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ORIGINAL RESEARCH PAPER

# Ecological features of mangroves as indicators of seawater intrusion

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**ABSTRACT**

**BACKGROUND AND OBJECTIVES:** Water filters are important ecosystem services in mangroves, playing an essential role in mitigating seawater intrusion and groundwater water management. However, ecological features that can be used as indicators of seawater intrusion in mangroves and the extent of mangroves' role in groundwater quality management in coastal areas are not well identified. This study aimed to determine mangroves ecological features that can serve as indicators of seawater intrusion.

**METHODS:** A geographic information system and geo-electric method were used, and remote sensing, vegetation survey, sample collection, and interview survey were performed.

**FINDINGS:** Seawater intrusion is the major problem affecting groundwater quality in coastal areas, especially mall islands. A structural equation model revealed that mean mangrove patch thickness, mean mangrove patch density, soil resistivity, soil porosity, and tree density explained 80–95 percent of the variation in seawater intrusion during wet and dry seasons in the entire study area. Seawater intrusion decreased with increasing mean patch thickness of the mangrove but increased with increasing mangrove patch density. That is, the landscape metrics of mangroves, such as mangrove patch thickness and density, were associated with type when substrate or soil and tree density were good ecological indicators of seawater intrusion. Using landscape metrics as ecological indicators is a relatively quick, cheap, and easy-to-apply method.

**CONCLUSION:** This study pioneers the use of novel landscape metrics—mean patch thickness and patch density—as ecological indicators of seawater intrusion, providing a quantitative framework that bridges mangrove structural attributes, soil characteristics, and collective influence on groundwater salinity regulation.

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## INTRODUCTION

Groundwater is the primary source of fresh water for the residents of small islands. Fresh water is essential for human life and their activities, such as drinking, bathing, washing, and cleaning, various industries, and agriculture (Shang *et al.,* 2016; Abbasnia *et al.,* 2018; Mello *et al.,* 2018). Water demands for food production, industry, and basic needs have increased (Shang *et al.,* 2016; Gohar *et al.,* 2018). Land use change and associated pollution are affecting groundwater quality, presenting a growing challenge, particularly for small-island-developing states (SIDSs), which were recognized in 1992 at the Earth Summit in Rio de Janeiro, Brazil (Gheuens *et al.,* 2019). According to the United Nations member states, SIDSs comprise 38 states, including Indonesia. As an archipelagic state, Indonesia consists of 17,504 islands, 77 percent (%) of which are categorized as small islands <2000 square kilometers ($km^2$) in size and most of which are located in eastern Indonesia, including Ambon Island (Lukman, 2021). Small islands are characterized by limited groundwater resources. They are generally vulnerable to environmental and socio-economic change and considerably affected by climate change (Gohar *et al.,* 2018; Gheuens *et al.,* 2019). The most common environmental threats to groundwater resources in coastal regions are seawater intrusion and anthropogenic pollution (Kura *et al.,* 2015; Vann *et al.,* 2020). Seawater intrusion is the landward incursion of seawater, seeping into terrestrial groundwater supplies and increasing salinity (Hilmi *et al.,* 2017). Population growth (and associated changes in land use), change in precipitation patterns, and sea-level rise are all drivers of seawater intrusion. Threats to groundwater supplies likely increase because of the continued expansion of urban settings, coastal development, and climate change (Ketabchi *et al.,* 2016; Gheuens *et al.,* 2019; Vann *et al.,* 2020). The potential impact can be devastating to small-island communities, which are subjected to many health problems, increased poverty, human capital loss, and unstable socio-economic and political platforms (Gheuens *et al.,* 2019). Thus, accessible indicators of saltwater intrusion should be identified to support timely and effective management strategies aimed at strengthening water security. As archipelagic states, SIDSs are typically characterized by long coastlines. Indonesia has the second longest coastline as 99,093 kilometers (km) in the world and a large coastal area (Aldrian, 2008; Setiawan *et al.,* 2016). This tropical coastal area is a suitable habitat for mangroves, making Indonesia the largest habitat of mangroves in the world (3,112,989 ha or 23%) and providing habitat for 67% of the world's true mangrove species (Noor *et al.,* 2006; Giri *et al.,* 2011;Thomas *et al.,* 2017). Mangrove forests provide a wide range of valuable ecosystem services (Duke *et al.,* 2007), control biogeochemical cycles, help to reduce pollutant loading, contribute to coastal nutrient cycles, and provide shoreline protection (Nguyen *et al.,* 2012; Lagomasino *et al.,* 2014; Santos *et al.,* 2014; Xiao *et al.,* 2019). Mangroves thrive at seawater–freshwater interfaces and are valuable mitigators of saltwater intrusion into terrestrial groundwater. The site-specific coverage of mangroves and associated vegetative metrics may provide insights into the risk of saltwater intrusion. Hilmi *et al.* (2017) established the importance of mangroves in mitigating seawater intrusion but did not quantify how structural characteristics, such as patch thickness, influence this process. Xiao *et al.* (2019) highlighted mangroves' role in nutrient cycling but lacked a focus on groundwater salinity regulation. As such, further study is required to explore the influence of geomorphic factors and correlations among mangrove metrics to develop a protocol for identifying sites of high risk to saltwater intrusion. Mangrove habitats can be described or categorized using vegetative and landscape metrics (Horstman *et al.,* 2018; Suyadi *et al.,* 2018a; Damayanti *et al.,* 2020). "Patch size" is the smallest level of heterogeneity in a landscape, which is commonly used in spatial metric analysis. It is defined as a single block of pixels that are spatially connected to each other (McGarigal *et al.,* 2012). A "forest patch" is commonly used as a proxy to assess forest degradation and fragmentation (Riitters *et al.,* 2000). Landscape metrics, such as patch size and shape index, are influenced by the characteristic and distribution of sediments or mangrove substrates (McGarigal *et al.,* 2012; Suyadi *et al.,* 2018a). Seawater intrusion is commonly detected using geo-electrical resistivity surveys or by collecting groundwater from wells. Well water sampling collects detailed information on salinity level and freshwater–seawater interactions (Chen *et al.,* 2018; Vann *et al.,* 2020). Seawater intrusion is influenced by soil properties, such as soil texture (gravel, sand, silt, and clay). The rate of organic matter breakdown is

then linked to microbial activity, which in turn can be altered by seawater intrusion (Weston *et al.,* 2011). Furthermore, mangrove zonation and distribution are influenced by soil type (Duke *et al.,* 2007; Suyadi, 2009). Interactions among soil type, biogeochemical cycles, and mangrove habitat characteristics imply that these ecological indicators should be identified and the extent of mangroves' role in mitigating seawater intrusion should be further assessed. A combination of remote sensing (RS), vegetation field surveys, geo-electrical resistivity survey, soil sampling, and water sampling was used in achieving these objectives, providing a suite of ecological indicators that can be readily mapped, and assessing locations at high risk of saltwater intrusion. In addition, strategies for managing water and coastal areas and mitigating seawater intrusion for small-island communities have been enhanced. This study addresses these gaps by developing and validating specific landscape metrics as indicators of seawater intrusion and exploring their interaction with substrate properties to provide a mechanistic understanding of mangrove functionality in groundwater salinity regulation. The aim of this study is to identify the key ecological indicators of seawater intrusion and to assess the role of mangrove in limiting seawater intrusion in a small island setting. The specific objectives of the study are as follows: 1) to assess the relationship between mangrove landscape metrics and soil properties (soil texture, soil resistivity, and soil porosity) and determine any correlation with terrestrial groundwater salinity (seawater intrusion) in wet and dry seasons and 2) to assess and map the health and spatial characteristics of fringing mangrove forests around Ambon Bay and the water quality and extent of seawater intrusion of groundwater in coastal areas. This study was conducted in Ambon Bay, Maluku, Indonesia, in 2022.

