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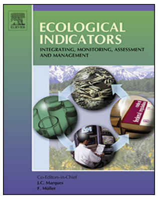

Original Articles

Development of a comprehensive mangrove quality index (*MQI*) in Matang Mangrove: Assessing mangrove ecosystem health

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ABSTRACT

Mangroves are multi-functional ecosystems providing resource provisions and various ecosystem services, all of which are critical to the local livelihood and national economy. However, unsustainable anthropogenic activities continue to undermine the health of these ecosystems resulting in environmental adversities and declining resources. This study aimed to formulate a Mangrove Quality Index (*MQI*) which took into consideration the mangrove forest, contributing components of a mangrove forest, soil, surrounding marine ecosystem, hydrology and the socio-economic variables. Three major sites representing the least, moderately and most-disturbed mangrove ecosystems in Matang, Malaysia were selected. These areas were used to assess the contribution of 43 variables from five categories, namely, mangrove biotic integrity, mangrove soil, marine-mangrove, mangrove hydrology, and mangrove socio-economic factors. Two types of indices were developed to indicate the status of each category, 1) Mangrove Quality Index for a specific category ($MQIS_i$) and, 2) Overall *MQI* to reflect the overall health status of the ecosystem. The indices for the five different categories were Mangrove Biotic Integrity Index ($MQIS_1$), Mangrove Soil Index ($MQIS_2$), Marine-Mangrove Index ($MQIS_3$), Mangrove-Hydrology Index ($MQIS_4$) and Mangrove-Socio-economic Index ($MQIS_5$). Using Principle Component Analysis, ten variables representing all the five categories were selected to formulate the overall *MQI*. They are aboveground biomass, crab abundance, soil carbon, soil nitrogen, number of phytoplankton species, number of diatom species, dissolved oxygen, turbidity, education level, and time spent fishing. We developed the overall *MQI* based on the total score obtained from each category. The health status of mangroves is ranked from 1 to 5 viz. 1 (worst), 2 (bad), 3 (moderate), 4 (good), 5 (excellent). In the Matang Mangrove, the health status of the least disturbed area is ranked 5, moderate disturbed area is ranked 4, while the most disturbed area is ranked 2. The Normalized Difference Vegetation Index (NDVI) supported the overall *MQI* developed. The NDVI for the least disturbed area in Matang ranged from −0.689846 to 0.652204, for the moderately disturbed area, it ranged from −0.732508 to 0.638625, while the most disturbed area ranged from −0.916667 to 0.314991.

1. Introduction

Mangrove ecosystem is among the most productive ecosystems in the world with well-established ecological, economic and cultural importance (Goessens et al., 2019). Mangroves play a critical role in sustaining the biological integrity and resources of the adjacent marine ecosystem and thus contribute significantly to the commercial fisheries and other regulatory ecosystem services. It provides breeding and nursery grounds to commercially and recreationally important fish. Manson et al. (2005) reported that the productivity of the off-shore

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areas was dependent on the presence of mangroves along the shores as the latter provided breeding and spawning grounds for sustaining the fish populations. In addition, mangroves become more important in safe guarding these ecological and the biotic dynamics as well as that of hydrological and sedimentation regulatory functions. They protect shorelines from strong wind, erosion and currents amongst other functions.

Mangrove ecosystem consists of a few major components including the forest, soil and the marine system. Mangroves soils are complex and highly variable, made up of river and marine alluvium, transported as sediment and deposited in the rivers and seas (Hossain and Nuruddin, 2016). Typically, mangrove soils comprise silt and clay combined with organic matter and salts with dark grey colour (Huergo et al., 2018). These soils usually have low nutrient availability but nutrient availability varies between mangrove sites (Reef et al., 2018). A study by Ukpong (1997) showed that nutrient availability is one of the three dominant components influencing mangrove structure and productivity. Mangrove productivity is often limited by the availability of nitrogen, phosphorous and iron in the mangrove soils (Naidoo, 2009; Alongi, 2011). Mangrove soils store more carbon than mineral soils (Chmura et al., 2003) due to carbon deposition from the accumulation of sediments brought by the river flow and also from the native sediments in the area. The carbon is an important energy source for diverse microbial community in the mangrove soils. The highly productive microbial community continuously transforms nutrients from dead mangrove vegetation into sources of nitrogen, phosphorus, and other nutrients that can be used by the plants (Holguin et al., 2001).

In terms of hydrology, the ecosystem is dynamic and influenced by both natural factors such as tidal effects, climate and seasonal variability, human factors such as land use change (Ardebili et al., 2006) and tourism activities (Giri et al., 2007). These components affect water circulation by generating turbulence and longitudinal mixing and trapping coastal water, influencing the rate of erosion and deposition of sediments in which mangroves grow. The quality of hydrology features could support the mangrove ecosystem functions including providing breeding ground for aquatic life and habitat for wildlife, nutrients cycling for mangrove vegetation (Pailles et al., 1993) and protection of shorelines (Kathiresan and Rajendran, 2005).

Russi et al. (2013) estimated the total economic value for mangrove range between USD1995 to USD215349 per hectare. The estimated foregone annual benefits in 2050 are estimated to be USD 2.2 billion, with a prediction interval of USD 1.6–2.8 billion. Sina et al. (2017) found that the total economic value of the mangrove ecosystem in the village of Pulokerto, District of Kraton is USD27593.58 per hectare per year. Bennett and Reynolds (1993) conducted a case study on the economic value of the Sarawak Mangrove Forest Reserve. They found that mangroves support marine fisheries worth USD21.1 million per annum and up to 3000 jobs, timber products worth USD123217 per annum, and a tourist industry worth USD3.7 million per annum. There are some existing economic estimation of Matang Mangrove, Taiping, Perak. For example, the estimated stumpage value of timber for poles (thinning) and charcoal production per hectare was US$ 68.20 and US $597.32, respectively. Additionally, employment opportunities are also important for the local community where the main activities include forestry (poles and production, replanting, and supply of forestry inputs), fishery (capture fisheries, cockles' production, fish processing), ecotourism, small business, boat buildings, repairs and maintenance, and other downstream fishery activities.

In spite of its huge socio-economic contribution to the nation, mangrove ecosystems are threatened by reclamation, pollution and other land-used activities resulting in habitat destruction, loss of biodiversity and decline in marine resources. The constant pressure exerted by anthropogenic (more than natural) events is responsible for its decline at a faster rate than that of tropical rainforests (Alongi, 2008). Along with mangrove cover depletion, the loss of its biodiversity and economic value are perturbing issues (Satyanarayana et al., 2012).

Despite the various threats to mangrove ecosystems, systematic assessment of such changes has not been studied. There were no methods specifically for mangroves (Bartoldus, 1999). Current methods are not appropriate to be applied to mangroves because of the many unique characteristics confined to mangroves such as plants and animals, water and sediment. For instance, despite the crabs playing an important role in the ecology of mangroves by effecting the chemical composition of soil, the growth and productivity of tree species, the aeration of the soil, the removal of harmful chemicals and the transportation of nutrients, they were not included in current methods (Hogarth, 2007). Due to the complex interactions of factors in determining the health of a mangrove ecosystem, a comprehensive assessment of all integrating factors at the ecosystem level is needed to select appropriate indicators that could adequately reflect its real-time health status. However, not all factors can be included in establishing the Mangrove Quality Index. Appropriate strategies should be used in selecting effective indicators for the mangrove ecosystem health status. Borja et al. (2009) suggested that an integrative ecosystem-based approach should recognize not only the importance of interactions amongst many species, but also the roles of abiotic factors (environmental parameters) and social, economic and institutional perspectives. Berezina et al. (2017) used different physical, chemical and biotic variables such as water salinity, phosphorus, trace metals, polycyclic hydrocarbon, macroalgae biomass, phytoplankton and benthic organisms to make a comprehensive assessment of the environmental status of coastal habitats. Lopez and Fennessy (2002) for example used the Floristic Quality Index for wetlands vegetation quality but its shortcoming was not incorporating abundance or dominance of plant species. Other measures of wetland quality include the estuarine rapid assessment procedure (Bartoldus, 1999). The index of biotic integrity (Gara and Stapanian, 2015) for wetlands was based on diversity and dominance but varied among vegetation classes. Marshall et al. (2018) suggested integrating different types of data via satellite remote sensing, geographical information system (GIS) and modelling as a useful approach to assess the status of a mangrove ecosystem. Yunus et al. (2014) suggested the Mangrove Vulnerability Index (MVI) using GIS to analyze social-ecological response to environmental change and measure susceptibility to damage and capacity to cope or adapt. Cao and Liu (2014) proposed the normalized difference vegetation index (NDVI) for a variety of remotely sensed imagery analysis related to vegetation. Ibrahim et al. (2015) and Lee and Yeh (2009) used NDVI to monitor shifting wetland vegetation while Kwongwonjan et al. (2012) found NDVI useful to classify mangrove and non-mangrove area.

