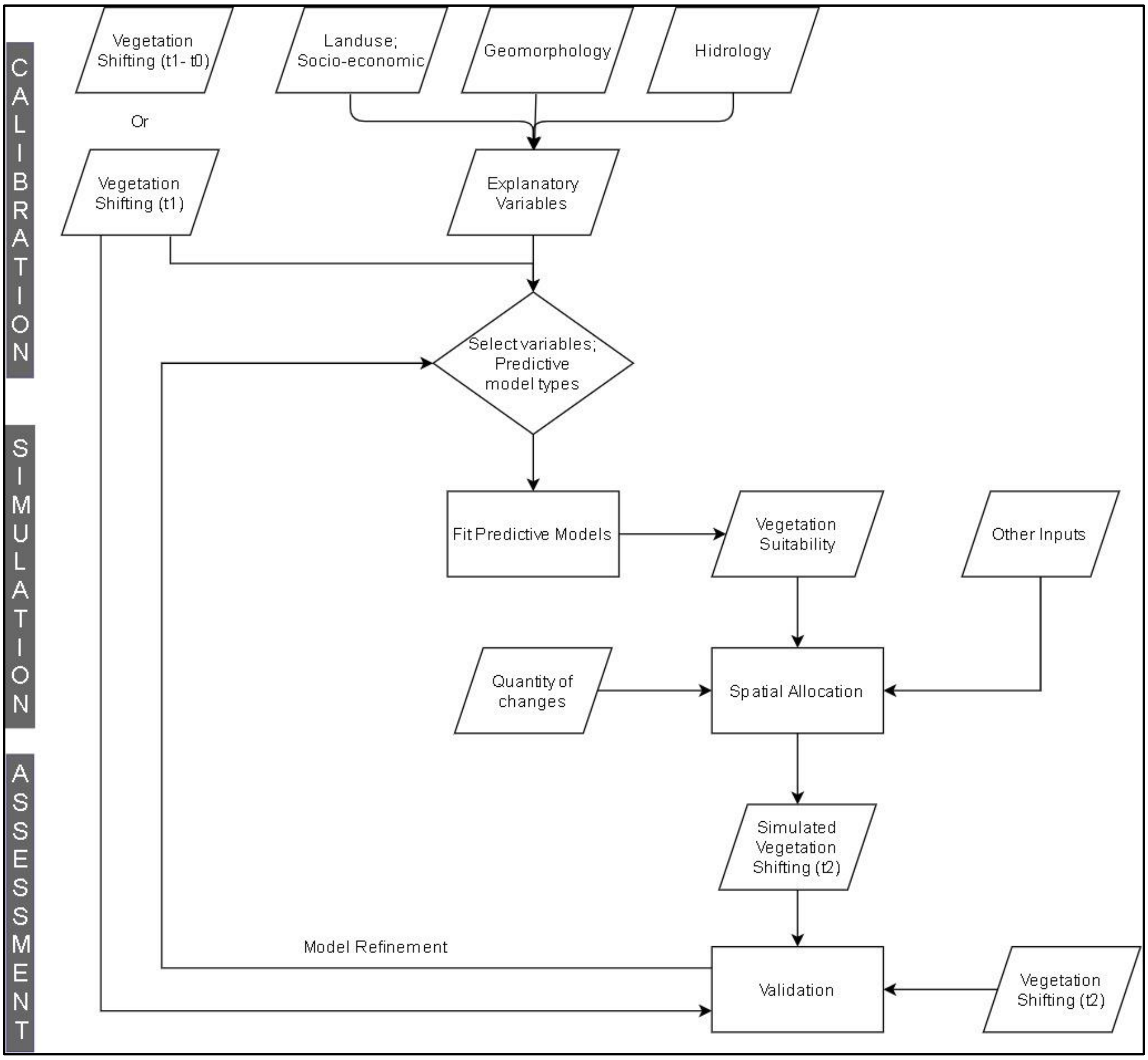

Figure 7. The vegetation shifting spatial model framework was adopted and modified from Moulds et al (2015) and Mas et al (2014).