## MATERIALS AND METHODS

### *Study area*

Ambon is a small island (80,390 ha; located in eastern Indonesia; 3° 46′ 07.6′′ S, 127° 56′ 26.4′′ E to 3° 31′ 16.7′′ S, 128° 21′ 07.5′′ E). It is the capital city of Maluku Province and the most populated island in the eastern part of Indonesia. Most of the population lives in the coastal area surrounding Ambon Bay and mostly concentrated to the north and south of the bay (Fig. 1). Ambon Bay consists of Inner Ambon Bay (IAB)

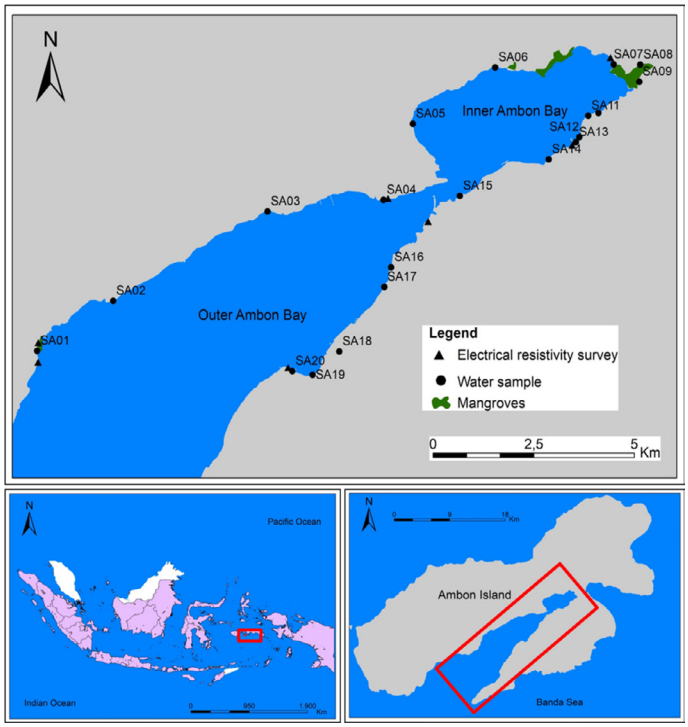


Fig. 1: Geographical location of the study area in Ambon Bay, Maluku, Indonesia

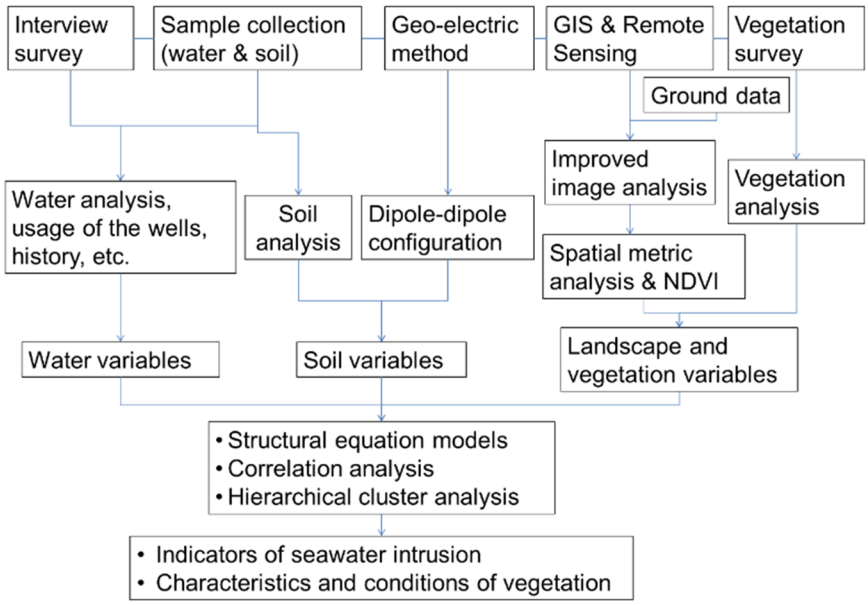


Fig. 2: Combination of some methods applied in this study to achieve the objectives.

and Outer Ambon Bay (OAB). IAB is a semiclosed bay separated by a shallow and narrow sill, and OAB is an open bay and directly connected to Banda Sea. The tide in Ambon Bay (IAB and OAB) ranges from 0.28 m to 2 meters (m) (mean, 1.01 m), with tidal currents of 8.3–29 cm at low tide and 9.0–50.0 cm/s at high tide. Water temperatures in Ambon Bay (IAB and OAB) fluctuate between 27.7 °C and 31.2 °C (mean, 30.5 °C), and salinity is 33.3–34.2 per mille (‰; mean, 33.78 ‰). Tide height, current, and salinity in IAB are lower than those in OAB (Gemilang *et al.,* 2017; Ondara *et al.,* 2017). Mangrove habitat is mostly concentrated in IAB because of marine conditions (e.g., current, tidal), and the geomorphological condition of IAB is more suitable for mangroves (Suyadi, 2009).

*Data and sample collections*

The study applied a geographic information system (GIS) and a range of methods, such as RS, vegetation surveys, geo-electric mapping, and sample (water and soil) collection followed by interview surveys (Fig. 2), which are required in obtaining spatial data, soil- and water-related data, vegetation, soil resistivity, porosity, and interview data from owners or users of wells.

Sentinel-2 satellite images from 2022 were combined with field mapping using global positioning system (GPS) tracking from 2019 for the generation of a raster dataset of mangroves. An improved image analysis method was applied, which used a combination of integrated parametric (maximum likelihood classification) and nonparametric classifiers (knowledge-based classification; Suyadi *et al.,* 2018b). In image processing, atmospheric correction was first implemented, followed by positional correction and image classification using supervised classification methods: parametric classifier of maximum likelihood classification and nonparametric classification of knowledge-based classification (Suyadi *et al.,* 2018b). This supervised classification, which is recently known as artificial intelligence (AI) or machine learning (ML), require field data for training samples. This classification method was selected because ground data for training samples were available and the method is simple to implement and results in high accuracy. Other image classification methods that incorporate advanced technologies, such as AI, ML, random forest, support vector machines, convolutional neural networks, recurrent neural networks, long short-term memory, and enhanced mangrove index can be applied for image classification but are unsuitable for this study because of the relatively low variation in mangrove vegetation and because the objectives

of the study are extremely complicated. Field data, such as vegetation characteristics and vegetation conditions, were used in determining training samples. Image classification accuracy was assessed using Kappa accuracy followed by field validation, and the ground-truth data of plots and drones were used. The ground-truth data were obtained from 42 sampling points (15 plots and 27 drone data), and drone and sampling plots were circular with diameters of 30 m. Data collected from the plots were GPS coordinates, mangrove species, number of trees, diameter breast height (DBH), canopy coverage, stratum coverage, and photographs. Positional error correction, atmospheric correction, classification correction, and Monte Carlo analysis (Suyadi *et al.,* 2018b) were applied to minimize classification error and to quantify image classification. The raster dataset of mangrove characteristics was exported to Fragstats 4.1. in Geotiff format, and the landscape metrics of mangrove patches were derived. Five landscape metrics were mapped: mean patch size, patch density, mean patch thickness, mean shape index, and largest patch index. These landscape metrics were selected because they are commonly used as spatial indicators for forestry ecological studies, especially for the assessment of forest degradation and fragmentation (Manson *et al.,* 2003; Vaz, 2014; Barau and Qureshi, 2015; Bryan-Brown *et al.,* 2020). The land cover map-2022 was provided by the Ministry of Environment and Forestry of the Republic of Indonesia. The study collected vegetative data from sixty-five 10 m × 10 m mangrove plots. The plots were located along line transects extending toward the sea and extension of the mangrove forest. The plots were 20 m apart along the line transect, and variation in vegetation was captured. The ground-truth plot, line transects (vegetation plots), water wells, and soil sampling points were selected using purposive random sampling, and the following parameters were used: variation in mangrove patch size, variation in vegetation, well age, well depth, and distance from shoreline. Geological map, land cover map, exisiting wells, and knowledge of salinity issue were incorporated for the selection of the point sampling location through purposive random sampling. Each mangrove within a plot was identified to species then measured for DBH at 1.3 m above the ground, tree height, and canopy coverage. Photographs of canopies were taken in nine points inside each plot, and canopy coverage was assessed using ImageJ software. A digital protractor was used in measuring the top tree angle from 10 m distance to the tree and then converted into tree height by using basic trigonometry. Fieldwork and sample collection were conducted between October and December 2020. Water samples were collected from 20 wells around Ambon Bay, which is located less than 200 m from the coastline (Fig. 1). Most of the wells are conventional wells (17), and only three are drilled wells. At the time of sampling, an interview survey was conducting on 20 well owners, and additional information about water color and taste, history, and usage of the wells was obtained. All of the wells are still used by the owners for washing and bathing, and nine wells are used for drinking. The depth of the wells ranges from 1 m to 32 m (mean, 6.85 m) and are located 0–4 m above sea level (masl; mean, 2.2 masl). The age of the wells was between 1 and 90 years (mean, 37 years). Water samples (20 samples) were analyzed in a certified Balai Teknik Kesehatan Lingkungan Laboratory (Registration No. 0022/LPJ/LABLING-1/LRK/KLH from Ministry of Environment and Registration No. LP-241-IDN from National Accreditation Committee). Twelve water quality parameters were measured (Regulation of Ministry of Health No. 32; 2017): salinity, total dissolved solids (TDSs), turbidity, iron, detergent, mineral content, nitrate, manganese, pH, temperature, flavor, and smell. Salinity was measured during the wet and dry seasons to determine seasonal influence on seawater intrusion. Soil samples (85 samples) were collected from plots along the transects and in the bottom of the wells at 0.5 m depth. Fresh soil samples were weighed and dried in an oven at 60 °C until a constant weight was reached. Using the method proposed by Hao *et al.* (2008), we calculated the porosity on the basis of particle density and bulk density. Resistivity data were extracted from field data and data extrapolated using geological maps (Saad *et al.,* 2012; Tjokrosapoetro *et al.,* 1993). Field measurements of resistivity (electrical resistivity) were performed using a single-channel resistivity meter, geo-electric method, and dipole–dipole configuration (Amukti *et al.,* 2023; Damayanti *et al.,* 2020). Measurements were obtained at 11 locations in the study site (Fig. 1), where the transects were perpendicular to the coastline. The transect length was 50–100 m. Electrode recordings were obtained at 10 m intervals

along each transect, and the penetration depth was 25 m. A single-channel resistivity meter used in this study was calibarated regularly before used in the field. In addition, the data are also compared and calibarated with other data (Amukti *et al.,* 2023; Damayanti *et al.,* 2020) and geological map to minimize potential error of resistivity measurements.