Indices on ocean health have been developed to assess the status of various marine ecosystems (Marigomez et al., 2013; Rombouts et al., 2013; Tian et al., 2011), but indices to evaluate the health status of mangrove area and its related ecosystems are limited. Karydis and Tsirtsis (1996), suggested five phytoplankton variables (species number, abundance, Menhinick's index, Kothe's index and evenness index) were found useful for assessing the trophic status of marine water. Lugoli et al. (2012) proposed size spectra sensitivity of phytoplankton index (ISS-Phyto) as an adequate tool to assess the ecological status of coastal marine waters. Ferreira et al. (2011) suggested hydrological and water quality index as management tools in marine shrimp culture. The Hydrological Index (HI) used four water quality variables which were salinity, turbidity, pH, and dissolved oxygen (Beltrame et al., 2006). There were also past studies that used population trends to determine health status of benthic communities (Quintana et al., 2010). Population dynamics of certain invertebrate species had been used to determine if is a community is stressed (Miserendino et al., 2008; Wildsmith et al., 2009) and this includes the fiddler crab, *Uca pugilator* (Wilkens and Fingerman, 1965) that could be used to address environmental health especially due to anthropogenic factors (Bergey and Weis, 2008). Fiddler crabs are rather easy to study due to the dense populations and relatively shorter time to observe (Bartolini et al., 2009).

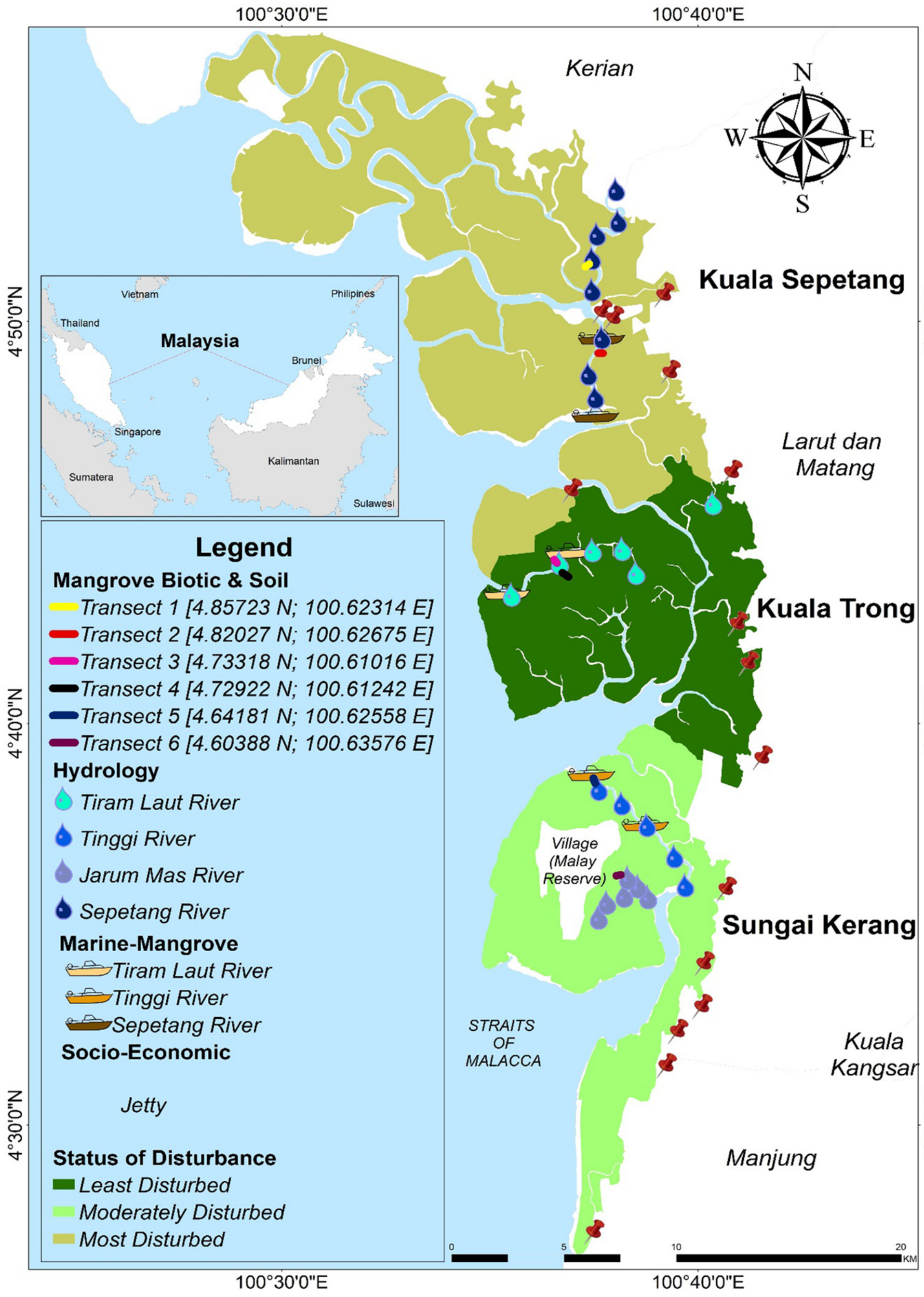

Fig. 1. Sampling stations in three different areas with different degrees of disturbance in the Matang Mangrove Forest, Perak, Malaysia.

Additionally, Brown (1997) showed that the aboveground biomass in tropical forests is useful for a range of applications from commercial harvesting of timber to the global carbon cycle which can be established for determining the carbon stored in the forest through increment or decrement. Biomass is an important indicator to show the ecological process hence the status of a site besides influencing the hydrologic parameters of a site such as runoff, erosion and infiltration. Furthermore, biomass attributes for the aboveground biomass such as diameter at breast height (DBH) of the tree bole can be easily measured and interpreted (Basuki et al., 2009).

Soil regulates important ecosystem processes such as water availability, nutrient cycles and carbon storage. Multimetric indices have been developed for various aspects of ecosystem using soil physical, chemical and hydrological variables. Costantini et al. (2016) reviewed potential soil indicators for the assessment of sustainable land management practices. Other indices used include soil nutrients (Andrews et al., 2002; Zornoza et al., 2008; Mukherjee and Lal, 2014) and carbon (Zhao et al., 2014).

Several studies have shown the importance of socio-economic variables in relation to the quality of natural resources. Amongst these are the education level and time spent. Kamri (2013) showed that the educational level of respondents provide significant effects with positive influence on natural resources in Gunung Gading National Park, Sarawak. Sharma and Leung (1998) also found that fisher's education level has a positive influence on technical efficiency on the longline fishery. Batista et al. (1998) identified the positive effects on fishermen's time spent on fishing around mangrove areas.

Monitoring temporal changes of mangrove health can also be done by using the remote sensing technique. The use of remote sensing is a reliable alternative to ground survey methods of mapping mangroves;

these alternative techniques are cost-saving and yield acceptable accuracy (Giri et al., 2007; Ibrahim et al., 2015). Principally, remote sensing is a process of gathering information about an object, area or phenomenon obtained from a distance, typically from satellite or aircraft. Information gathered are presented in raster images and are ready to be analyzed for several uses, namely, land cover changes (Ibrahim et al., 2015; Prasad et al.,2015), disaster observation (Voigt et al., 2007), species distribution and zonation pattern (Lee et al., 2016; Chun et al., 2011). Palmer et al. (2005) suggested that a guiding image could be useful to reflect the ecosystem health status.

Despite its importance, mangroves in Malaysia specifically, and the world at large, are still exposed to many threats especially from adverse economic activities upstream and in the mangrove ecosystem itself, which often lead to the decline of its quality. There still remains the issue of how to address mangrove health. With the remaining mangroves left in Peninsular Malaysia at approximately 97,500 ha (Latiff and Faridah-Hanum, 2014), the development of the *MQI* could be a way forward to determine mangrove health and provide solutions to rectify disturbances and take effective mitigation measures to protect the resource sustainability. Additionally, the *MQI* could be a useful tool for managers to employ for decision making in matters pertaining to the mangroves such as the intensity of rehabilitation, aquaculture project considerations and extent of resources' protection. A two-year project was undertaken in an effort to develop the *MQI* for assessing the status of mangrove ecosystem taking into account both biotic and abiotic variables including the socio-economic factors of the coastal community. The objectives of this study were, 1) to identify important variables that contribute to the development of mangrove indices: biotic integrity index, soil index, marine-mangrove index, hydrology index and socio-economic index, 2) to develop the overall *MQI*.

2. Materials and methods

2.1. Study site and metrics

The Matang Mangrove Forest Reserve (MMFR) in the state of Perak was chosen as the study site by virtue of it being the largest tract of well managed mangrove forest in Peninsular Malaysia. The Matang Mangrove Forest Reserve is located in the Northern region of Peninsular Malaysia, ranging from 4°56′03.54″ N and 100°28′33.26″ E in the North and 4°32′10.81″ N and 100°37′40.54″ E in the South (Fig. 1). This forest has numerous large and small rivers; joined with the coastal areas of Malacca Straits in the West. The Matang Mangroves are divided into four management zones namely Kuala Sepetang North, Kuala Sepetang South, Kuala Trong and Sungai Kerang. Logging activities are prevalent in the management zone of Kuala Sepetang; the logging method employed is clear felling and timbers harvested are mainly used to produce charcoal and poles. The logged areas are reforested naturally or replanted with species suitable for the inter-tidal zone. Sometimes, a combination of the above two methods is applied to repopulate the deforested areas with mangrove trees. Zones with less logging activities are often used for commercial recreation activities, which become sources of income for the local community. A variety of activities in these four zones brings out different contributions of mangrove forests in terms of vegetation status, water quality, abundance of marine life and social activities, especially for the inhabitants. Prior to the data collection, satellite image of Landsat 8 freely downloaded from USGS website (https://earthexplorer.usgs.gov/) projected with Kertau Rectified Skew Orthomorphic (RSO) coordinate system were used to classify the MMFR. Initially, the classification of MMFR was based on the density of canopy namely dense, moderately dense, low dense and open area (Rhyma et al., 2015). Ground truthing assesment further validated the variety of activities within MMFR causing different levels of disturbance in MMFR. Thus, the MMFR were re-classified into three categories, taking into account the diferent levels of disturbance viz., least disturbed, moderately disturbed and highly disturbed; these areas were used to study the metrics chosen (Fig. 1).

