Tree inundation period determination for mangroves rehabilitation monitoring

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Abstract. Mangroves services as coastal bioshield have been long acknowledged after the presence of mangroves has diminished a series of destructions from the extreme coastal force as a coastal barrier. However, to date, mangroves have been under threat mostly by anthropology activities. Mangroves deforestation happened at alarming rates and mangroves replanting, and rehabilitation effort yet to reach an acceptable success rate. To improve the success rate, mangroves inundation period monitoring using tacheometry method has been proposed. The approach used datum projected land elevation and mangroves tree height and overlay with annual tidal fluctuation from tide prediction tables. The output is a total inundation period for predetermined mangroves trees. Mangroves area geometry (MAG) was established at Kampung Sungai Melayu, Johor Bahru as a pilot area. Land elevation and mangroves tree height were measured using tacheometry method. Tidal fluctuations were generated based on the year 2020 Johor Bharu tidal prediction tables. From the overlay of these two datasets, five out of 40 mangroves tree in MAG area never been fully inundated but rather partly under the water surface during the high-water tide. A significant finding from the overlay is, two mangroves trees spending more than half of the year 2020 being submerged underwater and still survived. Despite the time consuming, tacheometry method for mangroves tree growth monitoring did provide a reliable and precise tree inundation period measurement.

1. Introduction
In the past two decades, many researchers have highlighted the potential for mangrove forests to protect coastlines against hurricanes, typhoons, and storm surges [1]–[9]. Mangroves also provide several other ecosystem services [10]–[14] such as nurseries for commercial fish stocks and storing large quantities of so-called "blue carbon" [14]–[25]. It has been suggested that restoration and encouraging mangroves to grow along populated coastlines could reduce risks associated with the sea-level rise [6], [7], [26]–[29] and other extreme natural disasters.

These important ecosystems are threatened by deforestation, which is reported to be proceeding at an alarming rate, despite all of the protection and services dedicated to them [3], [9], [16], [17], [23], [30]–[42]. Ironically, the regions with the largest (by area) mangrove forests, and that benefitted most from the protection available to them, are also the regions which have undergone the most rapid reduction in mangroves in the past decade. From 2000 to 2012, South East Asia (SEA) lost nearly 100,000 hectares of mangroves covering about 2% of the total mangroves area in the whole SEA. At the level of individual countries, the Republic of the Union of Myanmar (Myanmar) has lost more than 5% (27,770ha) of its mangroves during the 2000 – 2012 period. Although the Republic of Indonesia (Indonesia) underwent a reduction of only 1.7% of mangroves during the same period, it is equivalent to more than 48,000ha [43]. As a consequence, Indonesia alone has been responsible for almost half
of global mangrove deforestation [35]. This trend is particularly alarming since 30% to 50% of global mangroves are located in South East Asia [16], [35], [44]. At this rate, South East Asia eventually will lose at least 35% of its total mangrove area by 2050 and another 10-15% by 2100 [45]. To add to concerns about the loss of these important ecosystems, a number of the world's most vulnerable coastal cities are located in South East Asia [7] and mangrove losses certainly put these coastal cities in dire need for coastal defence.

Adopting mangroves as a coastal bioshield are increasingly common in low latitude countries. Indonesia, Sri Lanka, and Malaysia have begun the initiative following the 2004 tsunami. In 2010, the World Atlas of Mangroves mapped more than fifteen million hectares of mangrove forest from the site throughout the world. The highest percentage belongs to South East Asia with 33.5% of total world mangrove forests. However, from 1990 to 2010, the world has lost about half a million hectares of mangroves [46]. According to United Nations Environmental Program report, agriculture, aquaculture, and timber logging, pollution, hydrological alteration, extreme weather and climate change, urban development such as recreation facilities, transportation and settlement contribute to loss of mangrove forests [45]. In Malaysia, a restoration initiative at Kuala Selangor in West Coast Malaysia has been reported as a total failure after 70% of mangrove saplings died within the first eight months of the restoration [47]. The costs of that initiative were not publicly available, however, the construction of a breakwater and geotextile tube plus nursery and planting the mangrove seedlings are likely to have a significant cost. This failure was due to a lack of understanding on mangrove ecology and hydrological suitability because of no prior investigation on the hydrodynamics of the restoration site was performed prior to planting.