The suitability of a location for a particular mangrove community class generated by the transition represents the association between mangrove changes and explanatory variables. The transition is represented by the quantitative pattern of the changes generated from the multi-temporal mangrove maps. This approach presents the non-stationary pattern of the changes in each time step that is established from the calibration phase. Hence, this approach is more stable and with better results (Mas et al 2014). The suitability maps of each mangrove class are used as the primary input for the spatial allocation model to simulate the changes for the past or the future.

The last phase, the assessment phase, aims to assess the performance of the simulated maps through the validation process. The validation employs the actual mangroves map at certain time steps. If the simulated maps are not conclusive, they can be refined by reselecting the explanatory variables. Moulds et al (2015) mentioned that very few programs provide methods for validating model output. This could be one reason for the lack of proper validation in the literature, as Rosa et al (2014) pointed out. Hence, the validating process is conducted on different platforms or programs. This causes problems as each program uses a different interface, model form, and structure. The current study offers the integrated framework for modeling the shifting of mangroves communities, including the assessment phase, as adapted, and modified from Moulds et al (2015).

Future Directions. A considerable amount of data and information have been analyzed from various researches conducted since the 19th century. This review paper contributes to a better understanding of what has been happening in the SAL (past and current condition, changes, cause and results of the changes, and outcome of the changes). A conceptual model is also proposed to help explain and predict the future of the SAL. However, there remain several aspects of SAL's mangroves and resources management to be developed for further studies:

1. Life form or community levels of classification in mangrove maps; the availability of detailed mangrove maps in the SAL lags far behind the global development of remote sensing for mangrove mapping (Wang et al 2019). Most of the studies addressed the utilization of satellite data for discriminating mangroves from other land covers. Some of them can identify the variation of mangrove based on its canopy density, which is common in vegetation studies. That information helps understand the general condition of mangrove forests. However, it is not sufficient, because the changes of mangroves occur within its community or even at species level. This situation has been recognized in mangrove forests in the SAL since the mid 2000s. Therefore, further exploration of remote sensing approaches to generate mangrove maps into community levels is urgently needed.

2. Reliable spatial model; a conceptual model has been proposed. It can describe the process and the relationship among environmental variables that contribute to the variation of mangrove communities spatially and temporally through the current study. Moreover, there is a privilege to have a considerable amount of data and information on the SAL. Only few data remain unavailable. Therefore, it is possible to develop a reliable model of the SAL that can simulate the environmental changes in the region. However, the certainty of a model should be considered to avoid misleading information. Thus, the assessment of the model performances is critical. Fortunately, the proposed model framework in this paper has an assessment step in its model development.

3. Computer or mobile applications for data analysis; the ultimate goal of integrating data and information of the SAL and developing a spatial model is to have better communication between researchers, policymakers, and broader stakeholders. Through this goal, mangrove and coastal resources management in the SAL could be conducted in better ways than before. Therefore, the challenge of using the spatial model is how to introduce it in an easy-access platform. The model must be developed on user-friendly and interactive software or mobile applications, now known as the Internet of Things (IoT) technology, as it is already present in the daily life of society. Thus, anybody can add data and make a simulation on their own. The software or apps should have a menu to select any languages preferred by the users. Ordinary people who cannot understand Bahasa or English may still use this app, access the information, and actively engage in the management of the SAL environment.

Conclusions. This review demonstrates an example of irreversible damage to a coastal lagoon. Segara Anakan Lagoon in Indonesia is shrinking and may disappear in the near future. Heavy sedimentation from upland areas in the Citanduy Watershed is causing this, primarily as a result of land erosion caused by agricultural practices and other human activities. New islands formed in the lagoon as a result of sedimentation. These geomorphological changes triggered hydrological changes, specifically blocking the lagoon's west inlet, reducing seawater and making the water lagoon in the west part less saline. Along with forest cutting, this condition has an impact on the mangrove vegetation community, where *Derris trifoliata* and *Acanthus* spp. (understory mangrove species) thrive and are even invasive. From an environmental standpoint, the lagoon and mangrove habitat have been degraded, and these valuable resources may soon vanish. Therefore, the government and local communities must work more closely together to develop a strategy and implement it in order to manage their environment and natural resources. Scientists may provide data and information to aid them in determining the best options, as well as communicate with them in simple and friendly language.