A total of 43 variables encompassing the flora, fauna, water, soil and socio-economic livelihood were identified based on past studies relevant to the project, and relevant to the Malaysian Environmental Quality Index (2010) metrics (http://epi.yale.edu/indicators-in-practice/environmental-quality-indicators-malaysia). These variables were subjected to Principle Component Analysis (PCA) to determine the relevant metrics for the development of the overall *MQI*.

2.2. Field methods and analysis

2.2.1. Mangrove biotic integrity index

The mangrove biotic integrity index was developed from the assessment of five biological variables which are tree height, basal area, tree volume, aboveground biomass and crab abundance. Samplings were carried out from June 2015 to August 2016 in the Matang Mangrove Forest Reserve at three rivers (Fig. 1). Three (3) transects were established (Rhyma et al., 2015) at Sg. Tiram Laut river representing the least disturbed area, Sg. Jarum Mas representing moderately disturbed area and Sg. Sepetang representing the most disturbed area. For crab abundance, five (5) modified funnel pitfalls of Kent and McGuinness (2006) were buried and left for 24 h in each of the five sampling plots of size 10 m × 10 m each. Each plot was established at a distance of 50 m apart. The funnel was modified by affixing a plastic mesh to the end of the funnel thus the crabs were unable to escape after falling into the pitfalls at high tide. The crabs were then counted and released. For aboveground biomass estimation, all trees in the 10 m × 10 m plots with diameter at breast height (dbh) 5 cm and above were enumerated, measured and identified. To estimate the aboveground biomass, the allometric equation of Eswani (2016) was used, where aboveground biomass, $AGB = 45.87 + (0.02 \times D2H)$. D is diameter at breast-height (DBH) in cm; and H is the total height of the tree above ground level in metre.

2.2.2. Mangrove soil index

Soils samples were taken along 100 m length transect beginning from the riverbank and progressing inwards. Along each transect, starting 10 m from the beginning and then at 20 m intervals, plots of 10 m × 10 m were established. In each plot, three sample points were chosen and samples at 0–15, 15–30, 30–50, 50–100 cm depths were taken using an auger. Samples were put in tagged plastic bags and taken to the laboratory for air drying, sieved and tested for pH, N, C, S, P, K, Mg and Ca. The pH was determined from 1:2 × 40 g soil + 80 mL water suspension using a pH meter. For the nitrogen content, samples were air-dried, crushed and homogenized using a mortar and pestle, weighed into a tin cup. They are then placed in the auto sampler for instrumental analysis; 10 mg-12 mg samples were taken with 2–3 replicates to analyze nitrogen in the CHNS elemental analyzer (Fujine, 2014). To determine the concentration of calcium, digestion of samples with acetic acid was carried out (McCray and Ji, 2012); 10 mg-15 mg with 2–3 replicates were required to run these samples in the Atomic Absorption Spectrometer. These transects were established at four sites, i.e. Sungai Tiram Laut, Sungai Tinggi, Sungai Jarum Mas, and Sungai Sepetang. These sites represented different levels of disturbances, where Sungai Tiram Laut was the least disturbed, Sungai Tinggi and Sungai Jarum Mas were moderately disturbed and Sungai Sepetang was the most disturbed.

2.2.3. Marine-Mangrove Index

The marine-mangrove health index was developed from the assessment of ten biological variables including the number of species and abundance of total phytoplankton, diatoms, dinoflagellates, copepods and jellyfish. Monthly field samplings were carried out from May 2015 to April 2016 in the Matang Mangrove Forest Reserve in three rivers. Two stations in the Sg. Tiram Laut were selected to represent the least disturbed area (MO1 and MO2), Tinggi river to represent the moderately disturbed area (MT1 and MT2) and Sg. Sepetang as the most disturbed area (MS1 and MS2). At each station, duplicate zooplankton samples were collected using horizontal net tows (140 µm mesh) at a constant boat speed of 3–5 knots for one km in each direction of current flow during the high tide. At the same time, jellyfish were sampled by net (300 µm mesh) trawls for one km in the upstream direction. Zooplankton samples were preserved using buffered formalin with final concentration of 5% (Steedman, 1976). Triplicate phytoplankton samples (each 1000 mL) were collected using a Niskin water sampler and preserved with 10 mL of Lugol's solution (Throndson, 1978). In the laboratory, phytoplankton were concentrated to about 100 mL, placed in a counting chamber and were analysed using a compound and inverted microscopes. Zooplankton and jellyfish were sorted, identified and enumerated using a dissecting microscope.

2.2.4. Mangrove hydrology index

The Mangrove Hydrology index for the Matang Mangrove area was developed based on river physiography and 14 selected water quality variables. The hydrology data was collected at four rivers namely Sg. Tiram Laut (least disturbed) − 5 sampling points, Sg. Jarum Mas (moderately disturbed) − 5 sampling points, Sg. Tinggi (moderately disturbed) − 5 sampling points and Sg. Sepetang (most disturbed) − 8 sampling points. The sampling points were established at each river at 1–3 km distance depending on the length of the river. There were four replicates for each sampling point. The measurement was conducted during low and high tides for dry (June-July 2015) and wet (November-December 2015) conditions. At each sampling point, the river depth was measured using HawkEye® Handheld Digital Depth Sounder whereas river width using NIKON ProStaff 550 Range finder and velocity using SEBA Velocity Current meter. *In situ* water quality variables were measured using portable water sensors; turbidity using HACH Turbidity meter), pH and Dissolved Oxygen (DO) using HANNA Instruments 9829 multiparameters, whereas salinity, total dissolved solids (TDS), water temperature and electric conductivity (EC) were measured by using YSI 300 EC meter. Water samples were collected using 1 L polyethylene bottles, preserved in a cooler and analysed for biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), nitrate, phosphorus, ammonia-cal nitrogen (AN), fecal coliform, and oil and grease. Laboratory analysis was conducted following the Standard Methods for examination of water and wastewater (APHA, 2005). Detailed statistical analyses i.e. ANOVA and Pearson Correlation were conducted to assess the spatial variation (between rivers and sampling points) and temporal trends (seasonal and tides) of the hydrological data. The relationship between water quality variables with river physiography was also observed.

2.2.5. Mangrove socio-economic index

The socio-economic index was identified from the assessment of six socio-economic variables such as fish landing, time spent fishing, fishing effort, income, age and education. The survey was conducted in December 2015 involving 300 local fishermen around MMFR at several jetties. This study focused on three categories of disturbances which are least disturbed, moderately disturbed and most disturbed. The most disturbed fish landing in MMFR were jetties at Kampung (Kg.) Tebok, Kuala Sepetang, Kg. Menteri, Kg. Teluk Kertang, Kg. Matang Pasir and Kuala Jaha. The least disturbed areas included jetties in Kuala Trong, Sg. Punggur and Sg. Termelok while the moderately disturbed areas included jetties at Sg. Kerang, Kg. Kelubong, Permatang Raja, Sg. Che Rahmat, Kg. Bagan Panchor and Pantai Remis. This study focused on transforming the original variables of fishery activities and demographics information for the development of the socio-economic mangrove index using PCA. Sarbu and Pop (2005) mentioned that principal components are linear combinations of original variables. Helena et al. (2000) stated that the directions of maximum variance can be identified on the new axes which lie along them. The fish landing, time spent fishing, fishing effort, income, age and education were ordinated using PCA in Stata SE 14 statistical program to develop the index. Out of six variables, the two most important ones were used to determine the metrics for the development of the mangrove socio-economic index.

2.3. Statistical analysis

In the development of *MQI*, Principal Component Analysis (PCA) was used to select the most important metric from each category of metrics in the research. Principal Components Analysis (PCA) is a common method in selecting important metrics and for determining weights for components.

PCA is a data reduction technique. It involves reforming a set of correlated metrics with a set of 'principal components' which are uncorrelated. In PCA, maximum p components out of p metrics can be extracted. This will involve solving p equations with p unknowns. The variance in the correlation matrix is restructured into p eigenvalues. This is accomplished by finding a matrix V of eigenvectors. When the correlation matrix R is premultiplied by the transpose of V and postmultiplied by V, the resulting matrix L contains eigenvalues in its main diagonal. Each *eigenvalue* represents the amount of variance that has been captured by one component.

Each component is a linear combination of the p metrics. The first component accounts for the largest possible amount of variance. The second component, formed from the variance remaining after that associated with the first component has been extracted, accounts for the second largest amount of variance, etc. If the first few principal components explain a substantial proportion of the total variance, without losing a lot of variability, they can be used to represent the original metrics, thus reducing the number of metrics required. The principal components are extracted with the restriction that they are orthogonal. Geometrically they may be viewed as dimensions in p-dimensional space where each dimension is perpendicular to each other dimension.

Each of the p metric's variance is standardized to one. Each factor's eigenvalue may be compared to 1 to see how much more (or less) variance it represents than does a single metric. With p variables, there is $p \times 1 = p$ variance to distribute. The principal components extraction will produce p components which in the aggregate account for all of the variance in the p metrics. That is, the sum of the p eigenvalues will be equal to p, the number of metrics. The proportion of variance accounted for by one component equals its eigenvalue divided by p.