*Data analysis*

Prior to statistical analysis, mangrove landscape metrics data were normalized using the Min-Max normalization approach (Patro and Sahu, 2015). In addition, principal component analysis followed by penalized regression by selection and exclusion of multicorrelated variables were applied to minimize multicollinearity. Normalized difference vegetation index (NDVI) was used in categorizing mangrove health with the method describbted by Rotua (2017), based on the ratio of infrared and red band (Green *et al.,* 1998). Vegetation characteristics, including species composition, vegetation structure, zonation, and important value index, were calculated using a formula developed by Cox (1967). On the basis of the standard protocol published by the Ministry of the Environment Republic of Indonesia No. 201 (2004), the status of mangrove vegetation health was determined using tree density and canopy coverage (Dharmawan and Pramudji, 2017). Spearman rank correlation analysis was conducted to assess the correlation of dependent variables (salinity at dry and wet season) with independent variables related with the landscape metrics of mangrove, vegetation, and substrate or soil. Spearman rank correlation analysis was selected because it can measure nonlinear correlation for ordinal data and data with non-nomal disrtribution. Structural equation models (SEMs) were applied to determine the relationship between seawater intrusion (salinity during dry and wet seasons) and independent variables. SEMs are extensions of the general linear model that allows for the simultaneous testing of regression equations and can be used to assess the direct, indirect, and total effects of predicted variables (Schreiber *et al.,* 2006). Thus, SEMs are suitable for quantifying the direct and indirect effects of mangrove metrics and soil properties on seawater intrusion, providing a nuanced understanding of their interactions. Seawater intrusion variables (water salinity at dry and wet season) were grouped through hierarchical cluster analysis, and any relationship with measured independent variables was explored. Kruskal–Wallis test, followed by a Bonferroni post-hoc test, was applied to identify considerable differences in seawater intrusion variables (salinity at dry and wet season) and independent variables among seawater intrusion variables. Lastly, linear regression analysis was applied to assess the relationship between seawater intrusion and independent variables across the groups. Linear regression was suitable with data and can be used to identify key relationship between variables with complex interaction and multiple factors. Interview data were analyzed, and data cleaning was performed by meticulously reading the transcripts. The content, review, and refine themes were comprehensively examined, categorized, and coded, and the results were interpreted. Then, the interview data were used in confirming water and soil sample data.

## RESULTS AND DISCUSSION

*Groundwater quality and seawater intrusion*

In the clean water quality standard provided by the Indonesian Ministry of Health (No. 32, year 2017), groundwater quality in the study area was considered within acceptable levels, except water salinity, especially in the dry season (Table 1). The physical and chemical parameters of ground water, such as turbidity, pH, temperature, flavor, smell, TDS, iron, detergent, mineral content, nitrite, and manganese area were within the range of the clean water quality standard. That is, the groundwater in the study area was relatively unpolluted, but seawater intrusion was observed. This result was confirmed by interview data, which showed that the owner of wells (respondents) still use the water from the wells for washing and bathing. Few well owners used water from the wells for drinking because of seawater intrusion. Another study showed that the quality of water around IAB is within the range of the clean water quality standard, but a water sample from Batumerah Village was contaminated by *Escherichia coli* and had a high total coliform value (Uyara *et al.,* 2017).

Seawater intrusion (water salinity) in 80% of the wells sampled in this study exceeded the clean water quality standard (Table 1). Seawater intrusion increased during the dry season, ranging from 0.29 ppt to 7.4 ppt (mean, 3.51 ± 0.57 ppt) compared with that in the wet season when salinity ranged from

Table 1: Groundwater quality around the study area in Ambon Bay, Maluku

| Parameters of water quality | Mean | Min | Max | Quality standard* |
|---|---|---|---|---|
| Salinity at dry season In part per thousand (ppt) | 3.51 ± 0.57 | 0.29 | 7.4 | <0.5 |
| Salinity at wet season (ppt) | 0.25 ± 0.04 | 0.009 | 0.74 | <0.5 |
| Total dissolved solids Miligram per liter (mg/L) | 259.65 ± 39.3 | 29.1 | 780 | <1000 |
| Turbidity Nephelometric turbidity units (NTUs) | 1.55 ± 0.39 | 0.5 | 6.03 | <25 |
| Iron (mg/L) | 0.21 ± 0.07 | 0.033 | 1.007 | <1 |
| Detergent (mg/L) | 0.01 ± 0.002 | 0.001 | 0.036 | <0.05 |
| Mineral content $CaCo_3$ (mg/L) | 147.9 ± 21.82 | 68 | 433 | <500 |
| Nitrite (mg/L) | 0.036 ± 0.03 | 0.002 | 0.47 | <1 |
| Manganese (mg/L) | 0.107 ± 0.033 | 0.035 | 0.53 | <0.5 |
| pH | 6.9 ± 0.3 | 6.5 | 7.4 | 6.5–8.5 |
| Temperature | 28.1 ± 0.88 | 26.1 | 29.7 | Air temperature ± 3 |
| Flavor | No taste | No taste | No taste | No taste |
| Smell | No smell | No smell | No smell | No smell |

*Regulation of Ministry of Health No. 32 year 2017

0.009 ppt to 0.74 ppt (mean, 0.25 ± 0.04 ppt; Fig. 3). Some wells in the south of Ambon Bay and Tawiri (SA1) showed the above guideline values of salinity in both seasons. By contrast, seawater intrusion in Passo (SA8 and SA9), Negeri Lama (SA7), and Waiheru (SA6) were consistently within the acceptable salinity levels for both seasons, whereas other sites showed low salinity (e.g., Passo, Negeri Lama, and Waiheru), which were dominated by mangrove vegetation. This result is in line with spatial data, which showed that south of Ambon Bay had high seawater intrusion in the wet and dry seasons (Fig. 3). Many factors associated with seawater intrusion include dry and wet seasons, forest vegetation, especially mangroves, fresh ground water exploitation, and increase in sea level (Hilmi *et al.,* 2017; Ketabchi *et al.,* 2016; Pires *et al.,* 2017; Tamrin *et al.,* 2021).

This study showed that groundwater resources around Ambon Bay are already impacted by seawater intrusion. Seawater intrusion is one of the most important challenges for water security in many small island (Kura *et al.,* 2015; Gohar *et al.,* 2018; Chen *et al.,* 2018; Gheuens *et al.,* 2019; Vann *et al.,* 2020). Seawater intrusion occurs in other small islands in Indonesia and across the world, for example, Kadatua Island, Sulawesi, Indonesia (Tamrin *et al.,* 2021); Poteran Island, East Java, Indonesia (Tatas *et al.,* 2015); Kamala Beach, Phuket, Thailand (Vann et al., 2020); Kinmen, Xiamen, islands between China and Taiwan (Chen *et al.,* 2018); and Kapas Island, Trengganu, Malaysia (Kura *et al.,* 2015). Small island developing states was identified as high risk states for seawater intrusion which can increase vulnerability to disaster and socio-economic stability (Gheuens *et al.,* 2019; Gohar *et al.,* 2018). Seawater intrusion impacts not only groundwater quality but also groundwater quantity (Tamrin *et al.,* 2021).