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References

Akbar M. R., Arisanto P. A. A., Sukirno B. A., Merdeka P. H., Priadhi M. M., Zallesa S., 2020 Mangrove vegetation health index analysis by implementing NDVI (normalized difference vegetation index) classification method on Sentinel-2 image data case study: Segara Anakan, Kabupaten Cilacap. IOP Conference Series: Earth and Environmental Science 584:012069.

Ardli E. R., Wolff M., 2008 Quantifying habitat and resource use changes in the Segara Anakan Lagoon (Cilacap, Indonesia) over the past 25 years. Asian Journal of Water, Environment and Pollution 5(4):59-67.

Ardli E. R., Wolff M., 2009 Land use and land cover change affecting habitat distribution in the Segara Anakan lagoon, Java, Indonesia. Regional Environmental Change 9:235.

Ardli E. R., Yani E., 2020 Mangrove damage evaluation using two species of Acanthus as a biomonitoring agent, case study: Segara Anakan Cilacap, Indonesia. IOP Conference Series: Earth and Environmental Science 550:012001.

Arjasakusuma S., Pratama A. P., Lestari I., 2020 Assessment of gap-filling interpolation methods for identifying mangrove trends at Segara Anakan in 2015 by using Landsat 8 OLI and Proba-V. The Indonesian Journal of Geography 52(3):341-349.

DasGupta R., Hashimoto S., Okuro T., Basu M., 2019 Scenario-based land change modelling in the Indian Sundarban delta: an exploratory analysis of plausible alternative regional futures. Sustainability Science 14:221-240.

Dewi R., Zainuri M., Anggoro S., Winanto T., 2019 A spatio-temporal analysis on the composition and abundance of phytoplankton in Segara Anakan Lagoon area. IOP Conference Series: Earth and Environmental Science 406:012028.

Dewi R., Zainuri M., Anggoro S., Winanto T., Endrawati H., 2018 Spatio-temporal distribution of chlorophyll-a using multitemporal Landsat image and ground check in Segara Anakan Lagoon. E3S Web of Conferences 47:03007.

Dhannahisvara A. J., Harjo H., Wicaksono P., Nugroho F. S., 2018 Total suspended solid distribution analysis using Spot-6 data in Segara Anakan, Cilacap. Geoplanning: Journal of Geomatics and Planning 5(2):177-188.

Dharmawan B., Böcher M., Krott M., 2016 The failure of the mangrove conservation plan in Indonesia: Weak research and an ignorance of grassroots politics. Ocean & Coastal Management 130:250-259.

Dharmawan B., Böcher M., Krott M., 2017 Failure of science-based win-win solution in fishery management: Learnings from Segara Anakan waters, Central Java, Indonesia. Ocean & Coastal Management 141:82-89.

Farda N. M., 2017 Multi-temporal land use mapping of coastal wetlands area using machine learning in Google Earth engine. IOP Conference Series: Earth and Environmental Science 98:012042.

Ferichani M., Prasetya D. A., 2017 System of rice intensification increases rice productivity on saline soil. *Paddy and Water Environment* 15(3):649-657.

Geist S. J., Nordhaus I., Hinrichs S., 2012 Occurrence of species-rich crab fauna in a human-impacted mangrove forest questions the application of community analysis as an environmental assessment tool. Estuarine, Coastal and Shelf Science 96(1):69-80.

Giesen W., Wulffraat S., Zieren M., Scholten L., 2007 Mangrove guidebook for southeast Asia. FAO and Wetlands International, 769 p.

Hadisumarno, 1979 [Coastline accretion in Segara Anakan, Central Java, Indonesia]. Indonesian Journal of Geography 9(37):45-52. [In Indonesian].

Hapsari K. A., Jennerjahn T. C., Lukas M. C., Karius V., Behling H., 2020 Intertwined effects of climate and land use change on environmental dynamics and carbon accumulation in a mangrove-fringed coastal lagoon in Java, Indonesia. Global Change Biology 26(3):1414-1431.