For the Mangrove Biotic Integrity Index, the contribution of tree height, basal area, tree volume, aboveground biomass and crab abundance were ordinated using correlation-based PCA in StataSE14 statistical program. For the development of the Mangrove Soil Index, variables such as CNPK were ordinated using the PCA. In the development of the Marine-Mangrove Index, PCA was also applied to interpret the contribution of suitable metrics, such as the number of species, species abundance, and diversity of phytoplankton, copepods and jellyfish. The PCA was also used to determine suitable metrics from the seven (7) hydrological variables for the Mangrove Hydrology Index and socio-economic variables such as the fish landing, time spent fishing, income and education for the Socio-economic Index. The PCs were ordered in such a way, that the variance of the first PCs (PC1) was the highest; the variance of the second PCs (PC2) was the second highest, and so on, whereas the last PCs was the lowest in explaining the variation of the data sets (Mustapha and Abdu, 2012).

2.4. Development of the mangrove quality index (MQI)

The overall *MQI* in this research was developed based on all 43 variables from five categories, namely mangrove biotic integrity, mangrove soil, marine-mangrove, mangrove hydrology, and mangrove socio-economic. The purpose of developing the index for the mangrove forest was to obtain a measurement that reflects the quality of the mangrove forest. There are two (2) types of index that were developed, which are *MQI* for each category ($MQIS_i$) and overall *MQI*. Steps to develop the index are as follows:

1. Conduct Principal Component Analysis (PCA) of all variables in a category,
2. Identify few most important variables in the category. The most important variables are characterized by the highest score component of each principal component (PC),
3. Identify proportion of variability which can be explained by each important component. Let's name the proportion as p_i,
4. Multiply the proportion in Step 3 by the corresponding score component, Sc_i, of each important metric and we have $pSc_i = p_i \times Sc_i$,
5. Calculate the summation of Step 4 from all important metrics, $w_T = \sum pSc_i$,
6. Calculate the weight, w_i, of each important metric by dividing its corresponding pSc_i by w_T, or $w_i = \frac{pSc_i}{w_T}$
7. Calculate the mean, $\bar{x}$ and standard deviation, s of important variables (metrics) in Step 2.
8. *MQI* for a category is developed by standardizing a particular measurement. It is done to make sure that all important metrics have the same range of measurement although it originally comes from various units,

$$z_i = \frac{x_{ij} - \bar{x}_i}{s_i}$$

9. Multiply the weight, w_i (Step 6) with its corresponding z_i and then multiplied by 2, since there are 2 important metrics that need to be selected.
10. MQI Score *(MQIS)* of a certain category is calculated using the following formula:

$$MQIS_i = \sum_{i=1}^{j} 2w_i z_i$$

11. MQI for ith category (MQISi) is shown as follows, where 1 (worst), 2 (bad), 3 (moderate), 4 (good), 5 (excellent).

$$MQIS_i = \begin{cases} 1 \text{ if } MQIS_i < -1.5 \\ 2 \text{ if } -1.5 \leq MQIS_i \leq -0.5 \\ 3 \text{ if } -0.5 \leq MQIS_i \leq 0.5 \\ 4 \text{ if } 0.5 \leq MQIS_i \leq 1.5 \\ 5 \text{ if } MQIS_i > 1.5 \end{cases}$$

where, i = 1, 2, …,5 represent the *i*th category as follows: $MQIS_1$ (Mangrove Biotic Integrity Index), $MQIS_2$ (Mangrove Soil Index), $MQIS_3$ (Marine-Mangrove Index), $MQIS_4$ (Mangrove Hydrology Index), and $MQIS_5$ (Mangrove Socio-economic Index).

In order to obtain the overall *MQI*, Step 1-Step 10 is repeated for all categories. Then the summation of $MQIS_i$ in Step 10 for each category is calculated to obtain overall *MQI* (Step 12 and Step 13)

12. Overall $MQI = \sum_{i=1}^{c} MQIS$, where c is the number of categories
13. The range of overall *MQI* is defined as follows.

$$MQI = \begin{cases} 1 \text{ if } MQIS_i < -1.5 \\ 2 \text{ if } -1.5 \leq MQIS_i \leq -0.5 \\ 3 \text{ if } -0.5 \leq MQIS_i \leq 0.5 \\ 4 \text{ if } 0.5 \leq MQIS_i \leq 1.5 \\ 5 \text{ if } MQIS_i > 1.5 \end{cases}$$

where 1 (worst), 2 (bad), 3 (moderate), 4 (good), 5 (excellent)

2.5. Normalised difference vegetation indices (NDVI)

The NDVI was used to find the vegetation index with band combinations of the remote sensing data by measuring the ability of vegetation to reflect (near-infra red-NIR channels) and absorb (red channels) electromagnetic radiation (EMR) with values from −1 to 1. If the vegetation has low reflectance (or low value) in the red channel and high reflectance in the NIR channel, this will yield a high NDVI value nearing 1, and vice versa. The NDVI was determined through SPOT image with 1.5 m resolution using ERDAS 2014 platform. In order to confirm the reliability of the developed *MQI*, the most recent image upon completion of sampling was obtained. The NDVI obtained was then used to confirm the degree of disturbance of the sampling sites.

3. Results

With 43 variables selected and analyzed using PCA analysis, a total of 10 final selected variables were used in the formulation of the overall *MQI*. These variables represent the five major components of the mangrove ecosystem including Mangrove Biotic Integrity Index (2), Mangrove Soil Index (2), Marine-Mangrove Index (2), Mangrove Hydrology Index (2) and Mangrove Socio-economic Index (2). Each of the sub-category (*MQIS*) can also be used individually to assess the health status of the ecosystem's major components.

3.1. Mangrove biotic integrity index

From five variables subjected to the PCA, the aboveground biomass of the mangrove trees and the abundance of crabs contributed to 91% of the cumulative variation (Table 1). 74% of total variance of Principal Component 1 (PC1) is aboveground biomass (0.47) with the mean values 3.61 ± 0.04 whereas PC2 had high scoring on the abundance of crab (0.96) with the mean values 4.73 ± 7.54, contributed 17% of the total variation respectively. Therefore, the aboveground biomass and crab abundance were chosen in the development of the overall *MQI*.

3.2. Mangrove soil ndex

Six variables of soil metrics were subjected to PCA where soil Nitrogen and soil Carbon accounted for about 79% of the cumulative variation (Table 2). Principal Component 1 (PC1) explained 60.7% of the total variance and had high loading of soil Nitrogen (0.47) and soil Carbon (0.49) with mean values of 0.35 ± 0.03% and 10.71 ± 0.67%, respectively (Table 2). Meanwhile, PC2 has high loading of both soil Magnesium (0.68) and soil Calcium (0.68), which explained 18% of total variation with mean values 4766.50 ± 67.71 µg g^{-1} and 4.56 ± 0.09, respectively. The best two variables were chosen for the development of the overall *MQI* which are soil Nitrogen and soil Carbon.

3.3. Marine-Mangrove index

Of the ten variables subjected to PCA, the number and abundance of phytoplankton and diatoms species accounted for about 49.9% of the cumulative variation (Table 3). Principal Component 1 (PC1) explained 31% of the total variance and had high loading on number of

Table 1
Biotic variables (mean ± Standard error of the mean-SE) and principle component analysis (PCA) statistics from all the sampling sites in Matang mangrove with their corresponding PCA statistics.

Variables	Unit	Min	Max	PC1	PC2
Tree Height	M	4.77	8.45	0.36	0.19
Basal area	(m^2/ha)	0.09	0.35	0.46	−0.14
Tree Volume	(m^3/ha)	0.29	2.19	0.46	−0.14
Aboveground Biomass	(tonne/ha)	7.83	61.32	**0.47**	0.08
Crab Abundance	–	3	91	0.06	**0.96**
PCA statistics					
Eigen values				4.41	1.04
% variation				74.00	17.00
Cumulative % variation				74.00	91.00

Table 2
Soil variables (mean ± SE) from all the sampling sites in Matang mangrove with corresponding PCA statistics.

Variables	Unit	Min	Max	PC1	PC2
Soil C	%	5.19	22.23	**0.49**	0.16
Soil N	%	0.06	0.74	**0.47**	−0.22
Soil P	$\mu g\ g^{-1}$	1.97	4340	−0.37	−0.09
Soil K	$\mu g\ g^{-1}$	943	1710	−0.43	0.015
Soil Ca	$\mu g\ g^{-1}$	2036	9285	−0.34	0.68
Soil Mg	$\mu g\ g^{-1}$	3795.5	5714	0.34	0.68
PCA statistics					
Eigen values				3.64	1.08
% variation				60.67	17.97
Cumulative % variation				60.67	78.65

Table 3
Marine variables (mean ± standard error) and principle component analysis (PCA) statistics from all the sampling sites in Matang mangrove with their corresponding PCA statistics.