2. Mangroves for coastal protection

A sustained cross-disciplinary effort, involving substantial research funding, has been dedicated to gaining a better understanding of the physiology of mangrove species and the services they provide. Mangroves are among the taller plant species that straddle both land and sea [40], along with trees, shrubs, palms, herbs or ferns that inhabit tropical and subtropical intertidal coastal environments. These plants are more tolerant to both salt, and soil anoxia than non-mangrove plants, and in addition have propagules that can be dispersed by seawater. Mangrove forest species, with their coastal habitats and high biomass at the ocean-land interface, make mangrove forests ideal for coastal protection [1]–[4], [5], [6]. They provide the first biotic barrier to damp and attenuate the waves on the shore [5], [25], [48]–[54]. Mangroves geometry location at the front line of coastal environment setting indicates the abilities to play a major role in coastal protection against waves, storms, tsunamis and sea-level rise along with erosion [55].

2.1. Mangrove rehabilitation

There are three criteria currently adopted to evaluate the success of mangrove rehabilitation initiatives: (i) how much the new mangroves resemble the blueprint of rehabilitation, (ii) how long before mangrove in rehabilitation can recruit its ecosystem, (iii) the efficiency of the rehabilitation [56]. All three evaluation criteria were drawn based on the technical and scientific measurements that need to be assessed before the rehabilitation initiative goes to the field. The organisations that have been responsible for rehabilitation need to be equipped with both technical and scientific knowledge of coastal hydrodynamics, mangrove ecosystems and rehabilitation planning and management. Currently, the guidelines for mangrove rehabilitation are based on a document by Mangrove Map Action Project: 5 Steps to Successful Ecological Restoration of Mangroves [57]. The document highlights the importance of (i) Understanding the ecology of the mangrove forest at the site, (ii) Identifying hydrologic conditions of the site, (iii) Assessing the hydrologic changes within the site area that hinder natural propagules, (iv) Re-establishing the original hydrology of the site to encourage the natural rehabilitation effort (v) Prioritising for mangroves to grow naturally rather than replanting. All these highlights require common information; mangroves area boundary and water level (tides). Therefore, it is crucial to be able to establish options for the best practice to collect both data in a timely manner.
3. Mangroves Area Geometry
Managing mangrove rehabilitation programs requires prior understanding of the natural hydrology of the area and a careful assessment of the source of ecologic disturbance accordingly. The first step towards better manage mangroves rehabilitation area is by establishing Mangroves Area Geometry (MAG). MAG refers to the physical structure of the mangrove belt. It comprises the spatial distributions of mangrove trees within a predefined confined area. The capability of coastal vegetation to attenuate waves is a function of mangrove vegetation structure. It can be measured by species composition, diversity, stem height, basal area, tree density, age-class distributions [58] and spatial distribution [59]. All these elements were defined under mangrove area geometry (MAG). Previous studies of mangrove vegetation have found that species composition and diversity are influenced by temperature, with species richness decreasing with increasing latitude [34]. There were 36 species have been identified in Malaysia in 2010, and additional species was found in 2014 [61]. Numerous advanced studies on mangrove species composition have established species zonation patterns [62]. In general, patterns suggest that the spatial distribution of mangrove species is a function of tidal flooding, elevation and salinity.

3.1. Wave attenuation
Wave attenuation in mangrove forests is closely related to tree density [5], [53], [63]–[67]. Tree density is defined by the number of trees per area in regards to species composition; this metric disregards the precise spatial distribution of mangrove trees. Stem height and age class distribution are defined as a function of water level to calculate shear stress by the submerged vegetation, which is dependent on wave height and reduction in flow velocity alongside bed shear stress. Wave energy dissipation in this scenario is a function of stem density and stem and is a result of vertically distributed frictional force by the cylindrical shape in the oblique flow. In simple terms, dense mangrove vegetation will attenuate waves better than sparse mangrove belts. The environmental setting can influence patterns of species distribution. The hydrodynamic setting for each environment is controlled by the orientation of the coastline, the properties of the tide and wind. There is also a role of coastal seabed elevations that is related to the coastline progradation and degradation by tides as well as sediment deposition.