*Correlation of seawater intrusion with the landscape metrics of mangroves*

Image classification showed that the total mangrove area around Ambon Bay was 57.206 ha. The accuray of image classification was 89%, the kappa value was 0.887, and the validation value was 86.7%, all demonstrating that the accuracy of images classification in this study was high (>75%). In addition, 86.7% of the image classification matched the ground data. The uncertainty of image classification was relatively low (6%) because of the this study's improved image analysis method, which increased accuracy and minimized uncertanty to up to 67% relative to that of traditional image analysis (Suyadi *et al.,* 2018b). Mangrove vegetations were distributed in Passo (36,295 ha), Waiheru (13,948 ha), Negeri Lama (2293 ha), and small mangrove patches in the north of Ambon Bay (Fig. 4). Similarly, the area of mangroves in Ambon Bay in 2017 was 57.261 ha and was mainly distributed in the same locations as this study (Rotua, 2017). NDVI analysis produced mangrove vegetation index values of between −0.07

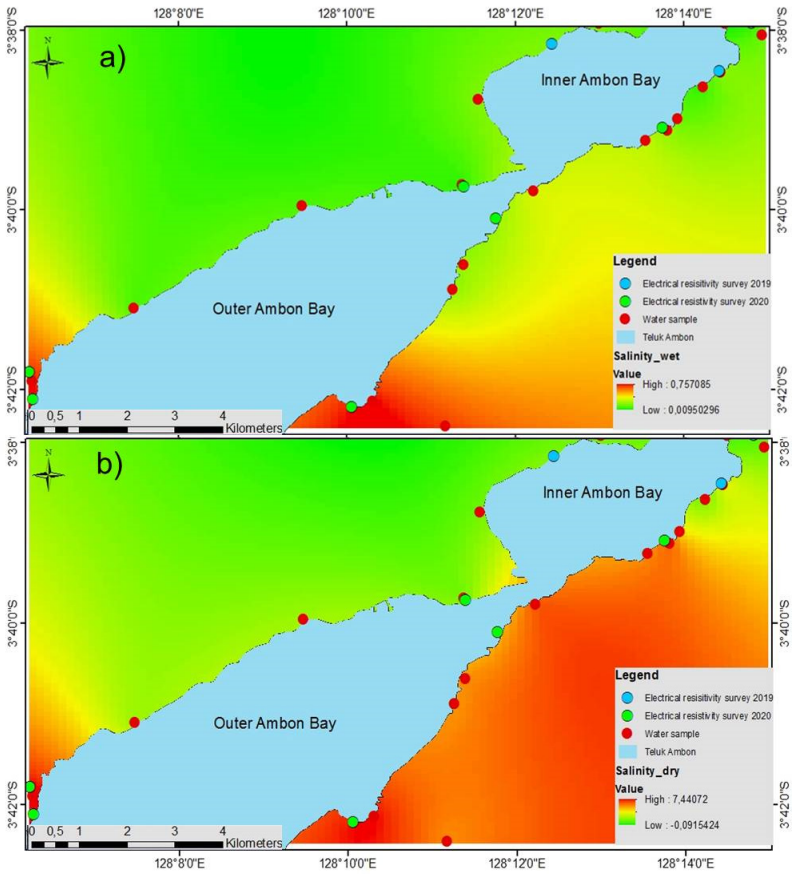


Fig. 3: Seawater intrusion (salinity) during wet season (a) and seawater intrusion during dry seson (b) accros Ambon bay, Maluku

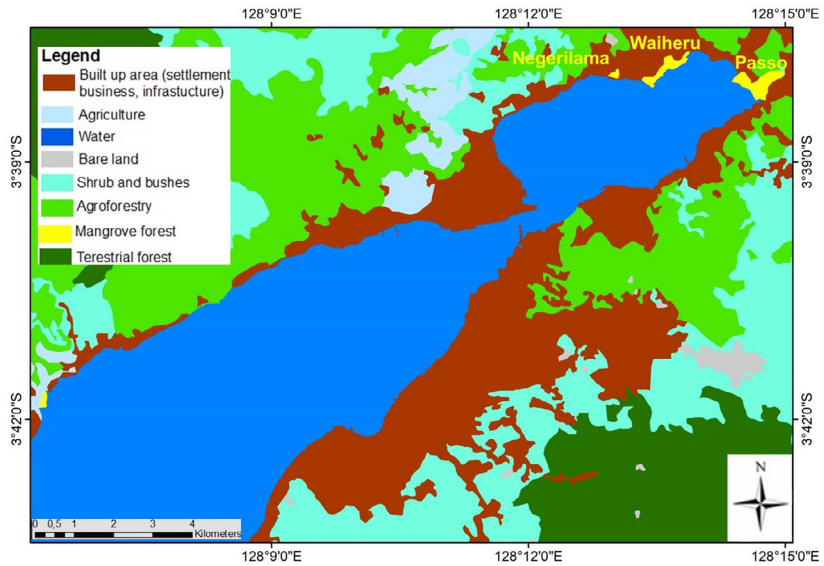


Fig. 4: Mangrove areas and other land cover around Ambon Bay, Maluku

Table 2: Correlation of landscape metrics with seawater intrusion (salinity) during dry and wet season.

| Predictors | Mean | Spearman (*rho*) Correlation | |
|---|---|---|---|
| | | Salinity at dry season | Salinity at wet season |
| Mean patch thickness of mangrove (m) | 69.82 ± 12.69 | −0.85* | −0.53** |
| Patch density of mangrove (n/ha) | 0.03 ± 0.02 | 0.62* | 0.61* |
| Mean patch size of mangrove (ha) | 0.66 ± 0.24 | −0.55* | −0.45** |
| Mean shape index of mangroves | 2.22 ± 0.58 | 0.56* | 0.52* |
| Largest patch index of mangrove | 0.89 ± 0.43 | −0.54* | −0.48** |

*p ≤ 0.01; **p 0.01–0.05

and 0.5 with the highest vegetation index (dense mangroves) measured in Passo, Waiheru, and Negeri Lama. This finding is supported by a previous study showing similar NDVI ranges, that is, the highest vegetation index values were found in Passo, Waiheru, and Negeri Lama (Amukti *et al.,* 2023; Rotua, 2017). Land cover around Ambon Bay was mostly composed of built-up areas followed by agroforestry areas, shrublands, bare lands, and agricultural lands (Fig. 4). Most of the built-up areas were around the coastal area of Ambon Bay, and agroforestry was mostly located in hilly and sloping areas.

Analysis of mangrove landscape metrics showed that the mangroves were predominant in the small patches (mean patch size, 2.66 ± 4.24 ha) and narrow bands along the coastline (mean patch thickness: 69.82 ± 12.69 m). The size of the mangrove patches in Ambon Bay was similar to the size of the mangrove patches in other small islands, such as Karimunjawa, Java, and Batam, Sumatra (KLHK, 2023) but much smaller than the mangrove patches in large islands in temperate regions, such as Auckland, New Zealand (Suyadi *et al.,* 2018a), and tropical regions, such as in Kubu Raya, Kalimantan and Sembilang National Park, Sumatra (KLHK, 2023). Spearman correlation analysis revealed a negative correlation between well water salinity (seawater intrusion) and mangrove mean patch thickness, and the density of mangrove patches was positively correlated with salinity ($p \leq 0.01$). Water salinity in the dry and wet seasons was low at a large mean mangrove patch thickness and increases with mangrove patch density (Table 2). Mean patch thickness ranged from 40.8 m to 540.5 m (mean, 69.82 ± 12.69 m), and patch densities were 0.01–2.4 patches per hectare (mean 0.03 ± 0.02 patches per hectare). The other landscape metrics, that is, mean (mangrove) patch size and largest patch index, showed a negative correlation with salinity, whereas mean patch shape index showed positive correlations (Table 2). Mangrove patch thickness likely reduces saline water ingress by increasing surface roughness and hydrodynamic resistance. The field study using transects revealed that the thickness or width of mangrove vegetation is significantly corelated with seawater intrusion (Damayanti *et al.,* 2020). An equation model also showed that the width of mangrove greenbelt explained 97% of the seawater intrusion (Hilmi *et al.,* 2017).

*Correlation of seawater intrusion with mangrove vegetation and its substrate*

Field surveys (transects) recorded 15 true mangrove species and one species of mangrove-associated species around Ambon Bay. Most of the mangrove stands in the study area do not display mangrove zonation, except Passo. The landward zone of mangroves in Passo were dominated by nypa (*Nypa fruticans*), and the middle and fringe (seaward) zones were dominated by true mangroves, such as *Rhizopohora* sp., *Excoecaria agallocha*, and *Sonneratia* sp. Mangrove tree density averaged across all sites was 655 stem/ha, and the mean canopy coverage was 19%. High tree density and canopy coverage were measured at Negeri Lama (the highest), Passo, and Waiheru (Table 3). The most dominant species were *Rhizopohora apiculata* (important value index: 60.8%) and *Sonneratia alba* (important value index 19.9%). These two species were distributed across all of the study sites around Ambon Bay, except Tawiri, which was dominated by *Excoecaria agallocha* (important value index, 72.5%). The mean DBH of mangroves was 14.2 ± 12.7 cm, and the mean tree height was 7.8 ± 4.5 m. Compared with another study (Suyadi 2009), the species composition and structure of mangrove vegetation in Ambon Bay within 15 years (2008–2023) were relatively