Variables	Unit	Min	Max	PC1	PC2
No. of phytoplankton species	Number	6	71	**0.51**	0.25
Phytoplankton abundance	cells ml^{-1}	42.00	856.39	−0.28	**0.60**
No. of diatom species	Number	1	58	**0.48**	0.21
Diatom abundance	cells ml^{-1}	0.93	834.32	−0.24	**0.61**
No. of dinoflagellates species	Number	1	17	0.32	0.30
Dinoflagellates abundance	cells ml^{-1}	0.29	317.56	−0.13	−0.02
No. of copepods species	Number	3	14	0.25	0.04
Copepods abundance	Ind. m^{-3}	165.22	48251.16	0.22	−0.23
No. of Jellyfish species	Number	0	8	0.39	0.05
Jellyfish abundance	Ind. m^{-3}	0	478.99	−0.03	−0.10
PCA statistics					
Eigen values				3.11	1.89
% variation				31.05	18.85
Cumulative % variation				31.05	49.90

phytoplankton (0.51) and number of diatom species (0.48) (Table 3). Meanwhile, PC2 had high loading on the abundance of phytoplankton (0.60) and diatom (0.61), which explained 19% of total variation. The best two variables were chosen for the development of the overall *MQI* which were the number of phytoplankton species and number of diatom species.

3.4. Mangrove hydrology index

Hydrology characteristics in mangrove areas are much influenced by extrinsic factors including tidal effects, seasonal variation, sea-water intrusion and pollution contribution from the upstream of mangrove-rivers. Seven metrics in hydrology subjected to PCA were identified, which are Electrical Conductivity (EC), Dissolved Oxygen (DO), pH, Turbidity, Total Dissolve Solid (TDS), Temperature and Total Suspended Solid (TSS). Out of those important metrics, two of them are the most important metrics that can be used as indicators to reflect the quality of mangrove forest. The two metrics are Dissolve Oxygen which comes from the first principal component and Turbidity which comes from the second principal component. These two components accounted for about 55.74% of the total variability (Table 4). The scores of principal component corresponds to each principal component as shown in Table 4. PC1 has the highest score of DO (0.58), which explained 30.95% of total variation with mean values 3.36 ± 1.89 mg/L. Meanwhile, PC2 has the highest score from Turbidity (0.64), which explained 24.79% of total variation with mean values 59.68 ± 40.21 NTU. Thus, these two variables were chosen for the development of the overall *MQI*.

Table 4
Water quality variables (mean ± SE) from all sampling points in MMFR with the corresponding PCA statistics.

Variables	Unit	Min	Max	PC1	PC2
EC	(μS/cm)	0.621	410.7	0.19	−0.02
Dissolved Oxygen	(mg/L)	0.16	10.42	**0.58**	0.10
pH	–	6.21	8.90	−0.09	−0.29
Turbidity	NTU (Nephelometric Turbidity Unit)	2.29	819	−0.21	**0.64**
Total Dissolved Solid	(mg/L)	0.24	57.3	0.52	0.06
Temperature	°C	24.3	32.2	0.55	−0.02
Total Suspended Solid	(mg/L)	0.1	41.7	0.05	0.69
PCA statistics					
Eigen values				2.17	1.74
% variation				30.95	24.79
Cumulative % variation				30.95	55.75

3.5. Mangrove socio-economic index

Of the six variables subjected to PCA, education level and time spent fishing accounted for about 44.5% of the cumulative variation percentage (Table 5). Principal Component 1 (PC1) explained 25.43% of the total variance and has high loading on education level (0.57) with the mean and standard error of 9.24 ± 0.138. Meanwhile, PC2 has high loading on the time spent (0.58) with the mean and standard error of 9.24 ± 0.183 which explained 19.07% of total variation. Thus, the best two variables chosen for the development of the overall *MQI* are education level and time spent of the fishermen based on highest significant score from the first two results of PCA.

Table 6 shows the developed *MQI* for Matang mangrove. PCA selected variables of each category is arbitrarily set and has a value within the range of empirical measurement. Assigning the value to the *MQI* index that has been formulated will produce both index for each *MQIS* and overall *MQI*.

4. Discussion

Only a few methodologies are currently available for integrating physico-chemical and biological factors in assessing ecological status on the basis of ecosystem-based approach (Mahoney and Bishop, 2017). Marshall et al. (2018) reported that key abiotic factors and biota were the critical measures to include in determining the status and risk of an estuarine habitat. Thus, in this study, we considered 43 key variables for the Matang mangrove including socio-economy. For the Matang mangrove ecosystem, ten variables to reflect mangrove biotic integrity, soil condition, marine environment, hydrological status and socio-economic status were deemed significant for the development of an ecologically and socio-economically important index, the *MQI*. Fig. 2 summarizes the work flow in the development of the MQI and its validation.

4.1. Mangrove biotic integrity index

Principle component analysis (PCA) of all the tested variables in this study showed that aboveground biomass and crab abundance contributed to the highest score of the total variance. Different levels of disturbances which are least, moderate and most disturbed gave different values significant in aboveground biomass and abundance of the crabs.

The aboveground biomass represents the physical condition of the mangrove forest and with the crab abundance could assist in determining the health of mangrove forest (Alongi, 2009; Goessens et al., 2019). Replanting of selected mangrove species could significantly

Table 5

Socio-economic variables (mean ± SE) and principal component analysis (PCA) statistics from all sampling sites in MMFR with corresponding PCA statistics.

Variables	Unit	Min	Max	PC1	PC2
Fish landing	Weight of fish catches (kg/day)	3	500	0.39	0.01
Time spent	Number of hours fished (hour)	2	24	0.39	**0.58**
Fishing effort	Number of days fished (days/week)	1	7	0.02	−0.54
Income	Monthly income (USD/person)	48.78	2073.17	0.39	0.34
Age	Fishermen's age (year)	18	81	−0.47	0.44
Education	Fishermen's education level (no of years)	1	16	**0.57**	−0.26
PCA statistics					
Eigen values				1.53	1.14
% variation				25.43	19.07
Cumulative % variation				25.43	44.5

promote high propagule predation by crabs and also result in increased tree biomass (Ashton, 2002; Ferreira et al., 2015). High aboveground biomass and high crab abundance forms a stable community structure in mangrove forest (Goessens et al., 2019). This is further supported by Ferreira et al. (2015) who found crabs to increase in number in the pristine or good area due to good propagule consumption.

In this study the higher abundance of crab is from the least disturbed area compared to high and moderately disturbed areas of the mangrove. The most disturbed area has the least number of crabs. According to Goessens et al. (2019), the sustainable wood production in the mangrove is related to ecosystem interactions between the biota including crab abundance and aboveground biomass.

The Mangrove Biotic Integrity Index obtained for the least disturbed area is 4 which is ranked good, representing the condition of the forest in this area which has a good vegetation stand and bigger diameter trees contributing to a reasonably good aboveground biomass as well as the presence of high numbers of crabs. The good condition of Matang forest and its reasonable aboveground biomass values is also supported by Faridah-Hanum et al. (2012). Ferreira et al. (2015) showed that selected species of the vegetation such as *Rhizophora apiculata* and *Rhizophora mucronata* in replanted forest like Matang could stimulate other functional groups in the forest such as crab assemblages. Ferreira et al. (2015) also suggested that plant height, crab assemblages and tree biomass increased significantly in replanted mangrove forest; here the least disturbed area had gone through first thinning and replanted 20 years ago. This was further supported by Goessens et al. (2019) who proposed that Matang mangroves replantation was appropriately managed with best practices. The moderately disturbed area gave a slightly lower score of 3 than the least disturbed area; its first thinning, and then replanting of this area was done several years later than the least disturbed area.

The high abundance of crabs was also due to their foraging activities. Some mangrove crabs are very selective in consuming the mangrove vegetation. It was found that mangrove crabs from the family Sesarmide would prefer to consume fresh leaves of *Rhizophora apiculata* and propagules of *Avicenna officinalis* (Ashton, 2002). Crab abundance with many burrows was noted to be high in areas with a good canopy cover that protects them from drying at certain times of the day, further supporting the mutual relationship between the crabs and mangrove vegetation. The most disturbed area having the lowest score, 1, ranked the worst; the lowest aboveground biomass obtained in this area was mostly from smaller diameter trees that were newly planted. In addition, the area was in a muddy and rather oily state making it unfavourable for the crabs.

For the Mangrove Biotic Integrity Index, crab abundance the aboveground biomass variables were chosen for the development of the overall *MQI*. Wilson (2009) used the number of crab holes instead of crab abundance as one of the variables to develop the mangrove quality index of Tampa Bay mangroves as crab holes are considered an indicator of condition because they can increase the quality of the habitat and the plant species (Hogarth, 2007). A score of 1 was assigned to the number of crab holes indicating the most pristine conditions and a score of 5 to the lowest quality mangroves (Wilson, 2009).

The vegetation variable that was found to be important for the development of Matang $MQIS_1$ was aboveground biomass and not the number of species or absolute density of trees as proposed by Wilson (2009). The number of plant species in some wetlands could be indicative of ecosystem health but not necessarily so with mangroves (Hogarth, 2007), hence biomass was a better choice for the development of Matang $MQIS_1$.

4.2. Mangrove soil index

Soil Mangrove Index consisted of soil Total Carbon (C) and Nitrogen (N). However, Phosphorous (P) and Potassium (K) were also prominent in the PCA. These four nutrients play an important role in mangrove productivity since these nutrients influence mangrove vegetation structure and species composition (Hossain and Nuruddin, 2016). However, soil in mangrove areas are largely known to have low nutrient availability (Lovelock et al., 2005). This low nutrient availability is determined by multiple factors such as sediment and nutrient fluxes, tidal range and substrate types. In order to overcome this limitation, mangroves have evolved traits for the acquisition and conservation of nutrients in low-fertility environments.