3.2. Coastal seabed elevations
Coastal seabed elevation at Peninsular Malaysia is modulated by the differing behaviour of adjacent ocean basins. Peninsular Malaysia is bounded by the Andaman Sea of the Indian Ocean on the west coast and the South China Sea on the east coast. The sheltered effect from the Island of Sumatra has created a shallow coast on the west coast Peninsular Malaysia as silt and clay from the river discharge are able to deposit along the coast, forming an alluvial plain (Omar et al. 2012). In the east coast, however, the coastal seabed elevation tends to be terminated in the steep sandy beach as the result of strong waves and current by the South China Sea.

Coastal seabed elevations could have an impact on wave attenuation rates due to their effects on wave breaking and the inundation period. At shallow areas such as beach and surf zone, waves will break at the point when the water depth is equivalent to the waves' height [5], [68], [69]. Thus, the elevation of the seabed must have a role in determining shoaling and refraction of the waves at the coast. Waves will lose most of their energy after breaking and will slow down the flow velocity. Due to this, the steep and slope coast will have different wave velocities. Since the coastal at the east coast Peninsular Malaysia steeper than the west coast, the attenuation rates by coastal mangrove are likely to differ. Figure 1 indicates the mechanism of waves attenuation by the coastal mangrove.

3.3. Mangroves tree inventory – height and weight
A physical tree characteristic parameter has to be accurately defined in order to use mangroves as a coastal bioshield. Tree height and weight provide crucial information in estimating the tree mass to damp and attenuate the waves as well as estimating tree biomass for carbon storage and sequestration. Allometric equation using tree dimensions; trunk diameter at breast height (dbh) and tree height (H) as a variable for the equation[70]. Tree height is also important variables that define mangroves forest
4. Defining Mangroves Area Geometry

4.1. Study Area
Kampung Sungai Melayu, Johor Bahru, Johor which located at 1°27'07" North and 103°41'48" East is a small rural area near to Kota Iskandar Nusajaya (Johor state government administrative centre). In 2013, this area opted for Program Iskandar Malaysia ecotourism pilot project that leads to mangroves conservation and rehabilitation initiatives [75]. The selection as the pilot area was due to the recent mangroves replanting and rehabilitation initiatives that have been carried out.

4.2. Horizontal and Vertical Control
Horizontal control has been established using a GNSS instrumentation by static position mode at benchmark number (BM) J0526 to control point (CP1). The observation was carried out for one (1) hour with 15 seconds logging interval. Three control points were established near to mangroves rehabilitation area, which later used as a reference point for detail survey around mangrove rehabilitation area.
The vertical control was established by transferring the vertical height datum from benchmark BM J0526 (E641357.727, N168575.964, 5.392m) to CP1 based on static observation method. The observed data were processed using Trimble Business Office software to obtain the control points coordinates.

4.3. Land Elevation and mangroves tree height
Land elevation was generated based on tacheometry data from a detailed survey. The detailed survey method commonly used in engineering survey to identify land elevation and feature height due to robustness and high precision measurement provided. Thus, detailed survey is a suitable method to measure the land elevation and mangrove’s tree height within the rehabilitation boundary. The measurement was acquired in the form of bearing and distance from a CP to the bottom and top of the mangrove tree. The detailed survey was perform based on radiation method due to the small size of the mangroves area and tree arrangement visibility. In tacheometry technique, the height of land elevation was calculate using the formula:

\[ RL_{pt} = RL_{stn} + Ht_{inst} \pm Vd - Ht_{tgt} \]  

where;
- \( RL_{pt} \) = Land Elevation  
- \( RL_{stn} \) = Height at reference station (CP1)  
- \( Ht_{inst} \) = Height of instrument  
- \( Vd \) = Vertical distance  
- \( Ht_{tgt} \) = Height of target

Land elevations were observed by targeting ground level at the mangroves tree root. Mangroves tree heights were defined by observing the tip of the mangroves tree top.