Table 3: Characteristics and conditions of mangrove vegetation in Ambon Bay, Maluku

| Sites | Canopy coverage (%) | Mangrove density (stem/ha) | Health status* | Mean tree diameter (cm) | Mean tree height (m) | Important index | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min. | Max. |
| Passo (SA8) | 17 | 1450 | Moderate | 19.1 ± 9.9 | 9.8 ± 3.4 | *Brugruiera parviflora* (BP): 11.8 | SA: 77.1 |
| Waiheru (SA6) | 16 | 1433 | Moderate | 10.8 ± 5.4 | 6.6 ± 2.1 | *Rhizopohora stylosa* (RS): 5.4 | *Rhizopohora apiculata* (RA): 86.2 |
| Negeri lama (SA7) | 20 | 1580 | Moderate | 11.8 ± 5.1 | 6.2 ± 2.3 | *Ceriops tagal* (CT): 3.8 | RA: 58.9 |
| Halong (SA13) | 14 | 503 | Poor | 8.8 ± 3.1 | 5.1 ± 2.1 | BP: 4.1 | RA: 88.1 |
| Rumah tiga (SA4) | 13 | 526 | Poor | 9.1 ± 3.5 | 5.4 ± 2.3 | RS: 1.8 | RA: 78.9 |
| Tawiri (SA1) | 15 | 243 | Very poor | 16.2 ± 10 | 7.8 ± 2.9 | *Sonneratia alba* (SA): 25.1 | *Excoecaria agallocha* (EA): 72.5 |
| OSM (SA19) | 12 | 108 | Very poor | 5.8 ± 2.4 | 4.5 ± 2.7 | RS: 3.1 | RA: 87.2 |

*Regulation of Ministry of Environment No 201 year 2004

Table 4: Correlation of mangrove vegetation and substrate (soil) with seawater intrusion (salinity) during dry and wet season

| Predictors | Mean | Spearman (*rho*) Correlation | |
|---|---|---|---|
| | | Salinity at dry season | Salinity at wet season |
| Soil resistivity (Ω) | 35.20 ± 26.67 | −0.90* | −0.76* |
| Soil porosity (%) | 16.84 ± 5.35 | 0.87* | 0.73* |
| Tree density (stem/ha) | 655 ± 32 | 0.55* | 0.53* |
| Canopy coverage (%) | 19 | 0.46 | 0.43 |
| Tree high (m) | 7.8 ± 4 | 0.42 | 0.39 |
| Tree diameter (cm) | 14.2 ± 12.7 | 0.44 | 0.41 |

*p ≤ 0.01; **p 0.01–0.05

unchange.

Plants (vegetation) play an important role in slowing groundwater flow, filtering pollutants, and seawater intrusion (Tatas *et al.,* 2015; Hilmi *et al.,* 2017; Pires *et al.,* 2017; Xiao *et al.,* 2019; Ding *et al.,* 2020). Root biomass and roots depth of healthy mangrove described groundwater balance and seawater intrusion (Damayanti *et al.,* 2020; Tatas *et a*l., 2015). Mangrove forests dominated by *Avicennia marina*, *Avicennia alba*, *Rhizophora styllosa*, *Sonneratia alba*, and *Sonneratia caseolaris* have the capability to reduce seawater intrusion (Hilmi *et al.,* 2017). Correlation analysis of this study showed that only tree0 or stem density is slightly correlated with seawater intrusion or water salinity (Table 4). Other vegetation parameters do not correlate with seawater intrusion but is correlated with tree or stem density.

Significant correlations were found between seawater intrusion and substrate of mangroves or soil parameters (soil resistivity and porosity). Soil resistivity was negatively correlated with salinity, whereas soil porosity showed a positive correlation (Table 4). The strength of these correlations was higher in the dry season compared than in the wet season. Soil resistivity was spatially variable, ranging from 0.2 Ω to 75.5 Ω (mean, 35.20 ± 26.67 Ω), as was soil porosity, measuring between 7.7% and 25.9% (mean, 16.84% ± 5.35%). Soil resistivity values were greater at the north of Ambon Bay. Similarly, vegetation cover, especially mangroves, was comparatively higher in the northern regions of Ambon Bay compared with the southern bay. Soil in the north of Ambon Bay was dominated by clay and silt (mud), whereas the substrate sampled in the south of Ambon Bay was dominated by sand

and coral fragments, representing a porous sediment profile. Compared with gravel and sand, clay and silt have high resistivity to seawater and low porosity (Banton *et al.,* 1997; Meyer *et al.,* 2019; Wendroth *et al.,* 2006). The water field capacity of clay and silt are much higher (31%–42%) than sand (10%–18%; Tatas *et al.,* 2015), slowing down saltwater intrusion. Site-specific soil or sediment texture is influenced by vegetation structure and composition, geological conditions, and sedimentation (Tjokrosapoetro *et al.,* 1993; Suyadi, 2009). The root systems of mangroves enhance soil compaction, lowering porosity and permeability and thereby limiting groundwater salinization. Organic matter, such as mangrove root biomass, interacts with soil, altering its porosity and permeability (Xiong *et al.,* 2018). Soil texture in association with mangroves play an important role as a field filter for seawater intruding into groundwater.

*Ecological features of mangroves as indicators of seawater intrusion*

The SEM revealed that two landscape metrics (mean mangrove patch thickness [p = 0.01] and mean mangrove patch density [p = 0.025]), one vegetation descriptor of tree density (p = 0.025), and the two substrate or soil descriptors (soil resistivity [p = 0.001] and soil porosity [p = 0.001] explained 80%–95% of the variation in seawater intrusion in the wet and dry seasons in all study sites ($r^2$ = 0.95, p = 0.001 and $r^2$ = 0.80, p = 0.001; Fig. 5). High patch density correspond (positively correlated) with high seawater intrusion because a high patch density indicates that a mangrove forest is highly fragmented into small mangrove patches. Soil porosity in the fragmented mangrove forest is higher than nonfragmented forest or areas with good mangrove conditions (Banton *et al.,* 1997; Hilmi *et al.,* 2017; Mello *et al.,* 2018; Meyer *et al.,* 2019; Pires *et al.,* 2017; Wendroth *et al.,* 2006). The root biomass and root depth of fragmented mangrove forest (high patch density) is lower than nonfragmented mangroves. Good mangrove coniditons are high mangrove patch tickness, high tree density, and high biomass of roots associated with a mud-dominated substrate which typically shows high resistivity to seawater intrusion (Banton *et al.,* 1997; Meyer *et al.,* 2019; Wendroth *et al.,* 2006). Mean patch thickness, tree density, and soil resistivity negatively explains sea water intrusion. By contrast, mean patch density and soil porosity positively explain sea water intrusion.

The predictors (indicators) of seawater intrusion (patch thickness, patch density, tree density, soil resistivity, and soil porosity) are also explained by other parameters, such as largest patch index, mean

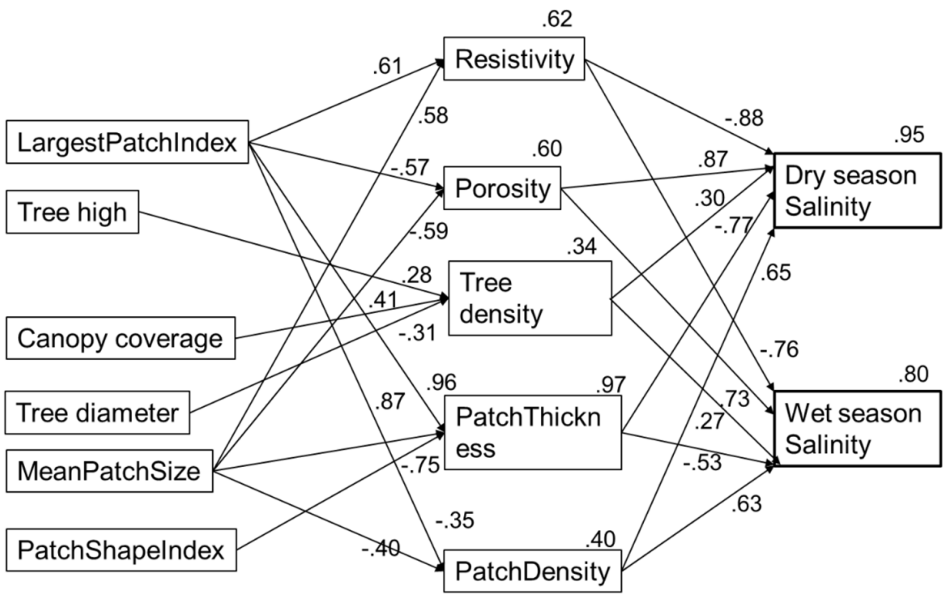


Fig. 5: Structural equation model showing the predictors (indicators) of seawater intrusion (salinity) in dry and wet seasons

patch size, patch shape index, tree height, tree diameter, and canopy coverage, which show positive and negative correlations (Fig. 5). For example, mean patch thickness was positively correlated with largest patch index and mean patch size but negatively correlated with patch shape index. Soil porosity and soil resistivity were closely linked to largest patch index and mean patch size (Fig. 5). This result indicates that patch thickness, patch density, tree density, soil resistivity, and soil porosity are the direct ecological indicators of seawater intrusion and are influenced by indirect factors or parameters. Hierarchical cluster analysis grouped seawater intrusion in the study area into three groups: groups 1 (low seawater intrusion area: mean 0.7 ± 0.4 ppt), 2 (moderate seawater intrusion area: mean 1.4 ± 0.3 ppt), and 3 (high seawater intrusion area: mean 5.5 ± 1.3 ppt; Fig. 6). This result supported by Kruskal–Wallis analysis showed that seawater intrusion in group 3 was significantly higher than those in groups 2 ($p = 0.014$) and 1 ($p = 0.018$), $\chi 2\ (2) = 8.75$, $p = 0.011$. Group 1 (low seawater intrusion area) was mostly located in the northeast of Ambon Bay, particularly in Passo, Waiheru, and Negerilama. The area is the largest habitat of mangrove in the Bay (Figs. 3 and 4). By contrast, mangrove in the south of Ambon Bay (the high seawater intrusion area/group 3) was extremely limited. The mangroves is heavily fragmented into single trees or extremely small mangrove patches.