In mangrove soils, N is considered as the primary nutrient that affects growth and structure of forest structure and composition (Elser and Hamilton, 2007). Nitrogen is important in mangroves trees because it is a major component of chlorophyll and amino acids, the building block of proteins. However, N in the mangrove area is limited due to strong weathering of old highly leached soils of the tropics.

Mangrove ecosystems are carbon-rich ecosystems capturing and preserving significant amounts of carbon (McLeod et al., 2011). They acquire carbon by photosynthesis, by macroalgae in colonizing root of aboveground biomass and microalgae carpeting portions of the forest floor and transport and deposition materials from upstream and from the adjacent coastal zone (Alongi, 2014).

Besides C and N, Phosphorus in the form of phosphate is another important nutrient in the mangrove ecosystems. It plays an important role in plant growth and vital component of DNA and RNA where both structures are linked together by a phosphorus bond. Phosphate in mangrove soils can be immobile and unavailable for plant use. Mycorrhiza fungi play an important role in solubilizing P making it available for plant uptake. However, this mychorrhiza can only be found in low salinity water. Additionally, Potassium also plays an important role in mangrove plant growth and reproduction. It helps in osmotic regulation, enzyme activation, protein synthesis and photosynthetic metabolism (Leigh and Jones, 1984). A high K:Na ratio in leaf and root cells is essential to maintain semi-permeability of the plasmalemma (Yates et al., 2002). Survival of mangroves in saline conditions depends on their ability to maintain this ratio. K limitation may lead to reduced flowering and seed set in some mangrove areas.

Principal component analysis (PCA) of measured soil metrics show

Table 6
Summary of Simulated *MQI* Values Based on ten Variables identified through PCA.

No.	Category	Variable	Environment *MQI* (*MQI*e, based on disturbance levels, a-c)		
			Least Disturbed (*MQI*ea)	**Moderately Disturbed (*MQI*eb)**	**Most Disturbed (*MQI*ec)**
1	Mangrove Biotic Integrity	Above Ground Biomass Crab Abundance	4 (21.47; 39.00)*	3 (32.00; 70.00)	1 (24.00; 10.00)
2	Mangrove Soil	Soil N Soil C	5 (0.30; 9.52)	3 (0.40; 9.60)	1 (0.50; 15.00)
3	Marine-Mangrove	No of Phytoplankton Species No of Diatom Species	5 (53.00; 38.00)	4 (27.00; 37.00)	2 (10.00; 12.00)
4	Mangrove Hydrology	Dissolved Oxygen Turbidity	4 (6.00; 7.00)	3 (4.00; 40.00)	2 (2.00; 91.00)
Overall Environment *MQI* (*MQIe*)	5	3	1		
	Socio-economic *MQI* (*MQIse*)				
5	Mangrove Socio-Economic	Education (Years of Education) Time Spent (Hours)	4 (11.00, 10.00)		
	Overall *MQI*	**5**	**4**	**2**	

* Random value for: (Variable 1; Variable 2).

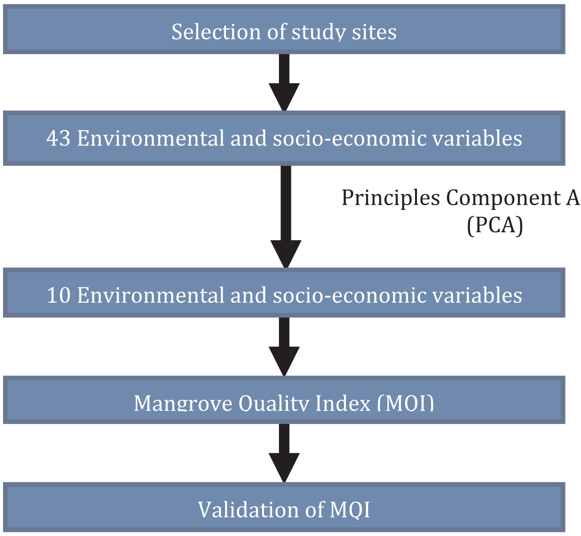

Fig. 2. Flow chart in the development of MQI and validation.

that soil Nitrogen and soil Carbon contributed to the highest score of the total variance. Both soil Nitrogen and soil Carbon accounted about 74% of the cumulative variation. Both nutrients are important in the growth and productivity of mangroves species (McLeod et al., 2011). These two soil metrics were used for the development of $MQIS_{2.}$

Soil Carbon content increases from the least disturbed sites to the most disturbed sites. Mean Soil Carbon content at the least, moderate and mostly disturbed areas were 8.7%, 9.20% and 17.50%, respectively. Soil Nitrogen content also follows a similar trend with soil Carbon content increasing as the level of disturbance increases. Mean soil Nitrogen content in least, moderate and most disturbed areas are 0.21%, 0.38% and 0.58%, respectively.

Mangrove forest disturbances opens the forest canopy allowing increasing solar radiation on to the forest floor. The increased soil temperature enhances microbial respiration and process of organic decomposition increasing the organic decomposition hence increasing the soil Carbon. This is also true for soil Nitrogen where higher disturbances cause increases in soil temperature and accelerate mineralization and nitrification of Nitrogen organic compounds.

4.3. Marine-Mangrove index

The marine-mangrove ecosystem is vulnerable to environmental stressors such as pollution and drastic fluctuations of habitat parameters resulting from habitat and climates change. Ventura and Lana (2014) established a vulnerability index of a mangrove ecosystem based on the exposure to stress, and the sensitivity and adaptive capacity of the mangrove system to the stressors. In this study, of ten different marine environmental variables (Table 3), only two (the number of phytoplankton and diatoms species) accounted for about 51% of the cumulative variation. Use of phytoplankton as an indicator of ecological change could probably be due to its critical position at the base of the aquatic food chain. Lugoli et al. (2012) also used phytoplankton as an index to assess the ecological status in marine and transitional waters.

Phytoplankton as the base of the aquatic food chain plays an important role in providing the energy for the rest of the trophic levels. Together with macrophytes, they determine the productivity of the ecosystem through photosynthetic process which are controlled by the availability of light, carbon dioxide and nutrients (Imaizumi et al., 2014, 2016). However, phytoplankton responses to the environmental change faster than macrophytes due to their smaller size and shorter growth cycle (Stanca et al., 2012). Thus, each phytoplankton species has its own characteristics of growth, and a group of phytoplankton species with similar requirements would often form a community with special structure that corresponds to the environmental quality (Yusoff et al., 2002, 2010).

Taxonomic composition of phytoplankton had been used widely to measure the impact of eutrophication (Cosme et al., 2017). Our data revealed that high distribution of phytoplankton species was found in the least disturbed area compared to moderately and highly disturbed area. High disturbances in coastal ecosystem will cause deterioration on the species diversity and species richness of phytoplankton communities (Mackey and Currie, 2001). In this study, there was a high correlation between disturbance levels at different sites with the phytoplankton species richness. Compared to other phytoplankton groups, diatoms were commonly being used as bioindicator because they normally respond to nutrient loading in coastal waters (Antonelli et al., 2017; Desrosiers et al., 2013). According to Shipe et al. (2006), coastal waters have higher primary productivity than the oceanic area, which consisted mainly of diatoms.

Principle Component Analysis (PCA) of all the marine biotic variables in this study showed that the number of species and abundance of the total phytoplankton and diatoms from two principal components contributed to 49.9% of the total variance. The sensitivity of the phytoplankton populations to environmental changes such as nutrients, turbidity and salinity resulted in changes of their species number and abundance (Nursuhayati et al., 2013; Revilla et al., 2009). Thus, for the development of the overall $MQIS_3$, the two most important variables (the number of total phytoplankton and diatom species) were identified, based on their high percentage of eigenvalues from the first principle component.

In the Matang mangrove ecosystem, Sg. Tiram river represented the least disturbed area since the surrounding mangrove forest was left intact and contributes only natural allochthonous materials to the river such as leaf litter in different stages of decomposition process. Thus, the total dissolved solids in this river was significantly higher than other rivers (Tinggi and Sepetang rivers), which were more turbid with high contents of suspended solids. Sg. Tinggi (classified as moderately disturbed) and Sg. Sepetang (the most disturbed) had significantly higher turbidity with erosion materials from the surrounding mangroves which undergo regular rotational harvesting as well as contribution from the upstream anthropogenic activities. Sg. Tiram which has higher water transparency and lower nutrients compared to the other two, showed an environmental index (*MQI*e) of 5 (on a scale of 1–5, Table 6), indicating that the area is relatively pristine. In addition, the river is not directly influenced by other incoming rivers from the mainland due to its location on an island, and this explains the significantly higher salinity in this area compared to the others. Sg. Tinggi which is categorized as moderately disturbed has *MQI*e of 4, indicating that the water was still good as it has problems mainly with nutrients from the cage culture activities that cause *Skeletonema* blooms from time to time. Sepetang river is subjected to both high silt and nutrient inputs showed an *MQI*e of 2, indicating that the poorest environment in the Matang mangrove area surveyed but does not constitute to be the worst case in the whole coastal waters. More disturbed mangrove ecosystem would have the *MQI*e value of 1 when the diversity of phytoplankton is badly affected by the environmental stressors. Since the marine area forms a significant part of the mangrove ecosystem, the Marine-Mangrove Index should be accounted in the formulation of the overall *MQI*. In this study, the choice of the two variables (the number of phytoplankton and diatom species) is appropriate as the values are relatively easy to determine, and they significantly reflect the real environmental conditions and status of the mangrove ecosystem.