Hariati F., Ajiwibowo H., Hadihardaja I. K., Nugroho J., 2019 Modeling adaptation to salinity intrusion in Segara Anakan estuary due to sea level rise. International Journal of GEOMATE 16(53):9-17.

Hinrichs S., Nordhaus I., Geist S. J., 2009 Status, diversity and distribution patterns of mangrove vegetation in the Segara Anakan lagoon, Java, Indonesia. Regional Environmental Change 9:275-289.

Holtermann P., Burchard H., Jennerjahn T., 2009 Hydrodynamics of the Segara Anakan lagoon. Regional Environmental Change 9(4)245-258.

Ihsan H. J., Ginting D. N. B., Amron, 2019 [Utilization of Landsat-8 imagery for study of changes in the lagoon area of Segara Anakan Cilacap]. INDERAJA 10(12):22-27. [In Indonesian].

Ismail, Sulistiono, Hariyadi S., Madduppa H., 2018 Condition and mangrove density in Segara Anakan, Cilacap Regency, Central Java Province, Indonesia. AACL Bioflux 11(4):1055-1068.

Jennerjahn T. C., Nasir B., Pohlenga I., 2009 Spatio-temporal variation of dissolved inorganic nutrients related to hydrodynamics and land use in the mangrove-fringed Segara Anakan Lagoon, Java, Indonesia. Regional Environmental Change 9:259.

Kennish M. J., Livingston R. J., Raffaelli D., Reise K., 2008 Environmental future of estuaries. In: Aquatic ecosystems: Trends and global prospects. Polunin N. (ed), Cambridge University Press, pp. 188-208.

Kennish M. J., Paerl W. H., 2010 Coastal lagoons: Critical habitats of environmental change. CRC Press, 568 p.

Kjerfve B., 1994 Coastal lagoon processes. Elsevier, pp. 1-8.

Lugra I. W., Setiady D., 2012 New land accretion from 2000-2003 at Segara Anakan Lagoon, south coast of west and central Java. Bulletin of the Marine Geology 27(2):99-107.

Lukas M. C., 2014 Cartographic reconstruction of historical environmental change. Cartographic Perspectives 78:5-24.

Lukas M. C., 2017 Widening the scope: linking coastal sedimentation with watershed dynamics in Java, Indonesia. Regional Environmental Change 17(3):901-914.

Máñez S. K., 2010 Java’s forgotten pearls: The history and disappearance of pearl fishing in the Segara Anakan lagoon, South Java, Indonesia. Journal of Historical Geography 36(4):367-376.

Mas J. F., Kolb M., Paegelow M., Camacho Olmedo M. T., Houet T., 2014 Inductive pattern-based land use/cover change models: A comparison of four software packages. Environmental Modelling & Software 51:94-111.

Moulds S., Buytaert W., Mijic A., 2015 An open and extensible framework for spatially explicit land use change modelling: The lulcc R package. Geoscientific Model Development 8(10):3215-3229.

Napitupulu M., Ramu K. L. V., 1982 Development of the Segara Anakan area of Central Java. In: Proceedings of the Workshop on Coastal Resources Management (Cilacap Region, Indonesia). Bird E. C. F., Soegiarto A., Soegiarto K. A., Rosengen N. (eds), LIPI, Jakarta, pp. 66-82.

Nordhaus I., Toben M., Fauziyah A., 2019 Impact of deforestation on mangrove tree diversity, biomass and community dynamics in the Segara Anakan lagoon, Java, Indonesia: A ten-year perspective. *Estuarine, Coastal and Shelf Science* 227:106300.

Olive C. A., 1997 Land use change and sustainable development in Segara Anakan, Java, Indonesia. Thesis, University of Waterloo, Ontario, Canada, 266 p.

Prayudha B., Siregar V., Ulumuddin Y. I., Suyadi, Prasetyo L. B., Agus S. B., Suyarso, Anggraini K., 2021 The application of Landsat imageries and mangrove vegetation index for monitoring mangrove community in Segara Anakan Lagoon, Cilacap, Central Java. IOP Conference Series: Earth and Environmental Science 944:012039.