The three groups of seawater intrusion areas (Fig. 6) corresponded with mangrove landscape metrics, mangrove vegetation, and their substrate or soil (Table 5). All the parameters of landscape metrics showed heavy mangrove fragmentation in the high seawater intrusion area (group 3), moderate fragmentation in the area of group 2, and low fragmentation in the low seawater intrusion area (group 1; Table 5). Further, vegetation analysis was performed according to the Decree of the Minister of Environment of Republik of Indonesia No. 201 (2004), which provides mangrove health standard. The condition of mangrove vegetation was moderate

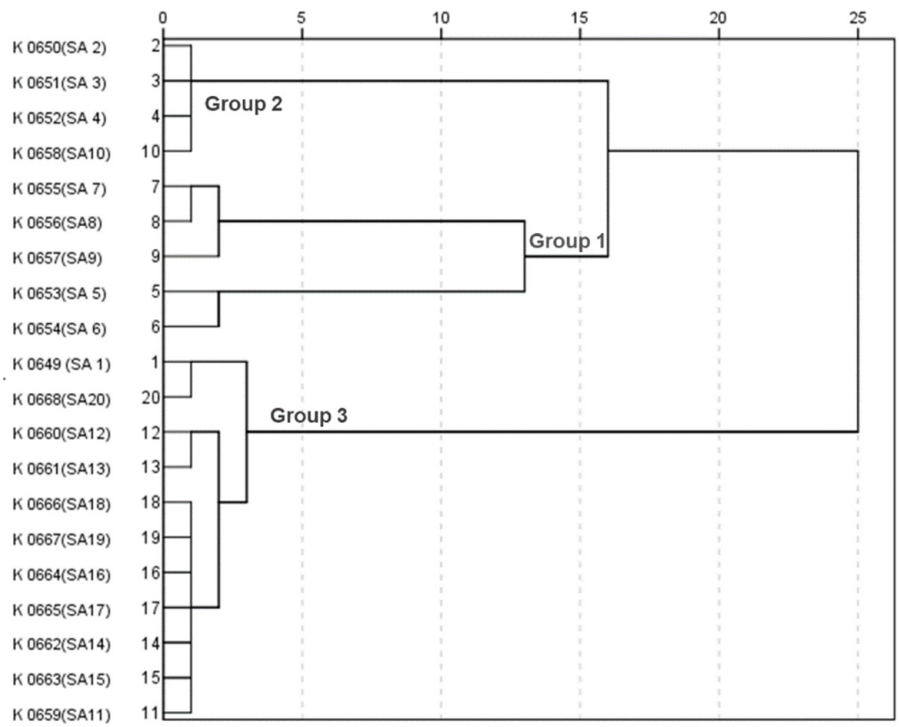


Fig. 6: Hierarchical cluster analysis grouped seawater analysis into three groups: group 1, moderate seawater intrusion (mean 1.4 ± 0.3 ppt); group 2, low seawater intrusion (mean 0.7 ± 0.4 ppt); and group 3, high seawater intrusion (mean 5.5 ± 1.3 ppt)

Table 5: Variation of landscape metrics of mangrove, mangrove vegetation, and its substrate/ soil in three groups of seawater intrusion areas

| Parameters | Group 1 | Group 2 | Group 3 |
|---|---|---|---|
| Seawater intrusion (ppt)* | 1.4 ± 0.3 | 0.7 ± 0.4 | 5.5 ± 1.3 |
| Mean resistivity (Ω) | 66.1 ± 23.1 | 55.5 ± 5.4 | 14.7 ± 9.0 |
| Porosity (%) | 11.2 ± 4.3 | 12.7 ± 0.8 | 20.8 ± 2.9 |
| Mean patch size (ha) | 1.92 ± 4.4 | 8.04 ± 3.7 | 0.49 ± 1.5 |
| Thickness patch (m) | 13.15 ± 9.1 | 54.98 ± 3.4 | 6.26 ± 4.3 |
| Patch density (patches per hectare) | 0.01 ± 0.01 | 0.02 ± 0.003 | 0.05 ± 0.02 |
| Shape index | 2.47 ± 0.3 | 1.57 ± 0.5 | 2.44 ± 0.5 |
| Largest patch index | 0.88 ± 0.3 | 1.41 ± 0.2 | 0.64 ± 0.7 |
| Fragmentation | Low | Moderate | Heavy |
| Mangrove vegetation* | Moderate | Poor | Very poor |

*Decree of the Minister of Environment No. 201 of 2004

in the area with low seawater intrusion (group 1) and high in the area with high seawater intrusion area (group 3; Table 5). Soil resistivity and soil porosity were also significantly different among tree groups of seawater intrusion areas, $\chi 2$ (2) = 8.82, p = 0.011 and $\chi 2$ (2) = 8.95, p = 0.011, respectively. High seawater intrusion corresponded with heavy mangrove fragmentation (patch thickness of 6.26 ± 4.3 m and patch density of 0.05 ± 0.02 patches per hectare) and very poor mangrove vegetation (Tables 3 and 5). This result indicates that the critical thresholds for mangrove patch thickness and patch density in this study were 6.26 ± 4.3 m and 0.05 ± 0.02 patches per hectare, respectively. Local environmental conditions, mangrove ecosystem characteristics, and level of ground water extraction may play important roles in determining critical thresholds. For example, patch thickness falls below 50 m, and tidal forces and storm surges are more likely to breach the mangrove barrier, promoting the intrusion of seawater into coastal groundwater systems (Das and Crépin, 2013; Zhang *et al.,* 2012). Similarly, a canopy density below 70% compromises the ability of mangroves to reduce soil salinity and maintain adequate hydrological conditions for coastal ecosystems (Danielsen *et al.,* 2005; Krauss *et al.,* 2008). These thresholds align with global studies, indicating that mangrove forests with high structural integrity as defined by patch size and density exhibit high resistance to hydrodynamic forces and good functionality as coastal buffers (Spalding *et al.,* 2010; Lee *et al.,* 2014). For instance, in small-island settings, such as the Philippines, mangrove restoration projects have demonstrated that achieving a minimum thickness of 50–100 m is critical for reducing the impacts of seawater intrusion and ensuring long-term sustainability (Danielsen *et al.,* 2005). These thresholds provide actionable benchmarks for seawater intrusion monitoring using ecological indicators and seawater intrusion mitigation through mangrove restoration. Restoration efforts should prioritize areas where mangrove thickness and density can meet or exceed these critical values, ensuring effective ecological functionality to mitigate seawater intrusion. For degraded areas with suboptimal thresholds, restoration using native species and techniques, such as hydrological restoration, should be implemented to rebuild mangrove cover (Krauss *et al.,* 2008). Furthermore, the regular monitoring of patch metrics and seawater intrusion using RS and field surveys can be used in evaluating seawater intrusion risk and ensuring that restoration projects maintain these critical thresholds over time (Spalding *et al.,* 2010; Zhang *et al.,* 2012).