5. Generating Annual Tidal Fluctuation Level
The tidal data used to generate tidal fluctuation near the research area were digitised based on tide prediction table for Johor Bharu from the year 2020 which obtained from the Department of Survey and Mapping Malaysia (DSMM). The prediction values were derived based on tidal constituent from the standard port at Johor Bharu. Tidal level values were stored in a free form text file and transformed into a row and column format in the SQLite3 database.

5.1. Water depth
The water depths for this research were defined as the vertical distance between land elevation surface to water level surface. Both surfaces have been reduced (referenced) to National Geodesy Vertical Datum (NGVD). Water depths calculation was a function of datum reduced high-low water level surface in 24 hours tidal cycle and stored in the SQLite3 database.

5.2. Mangroves tree inundation period
While inundation is commonly measured as an area or distance covered by water above the dry area, it is also applicable as a way of measuring total water level that occurs on the normally dry ground [76]. Inundation period for mangroves trees in MAG was obtained by compositing mangroves tree height and water depth.

Fully inundation occurred when the water depth is higher than the land elevation.

\[ Sub_f = WL \geq (RL_{pt} + TH) \]  

Partly inundation occurred when the water depth is higher than the land elevation but lesser than mangroves tree height.

\[ Sub_{ni} = TH > WL > RL_{pt} \]
Annual inundation period is total hours when the water depth is higher than the land elevation based on equation (4):

\[ A_i = WL > RL_{pt} \]  

(4)

where;
- \( Sub_i \) = Inundated
- \( Sub_{ni} \) = Partly Inundated
- \( WL \) = Water Depth
- \( RL_{pt} \) = Land Elevation
- \( TH \) = Mangroves tree height
- \( A_i \) = Annual inundation period

### 6. Annual inundation period at mangroves area geometry

Coordinates for CP1 after the processing is E63375.595, N160599.322 and elevation is 9.317m. For tidal fluctuations prediction, the highest water level for the year 2020 will reach 3.46m at 0100 hours on 19 October. The lowest water level is -0.21 at 0700 hours on 10 Mei 2020. The pattern is rather interesting considering certain circumstances when tidal fluctuation near the MAG exceeding NGVD.

#### 6.1. Mangroves tree inundation period

All mangroves tree in MAG boundary (Figure 3) experienced inundation fully except for fives tree (PKK14, PKK19, PKK21, PKK23, PKK30). These trees were taller than the highest water level for the year 2020. Although not fully inundated, part of the tree’s structure still experienced inundation for a certain period, especially during high water tide. It occurs when the water depth is higher than the land elevation but lower than mangroves tree top. A significant fact that two trees have been identified being inundated for an accumulated hour of more than six months; PKK35 with 5109 hours/year and PKK40 5152 hours/year.

![Figure 3 Mangroves Tree Inundation Period](image)

### 7. Conclusions

Although mangroves planting and rehabilitation seem to be the least progressive measure in coastal protection compared to an artificial structure such as seawalls, breakwaters, groynes and gabions, however, mangroves did have a good record of protecting the coastal area for a long run. Compared to
artificial structure, mangroves barely need any maintenance except to be protected from anthropological disturbance so it can naturally nurture. There are many approaches currently in practice to observe mangroves planting and rehabilitation progress, though, tacheometry was not one of it. This approach as robust as it be, and still time-consuming besides required a well-trained human operator. Despite that, tacheometry did a remarkable alignment between tidal data, land elevation and mangroves tree height. Evidently, tacheometry put the best effort to cater inundation period investigation for the least confined area with higher precision requirements than ordinary hydrodynamic studies, perhaps a coastal area that been severely degraded by tidal fluctuations. For the pilot study, Kg. Sungai Melayu Johor tree inundation period has been successfully monitored based on MAG that obtained from tacheometry survey.

This research has provided an early insight into the mechanism of mangroves tree height and inundation study. In order to fully appreciate mangroves services for coastal bioshield, it will be incomplete without further research on mangroves tree width function in dissipating the waves. For the higher accuracy, it will be a great enhancement for the tidal observations to be held at the research area (local tides) rather than using tidal predictions data as it will give a better representative of locality water level.

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