In the Matang mangrove-marine environment, phytoplankton species and diatom species were the two most important metrics identified by PCA. Berezina et al. (2017) used phytoplankton as a biotic index to characterize the quality of the entire water column of a coastal habitat, where they classified the environment into a five-grade scale; where, 1 = high, 2 = good, 3 = moderate, 4 = poor and 5 = bad. Many studies used the phytoplankton community structure as biological indicators for water quality and marine ecosystem health status (Lugoli et al., 2012; Ali and El Shehawy, 2017; Wasmund et al., 2017), supporting the selection of phytoplankton as indicators of mangrove-marine cosystem health in this study. Ali and El Shehawy (2017) reported a significant decrease of phytoplankton species diversity as a response to pollution in the rover Nile, Egypt. Lugoli et al. (2012) established a size-spectra sensitivity phtoplankton index (ISS-Phyto) to dicriminate natural vs anthropogenically caused polluted/disturbed conditions.

4.4. Mangrove hydrology index

Hydrology characteristics in mangrove areas are much influenced by natural behaviour in mangroves i.e. high and low tides and seasonal variation (Gopal and Chauhan, 2006). The stream network in mangroves also varies between places depending on the inland formation (Perillo, 2009). Some rivers flow from inland area and discharge at the mangroves, bringing all water and pollutants from upstream sources to the mangrove area. Some streams flow within mangrove areas and the hydrology characteristics are much influenced by the soil type, vegetation and human activities including tourism, economics (i.e. fishing), logging, agriculture etc. around the mangrove areas (Alongi, 2002). The hydrology characteristics including the water quality in the area is important for sustaining mangrove health due to the threats of land use change and climate change. Water quality study was conducted to characterize the mangrove health in terms of the quality of water. The water quality parameters selected for this study were DO, pH, EC, Turbidity, TSS, TDS, salinity, temperature, BOD, COD, NH_3-N, NO_3-N, $PO_3{}^4$ and Fc. DO and Turbidity were selected based on the highest importance of parameters through PCA as indicators for the Mangrove Hydrology Index.

Dissolved Oxygen (DO) is the amount of oxygen that is dissolved and available in water (Said et al., 2004). Small amounts or concentration of oxygen that dissolves in water limits the availability to aquatic organisms. DO measures the amount of oxygen dissolved in a stream, lake, ponds or irrigation water (UNEP, 2001). The analysis of DO is important in water quality monitoring programs (Cox, 2003; Hanrahan, 2012). DO is essential to fish and all other aquatic organisms at all stages of their life, metabolism of aerobic organisms and also directly influences inorganic chemical reactions. As a general indicator water quality, DO levels that fall below 5 mg/L are indicative of biological stress. DO concentration must be high enough to support the variety of aquatic organisms and aquatic plants (Smith, 2004; Rosli et al., 2010; Hanrahan, 2012).

Turbidity refers to how clear the water condition is (APHA, 2005). It indicates the amount of fine particles suspended in water (WRHMD, 2009) such as clay, silt, organic matter, industrial wastes, sewage plankton or decomposer organisms. High turbidity is caused mainly by large concentrations of sediments that are washed off in catchments into streams and rivers and ultimately into estuarine and marine environments. Particles absorb heat from the sunlight, thus raising water temperature which will decrease dissolved oxygen levels (RAP, 2002; UN GEMS, Water, 2005). High turbidity prevents the sunlight from reaching the aquatic plants below the water surface. This will lower the rate of photosynthesis which will decrease the amount of oxygen produced by plants (Johnson et al., 1999).

Principle Component Analysis (PCA) of all the hydrology and water quality variables in this study showed that DO and Turbidity contributed to 55.75% of the total variance. Thus, for the development of $MQIS_4$, the two most important variables (DO and Turbidity) were identified, based on their high eigenvalues from the first principle component. In our study, DO was significantly correlated with Salinity, TSS and Temperature. The *in situ* measurement of both DO and Turbidity are easy and fast for the validation process which could promote efficient practical assessment of hydrology health in mangrove when applying the developed $MQIS_4$.

The variables DO and Turbidity were used to test three different conditions of mangrove forests here viz., least disturbed (*MQI*ea), moderately disturbed (*MQI*eb) and highly disturbed (*MQI*ec). The least disturbed mangrove forest (*MQI*ea) gave values of DO and Turbidity (6 and 7, respectively) where input in the developed *MQI* and the score obtained for *MQI*ea was 4 which is categorized as a good quality mangrove forest. For moderately disturbed mangrove forest (*MQI*eb), the two values of DO and Turbidity (4 and 40, respectively) were input in the developed $MQIS_4$ and the score obtained for *MQI*eb was 3 which is categorized as a moderate quality mangrove forest. Meanwhile, for the highly disturbed mangrove forest (*MQI*ec), the two values of DO and Turbidity (2 and 91, respectively) were input in the developed $MQIS_4$ and the score obtained for *MQI*ec was 2 which is categorized as a bad. Thus, the two variables, DO and Turbidity were proven worthy variables which can represent the hydrological condition of the mangrove forest area through the developed $MQIS_4$.

4.5. Mangrove socio-economic index

Two socio-economic variables from the PCA were found to have significant relationships in explaining the quality of mangrove (Table 5). Fishermen's education level and time spent in the observed mangrove area were found to have significant influence as an indicator of mangrove socio-economic factor. Positive scores of the two variables indicate that an increase in years of education and higher hours spent for fishing contributed to higher tendency of local reliance and on the quality of the mangrove.

Braga et al. (2017) found that fishermen with higher educational level possess more positive attitudes in relation to environmental conservation issues. In addition, Sawairnathan and Halimoon (2017) found that educated people and those living close to the mangrove forest are more willing to support the conservation of mangroves. Sharma and Leung (1998) found that the fishermen's education level has a positive influence on technical efficiency on longline fishery. The effect of education on an individual is more lasting in that it will increase his or her knowledge and may eventually impact the cognitive ability of a person. This will normally shape his perception and attitude in a more matured manner in portraying a better understanding on warning signs of mangroves vulnerability, hazards and risk misperception (Collins, 2014; Quader et al., 2017). It was also found that time spent in the mangrove environment results in a positive relationship with the quality of mangrove. The more a local spends time as a fisherman in the mangrove area, the higher his dependence on that ecosystem. This is in line with Batista et al. (1998) who identified the positive effects of fishermen's time spent on fishing around mangrove areas. Thus, it is important for them to conserve the mangrove because it is their main source of income.

The value of the two variables was randomly selected within the range of standard deviation with mean as a base value. Eleven years of education was fit for the test as it portrays local likelihood of studying until secondary school. Meanwhile 10 h spent in fishing activities is relevant and relates well with the fishermen's routine, which usually starts early in the morning and ends in the evening. The overall rank for the observed Mangrove Socio-economic Index was ranked as (4) which signifies good ecosystem quality as highlighted in Table 6. The rank defines that locals do depend on the existence of the mangrove based on the factors of fishermen's education level with duration allocated for fishery in a day.

Higher education level of fishermen may constitute with better awareness on mangrove conservation. Although this study did not quantify the quality of education, a rough estimation is made based on the period of learning perceived by respondent with perception that longer time spent in education leads to a better understanding and appreciation of the ecosystem. The lack of education and experience in understanding nature leads to lower awareness and proper attitude of fishery which causes adverse influence to the ecosystem. Walton et al. (2006) found that locals with good education background are generally willing to pay more for ecosystem conservation compared to those who are lacking. On the other hand, locals with poorer education background are willing to accept lower prices when selling land although they depend much on the mangrove ecosystem for their livelihood.

Insufficient knowledge on the environment is also found to be a factor to poor living conditions among locals that depend much on an ecosystem service (Saavedra-Díaz et al., 2015). There are pull factors for local demands to better understand nature through awareness and educational programs (Saavedra-Díaz et al., 2016). Being in poor conditions and lacking in knowledge are linked with the local's problem to assess other opportunities to improve their living. Glaser (2003) implied that having inferior knowledge is connected with youth entrance in fishery sectors as they fail to realize alternatives of income generation despite the older generation not desiring their inheritance of the occupation. Given another perspective, if the community has been well taught, the youth is anticipated to move outside of their origin for higher income and better living which in turn decreases the level of local dependence on mangroves.

Pertaining to this study, a mangrove area can be ranked as at least (4) when the community generally ends their formal school period which is 11 years. Higher education levels among locals may lower community dependence on mangroves in a longer time frame, however, proper attitude towards nature and willingness to conserve will be favorable if awareness is well nurtured within the community. This shows that sufficient education in school gives rise to positive mangrove awareness and dependence.

Time spent can be defined as the duration of an activity for the collection of resources (Ekka and Pandit, 2012). In general, time spent consists of duration traveling to and searching for species pooling area, including the period of, waiting, catching, and related technical carried out at the capturing site (Cooke and Beddington, 1984; Sathirithai, 1998; Albert et al., 2015). This factor influences fishing effort of marine products which is also associated with other factors such as species catch rate (Roberts and Sargant, 2002). Catch rate can be considered low if a fishermen aims for a particular species in specified quantity and quality which also depends on fishing effort made. In a way, catch rate is related to species abundance and in turn also impacts a fisherman's time accommodated for harvesting (Cooke and Beddington, 1984). Lower quantity of produce in a longer time of harvest causes several economic losses to fishermen which can be seen from higher expenditure for resources such as fuel (Sanchirico, 2000). In addition to that, longer period of time spent for smaller harvest quantity proves to be a waste of opportunity cost considering that fishermen may able to generate more income from other activities.