The regression analysis showed that the correlation of parameters of mangrove landscape metrics, mangrove vegetation, and their substrate or soil with seawater intrusion (salinity) varied among groups of seawater intrusion areas (Fig. 7). A good fit between mangrove patch thickness and seawater intrusion was found in the low- and high-seawater-intrusion areas (groups 1 and 3) during the dry and wet seasons (Fig. 7). Soil resistivity was strongly correlated with seawater intrusion (salinity) in all seawater intrusion areas (groups 1, 2, and 3). This result indicates that the ecological indicators (patch thickness, patch density, tree density, soil resistivity, and soil porosity) can be used in determining seawater intrusion in spesific areas

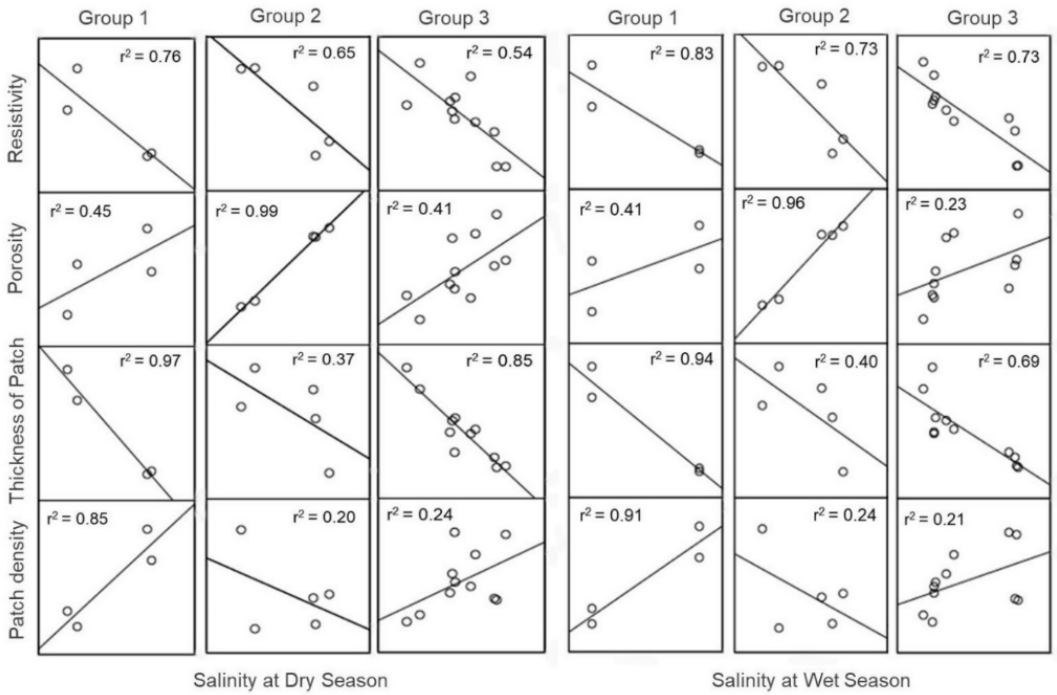


Fig. 7: Correlations of mangrove landscape metrics and mangrove substrate (soil) with seawater intrusion (salinity) in three groups of seawater intrusion areas during dry and wet seasons

or zones. Seawater–groundwater exchange rates in areas or zones where mangrove cover are dominant are much lower than those in areas dominated by other types of land cover, such as agricultural lands, shrublands, and built-up areas or bare lands (Xiao *et al.,* 2018). In addition, fresh groundwater continuously flow to the landward and middle zones of mangroves, serving as an important sink of seawater particles (Xiao *et al.,* 2019).

The limitation of this study is that groundwater extraction was excluded because of data limitation. However, Ambon Bay and mangrove areas (e.g., Passo, Waiheru, and Negeri Lama) are surrounded by built-up areas (housing, commercial, and agriculture areas), and thus the levels of water extraction around Ambon Bay were similar. Incorporating time-series data (monitoring data) with long temporal scale will considerably improve the reliability and clarity of findings related to mangrove ecosystems and seawater intrusion risks. Long-term datasets will capture seasonal and interannual variability in environmental factors, such as salinity, monsoon, season, tidal patterns, and mangrove landscape and vegetation dynamics. For example, time-series satellite imagery integrated with the time-series of field measurements will reveal the patterns of or change in the landscape metrics of mangroves (e.g., patch thickness and patch density) and and the progression of seawater intrusion over time, allowing for the identification of slow-onset processes that short-term studies might miss. Furthermore, incorporating real-time data collection can help to identify fluctuations in or the dynamics of mangrove and seawater intrusion. This approach provides a means for early warning regarding mangrove degradation and seawater intrusion potential. The results of this study demonstrate that landscape scale of mangrove metrics can be used as ecological indicators of seawater intrusion in coastal areas. Mangrove patch thickness and patch density were particularly strong indicators of seawater intrusion around Ambon Bay. However, in some locations, seawater intrusion is exacerbated by sea-level rise (Hilmi *et al.,* 2017; Ketabchi et al., 2016; Pires *et al.,* 2017; Tamrin *et al.,* 2021), which can alter the effectiveness of the proposed ecological indicators

of seawater intrusion. Therefore, large and wide (thick) mangrove patches are crucial to ensuring the efectivness of these ecological indicators. A large and thick mangrove patch with healthy mangrove vegetation is a good sediment trap that can offset the effect of increase in sea level. In addition, habitat shifting and mangrove expansion enable mangroves to be highly effective in adapting to sea-level rise (Duke *et al.,* 2007; Goldberg *et al.,* 2020; Suyadi *et al.,* 2008a). Using these landscape metrics in exploring potential seawater intrusion has many benefits. The integration of field sampling and RS can be applied anywhere, and this approach is relatively quick, cheap, and straightforward. This approach can be applied by policy makers and coastal managers responsible for much of the policy and management of groundwater and mangrove ecosystems. However, skills in the use of GIS and RS are required, and some field skills are needed to derive ground truth from GIS outputs.

*Management implications*

Some mangrove features have high potential as ecological indicators of seawater intrusion and mangrove forest and play important role in evaluating groundwater quality and availability. However, mangrove forests around Ambon Bay, especially the south of Ambon Bay, were highly fragmented. This condition is indicated by the low mean patch thickness (69.82 ± 12.69 m) and high mangrove patch density (0.03 ± 0.02/ha; Table 2, Fig. 5). All the parameters of landscape metrics showed heavy fragmentation in the south of Ambon Bay (group 3) and relatively low fragmentation in the north of Ambon Bay (group 1; Table 5). The high level of mangrove fragmentation is further supported by the low mean patch size (0.66 ± 0.24 ha), irregular patch shape index (2.22 ± 0.58), and small largest patch index (0.89 ± 0.43). On the basis of the guidelines provided by the Indonesian Ministry of Environment (No 201, 2004), the status of mangrove vegetation health in Ambon Bay was categorized as moderate (group 1, low seawater intrusion areas), poor (group 2, medium seawater intrusion areas), and very poor (group 3, high seawater intrusion areas; Table 5). This descriptive analysis is further supported by NDVI analysis, which showed similar findings. In terms of the NDVI value, mangroves in group 1, which included the low seawater intrusion areas (e.g., Passo, Waiheru, and Negeri Lama) had moderate heatlh status (NDVI, 0.43–0.5), group 2, which are medium seawater intrusion areas, such as Halong (SA13) and Rumah Tiga (SA4), had poor health status (NDVI, 0.22–0.42), and group 3, which had high seawater intrusion areas, such as Tawiri (SA1) and OSM (SA19), had very poor health stauts (NDVI, 0.01–0.21). Another study showed that the mangrove area in Ambon Bay had decreased from 85.689 ha in 1995 to 57.206 ha (Rotua, 2017). Mangrove deforestation and fragmentation not only occurred at the local scale, particularly in Ambon Bay, but also continues to be a national and global issue. Mangrove forest cover worldwide had decreased, and 62% of the mangrove cover had degraded from 2000 to 2016 (Goldberg *et al.,* 2020). Indonesia has one of the highest total areal losses of mangroves and has shown increasing forest fragmentation, and 40% of the country's mangrove forests had been cleared or degraded (Andrew *et al.,* 2015; Murdiyarso *et al.,* 2015; Basyuni and Sulistiyono, 2018; Bryan-Brown *et al.,* 2020). The mangrove deforestation and degradation rate is 14% per year (Giri *et al.,* 2011; Murdiyarso *et al.,* 2015; Thomas *et al.,* 2017. Mangrove deforestation in Indonesia emit large amounts of carbon dioxide (Murdiyarso *et al.,* 2015), and illegal logging has reduced approximately 56% of aboveground biomass in Lubuk Kertang Forest, North Sumatra, for only one year (Basyuni *et al.,* 2025). The high rates of mangrove deforestation and fragmentation in Indonesia will considerably impact groundwater quality by promoting seawater intrusion, particularly in small islands (Hilmi *et al.,* 2017; Pires *et al.,* 2017; Mello *et al.,* 2018; Goldberg *et al.,* 2020). The root causes of mangrove deforestation and fragmentation in Indonesia are illegal logging, pollution (e.g., plastic and oil spil pollution), and mangrove conversion into lands for aquaculture, agriculture, housing, and business construction. The findings of this study highlight the importance of mangrove conservation (law enforcement and strict protection) for remaining mangroves and restoration programs for restoring degraded mangroves. The focus of this study is the development of a massive mangrove greenbelt with optimal patch thickness and density and capability to mitigate seawater intrusion. Implementing strict penalties for illegal logging, expanding protected