Purba M., 1991 Impact of high sedimentation rates on the coastal resources of Segara Anakan, Indonesia. Proceedings of the ASEAN/US Technical Workshop “Toward an Integrated Management of Tropical Coastal Resources”, Singapore, pp. 143-152.

Ramdani F., Rahman S., Giri C., 2018 Principal polar spectral indices for mapping mangroves forest in South East Asia: study case Indonesia. International Journal of Digital Earth 12(10):1103-1117.

Reichel C., Frömming U. U., Glaser M., 2009 Conflicts between stakeholder groups affecting the ecology and economy of the Segara Anakan region. Regional Environmental Change 9:335.

Romimohtarto K., Hutagalung H., Razak H., 1991 Water quality of Segara Anakan-Cilacap (Central Java, Indonesia) with a note on lagoon fisher. Proceedings of the ASEAN/US Technical Workshop “Toward an integrated management of tropical coastal resources”, Singapore, pp. 131-142.

Rosa I. M. D., Purves D., Carreiras J. M. B., Ewers R. M., 2014 Modelling land cover change in the Brazilian Amazon: temporal changes in drivers and calibration issues. Regional Environmental Change 15:123-137.

Sari L. K., Adrianto L., Soewardi K., Atmadipoera A. S., Hilmi, E., 2016 Sedimentation in lagoon waters (Case study on Segara Anakan Lagoon). AIP Conference Proceedings 1730:080002.

Sastranegara M. H., Yuwono E., Sukardi P., 2007 [Illegal logging of mangroves at the Segara Anakan Cilacap, Java, Indonesia: A conservation constraint]. In: [Synopsis of ecological and socio-economic aspects of tropical coastal ecosystem with special reference to Segara Anakan]. Yuwono E., Jennerjahn T., Sastranegara M. H., Sukardi P. (eds), Research Institute of the University of Jenderal Soedirman, Purwokerto, Indonesia, pp. 21-27. [In Indonesian].

Sukardjo S., Yamada I., 1992 Biomass and productivity of a *Rhizophora mucronata* Lamarck plantation in Tritih, Central Java, Indonesia. Forest Ecology and Management 49(3-4):195-209.

Supriatna S., Purwadhi S. H., Purwanto A. D., 2018 The spatial dynamics model of mangrove forest changes in Segara Anakan, Cilacap. AIP Conference Proceedings 2023:020189.

Suwarso, Wasilun, 1991 The crab fishery around the mangrove areas of Segara AnakanCilacap, Java, Indonesia. Proceedings of the ASEAN/US Technical Workshop

"Toward an integrated management of tropical coastal resources", Singapore, pp. 57-60.
Syakti A. D., Demelas C., Hidayati N. V., Rakasiwi G., Vassalo L., Kumar N., Prudent P., Doumenq P., 2015 Heavy metal concentrations in natural and human-impacted sediments of Segara Anakan Lagoon, Indonesia. Environmental Monitoring and Assessment 187:4079.
Tomlinson P., 2016 The botany of mangroves. 2nd Edition. Cambridge University Press, 419 p.
Wang L., Jia M., Yin D., Tian J., 2019 A review of remote sensing for mangrove forests: 1956-2018. Remote Sensing of Environment 231:111223.
Winarso G., Purwanto A. D., 2014 Evaluation of mangrove damage level based on Landsat 8 image. International Journal of Remote Sensing and Earth Sciences 11(2):105-116.
Yuwono E., Jennerjahn T., Nordhaus I., Riyanto E., Sastranegara M., Pribadi R., 2007 Ecological status of Segara Anakan, Indonesia: A mangrove-fringed lagoon affected by human activities. Asian Journal of Water, Environment and Pollution 4(1):61-70.
*** ADB, 2006 Indonesia: Segara Anakan conservation and development project. Asian Development Bank (ADB), Completion report, 51 p.
*** ASEAN/US CRMP, DGF, 1992 The integrated management plan for Segara Anakan-Cilacap, Central Java, Indonesia. ICLARM Technical Report 34, 100 p.

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