Fishermen who are willing to spend more time for capture in an ecosystem shows their high dependency on the availability of resources there. The situation in the Matang Mangrove Forest shows a decline in the fishery yield, mainly due to mangrove areas being converted to other land use such as agriculture, housing, aquaculture, shrimp farming, ecotourism areas, and industrial development. Changes to landscape alter ecological function that influences resource readability, which also prompt uncertainty to production function (Barbier, 2000). However, the increased time spent is also found to further cause reduction to species abundance (Sanchirico and Wilen, 1998). High number of fishermen in an area creates stiff competition which persuades them to commit more time for harvesting in the short run. Overcapacity of fishermen in an area causes adverse impact to the habitat. In the long run, the area requires more incentives for conservation due to an increase of dependence among fishermen to the ecosystem (Sanchirico, 2000).

It was found that the time spent i.e. 10 h for harvesting, shows significant dependence of the fishermen to the mangrove area which yields an index rank of (4). Although profit or the amount of produce is able to provide relevant economic information on the fishermen, time

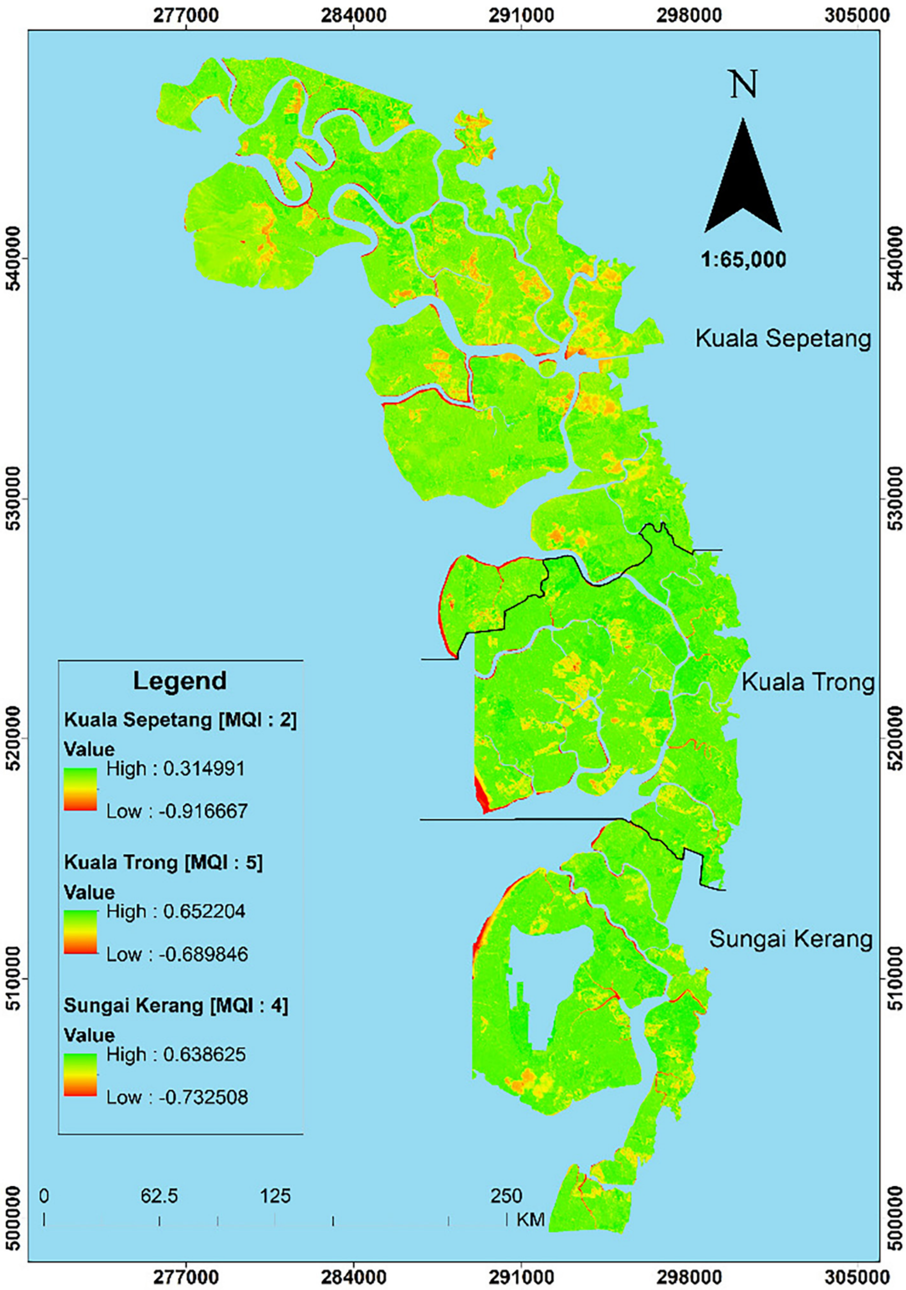

Fig. 3. Computed NDVI image with three different degrees of disturbances of the Matang Mangrove Forest.

spent shows a measure of how much the fishermen relied on resources availability in an ecosystem (Ruitenbeek, 1992). The longer the time taken by the fishermen to obtain resources depicts the community's high reliance on the ecosystem for income generation. This also indicates the need to conserve the area where resources may be in decline requiring higher time spent for harvest (Hutchison et al., 2014). The combined factors of educational years and time spent can be interpreted as the mangrove being of good quality. Thus, in term of socio-demography, if a community spends longer time in education it will increase their awareness on the proper attitude in fishery and the need to conserve the area; also, longer time spent for resource collection shows high community dependence on the mangrove forests which indicates the need for conservation.

4.6. *Mangrove ecosystem health and MQI*

The Matang mangrove forest undergoes 15–25 years of rotational timber production system (Roslan and Nik Mohd Shah, 2014) resulting in uneven forest stand age with different species and density. This will produce variations in the images captured by remote sensing. From the working plan of Matang mangroves within the studied compartment (Rhyma et al., 2015), areas ranked as 5 (least disturbed) and 4 (moderately disturbed) were harvested in 2011 and 2013, respectively, and ranked as 2 (most disturbed) for the area harvested in 2015. In order to verify the ranking of these areas, recent image analyzed through NDVI gave values of −0.916 to 0.315 for the area ranked as 2, −0.732 to 0.638 for the area ranked as 4, and −0.689 to 0.652 for area ranked as 5 (Fig. 3). The NDVI values nearing 1 in areas ranked as 4 and 5 show the vegetation is more dense while NDVI value nearing −1 in areas ranked as 2 shows the area being less dense with vegetation, hence supporting the overall *MQI* obtained to indicate the Matang mangrove ecosystem health.

5. Conclusions

Currently, indices to measure the status of mangrove are not comprehensive, therefore integrative ecological-socio economic based approach is crucial in measuring the overall performance and health status of an ecosystem. Thus, this study explored all key biological, hydrological, ecological and socio-economic perspectives of the Matang mangrove ecosystem, covering the whole range of conditions from disturbed to pristine states, both in terrestrial and marine environments. In assessing an ecosystem mangrove health status based on the ecosystem approach, 43 variables were selected from five categories (mangrove biotic integrity, mangrove soil, marine-mangrove, mangrove hydrology, and mangrove socio-economic), and these key parameters were measured over a period of one year to cover the various seasons in a tropical setting in three different habitats categorized as disturbed, moderately disturbed and pristine conditions.

In this study, 43 variables were subjected to PCA and related statistical analyses where ten key important variables were selected to be accounted in the final determination of the overall *MQI*. Based on these ten variables, the $MQIS_4$ was developed using Principal Component Analysis (PCA) to reflect the overall status of mangrove ecosystem health. This overall *MQI* was obtained based on the score ($MQIS_i$) of ecosystem-socio-economic categories which were Mangrove Biotic Integrity Index ($MQIS_1$), Mangrove Soil Index ($MQIS_2$), Marine-mangrove Index ($MQIS_3$), Mangrove Hydrology Index ($MQIS_4$) and Mangrove-Socio-economic Index ($MQIS_5$). Two most important variables from each category were selected by PCA for the development of $MQIS_i$ and overall *MQI*. The application of this *MQI* on the Matang mangrove ecosystem showed that the least disturbed area was ranked as excellent (5), moderately disturbed area as good (4), and the most disturbed area as bad (2). Normalized Difference Vegetation Index (NDVI) supported the developed overall *MQI* where it is reflective of the three different types of disturbance; NDVI values nearing 1 shows higher vegetation cover while that nearing -1 indicates lower vegetation cover. The NDVI values obtained tallied with the overall *MQI*. The Matang mangrove forests can be managed with the objective of improving quality based on the overall *MQI* developed, in which an increasing *MQI* score indicates the increasing quality of the mangrove. Thus it will be a useful tool for monitoring and managing the health of mangroves in Matang and beyond.

The application of MQI will help to reduce manpower, time and cost in monitoring the mangroves compared to the current practice of checking manually the timber stock volume data as an indicator of mangrove health. MQI can form a basis for potential smart automated monitoring system using Internet of Things (IoT) and artificial intelligent technologies. This would ensure the sustainability of the mangrove ecosystem and its services for the current and future generations.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.02.030. These data include Google maps of the most important areas described in this article.

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