mangrove areas, and restoring degraded mangrove are effective strategies for reducing mangrove degradation due to illegal logging and mangrove conversion. These actions should be integrated with community-based mangrove conservation strategies, such as increasing public awareness, providing sustainable alternative livelihoods, and encouraging community participation in reducing pollutants, especially plastic and oil spill. The implementation of laws designed to protect native vegetations, such as mangroves, mangrove restoration, improved soil management practices, and fresh groundwater management are required to prevent potential seawater intrusion (Ellison *et al.,* 2017; Mello *et al.,* 2018; Pires *et al.,* 2017). Law enforcement and mangrove forest protection should be supported by strong and harmonious laws and policies in central and local governments. Strengthening the legal framework through the establishment of mangrove-specific law and policies will fill existing gaps, such as inadequate penalties, insufficient monitoring, and unclear land ownership issues, which often lead to mangrove exploitation. Community-based mangrove conservation and restoration should be legally recognized and supported by laws and policies. Another critical law and policy measure is the integration of mangrove conservation and restoration into climate adaptation and mitigation strategies, such as blue carbon and carbon credit regulation. In addition, some international frameworks, such as the Ramsar Convention on Wetlands and the United Nations Sustainable Development Goals, can guide countries in implementing global best practices for mangrove conservation, strengthen law enforcement mechanisms, enhance funding opportunities, and facilitate cross-border collaboration on conservation and restoration efforts. Mangrove restoration strategies, such as mangrove greenbelt development, are vital to mitigating seawater intrusion and sustaining potable groundwater resources (Hilmi *et al.,* 2017; Pires *et al.,* 2017; Mello *et al.,* 2018). However, the socio-economic status of local communities relies on coastal resources and influences the success of mangrove conservation and restoration. Therefore, ensuring that local communities receive socio-economic benefits from mangrove conservation and restoration is important. Enhanced mangrove forest management, soil management, and mangrove restoration have many benefits because thick and healthy mangroves have numerous essential ecological functions and ecosystem services, such as water filtering, biodiversity maintenance, and climate change mitigation through carbon sequestration (Ellison *et al.,* 2017; Pires *et al.,* 2017; Mello *et al.,* 2018; Jung *et al.,* 2021). Moreover, mangrove conservation and restoration provide direct (e.g., mangrove nursery, mangrove planting, ecotourism, nontimber products, and carbon credit) and indirect (e.g., ecological functions, silvofihsery, fishing ground, and nursery ground) economic implications for communities. Improved soil management is important to ensuring the availability and quality of ground fresh water, controlling erosion and soil vertility, and maintaining soil resistivity. A modeling study showed that forest restoration is achievable and financially feasible (Pires *et al.,* 2017). Climate change adaptation and carbon financing strategies should be integrated to attract funding for mangrove conservation and restoration. Local community organizations and citizen conservation play critical roles in the success of mangrove conservation and restoration. Effective strategies for enhancing community engagement are as follows: 1) improving knowledge and skills needed for mangrove conservation and restoration through training and capacity building, 2) fostering a sense of ownership and accountability through participatory decision-making and stewardship rights and responsibilities over mangrove areas, 3) providing alternative incomes through eco-tourism and sustainable aquaculture practices (e.g., silvofishery), 4) providing education and public awareness especially for children, teenagers, students, and women (mothers), and 5) establishing incentives or payments for ecosystem services or access to carbon financing programs through carbon credits. These strategies can motivate communities to actively contribute to conservation and restoration initiatives. Thus, the proposed solution can be summarized as an integrated approach linking ecological, hydrological, and socioeconomic aspects to improve water sources and mangrove management in small islands. These proposed solutions can be applied to other small islands because most small islands face similar challenges, such as limited resources of groundwater and high

risk of seawater intrusion (Kura *et al.,* 2015; Gohar *et al.,* 2018; Chen *et al.,* 2018; Gheuens *et al.,* 2019; Vann *et al.,* 2020). Small islands have similar environment conditions, such as geomorphological condition, oceanic condition, and coastal conditions, including mangrove type (e.g., carbonate setting). The proposed solutions can be easily scaled up to large coastal areas because most large coastal areas (e.g., coastline area, estuarine area, and riverine area) are good habitats for mangroves.

## CONCLUSION

Seawater intrusion poses a considerable threat to groundwater quality in coastal areas, particularly in small-island settings where communities heavily rely on fresh groundwater for daily needs. The findings of this study underscore the critical role of mangrove ecosystems in mitigating seawater intrusion and highlight specific ecological features as reliable indicators. Specifically, landscape metrics, such as mangrove patch thickness and patch density, in conjunction with soil characteristics, such as soil resistivity and porosity, explained up to 80% of the variation in seawater intrusion level in the study area. These relationships reveal the complexity of interactions between vegetative and substrate parameters in controlling groundwater salinity. Seawater intrusion was negatively correlated with patch thickness and soil resistivity, suggesting that thick or wide patches, dense vegetations, healthy mangroves, and compact substrates are effective barriers against seawater ingress. Conversely, a positive correlation with patch density and soil porosity indicates that fragmented mangroves and porous soil exacerbate the issue. These findings provide compelling evidence that conserving and restoring mangrove habitats are needed for sustainable groundwater quality. Mangrove forests around Ambon Bay and many mangroves in other locations in Indonesia were categorized as “unhealthy” because of high fragmentation and low tree density and canopy coverage, reflecting alarming mangrove degradation caused by conversion into other land use types (such as ponds, houses, and business centers), illegal logging, pollution, and unsustainable land-use practices. Effective coastal management strategies are urgently required to address these challenges. Key interventions include the implementation of mangrove greenbelt development, active mangrove restoration programs, and stringent native vegetation protection laws. These measures should be complemented by improved soil management practices to enhance soil resistivity, reduce porosity, and further mitigate the risk of seawater intrusion. The integration of RS and field-based assessments, as demonstrated in this study, provides a cost-effective and scalable approach for monitoring and managing seawater intrusion risk. A more holistic approach for water resource management is needed to secure groundwater availability for future generations, encompassing limiting groundwater extraction, enforcing regulations on coastal development, and promoting community awareness of the ecological and economic benefits of mangroves. Furthermore, future research should explore the long-term impacts of climate change, such as rising sea levels and altered precipitation patterns, on seawater intrusion dynamics in small islands. Integrating ecological, hydrological, and socioeconomic dimensions will ensure comprehensive solutions to the multifaceted challenges posed by seawater intrusion. Mangrove conservation and restoration are indispensable for mitigating seawater intrusion and securing freshwater resources in coastal and island settings. The adoption of evidence-based management practices, informed by ecological indicators, such as those identified in this study, will be crucial for achieving sustainable water security in small-island states, such as Ambon. These efforts must be prioritized to safeguard the livelihood and well-being of coastal communities, ensuring resilience against environmental degradation and climate change. This study advances the theoretical framework of mangrove functionality by demonstrating the importance of landscape metrics in regulating seawater intrusion and bridges gaps in previous research. Future studies should explore the long-term impacts of climate change, such as rising sea levels and altered precipitation patterns, on the efficacy of mangrove metrics in groundwater regulation.

## AUTHOR CONTRIBUTIONS

Suyadi contributed in conceptualization, research grant, research design, fieldwork, data analysis, model development, investigation, methodology, writing-original draft, revising, editing, and

visualization. M. Basyuni, contributed in research grant, investigation, drafting, revising, and editing. Debra Stokes, contributed in drafting, revising, and editing. R. Amukti contributed in fieldwork, resistivity and porosity data collection, and geo-electrical data analysis. C. Damayanti contributed in fieldwork, resistivity and porosity data collection, and geo-electrical data analisis. A. Mubaraq, contributed in drafting, revising, and editing. Y.I. Rahmila contributed in drafting, revising, and editing.

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## CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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## ABBREVIATIONS

| | |
|---|---|
| *%* | Percent |
| */ha* | Per hectare |
| */sec* | Per second |
| *‰* | Per mille |
| *$^{o}C$* | Degrees Celsius |
| *BP* | *Brugruiera parviflora* |
| *BTKL* | Balai Teknik Kesehatan Lingkungan/ Environment health |
| *$CaCo_3$* | Calcium carbonate |
| *cm* | Centimeter |
| *CT* | *Ceriops tagal* |
| *DBH* | Diameter breast height |
| *EA* | Excoecaria agallocha |
| *e.g.* | Exempli gratia |
| *GIS* | geographic information system |
| *GPS* | Global positioning system |
| *ha* | Hectare |

| | |
|---|---|
| *IAB* | Inner Ambon Bay |
| *km* | Kilometer |
| *km²* | Square kilometer |
| *masl* | Meter above sea level |
| *m* | Meter |
| *mg/L* | Milligram per litre |
| *NDVI* | Normalized difference vegetation index |
| *NTU* | Nephelometric turbidity units |
| *OAB* | Outer Ambon Bay |
| *PES* | Payments for ecosystem services |
| *pH* | Potential of Hydrogen |
| *ppt* | Part per thousand |
| *RA* | *Rhizophora apiculata* |
| *RS* | *Rhizophora stylosa* |
| *RS* | Remote sensing |
| *SA* | *Sonneratia alba* |
| *SEM* | Structural Equation Models |
| *SIDS* | Small Island Developing States |
| *TDS* | Total Dissolved Solids |
| *UN* | United Nations |
| *UNSDGs* | United Nations Sustainable Development Goals |

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