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MANGROVE FORESTS: PROTECTION AGAINST AND RESILIENCE TO COASTAL DISTURBANCES

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This review paper discusses the role of mangroves in coastal protection and provision of ecological services as well as their vulnerability and resilience to coastal disturbances such as tsunamis, hurricanes and sea level rise. Mangroves have been observed in field studies, laboratory experiments and numerical simulations to offer some degree of protection from tsunamis and hurricanes. The magnitude of energy reduction strongly depends on three major factors, namely mangrove structures, topography-bathymetric features and wave characteristics. Mangroves are vulnerable and resilient to a variety of coastal disturbances, both natural and anthropogenic. Their vulnerability and resilience depend on the intensity, duration and frequency of the disturbances. Tsunamis and hurricanes are infrequent disturbances of high intensity and short duration. Sea-level rise and mangrove deforestation, on the other hand, are chronic events that evolve gradually over a longer period. A relentless government-community campaign is needed to cultivate awareness and education regarding the vulnerability of mangroves and their invaluable ecological services. Both soft and hard approaches are needed to reduce the adverse impacts of coastal disturbances on humans and mangroves.

Keywords: Tsunami, hurricane, sea level rise, deforestation

INTRODUCTION

Mangrove forests live in the tropical and subtropical regions at the interface between marine and terrestrial environments. These forests grow around the mouths of rivers, in tidal swamps, and along coastlines, where they are regularly inundated by saline or brackish water. Mangrove forests support a myriad of physical and ecosystem services (Stokstad 2005), providing economic values that are just beginning to be recognised (Barbier et al. 2008, Perillo et al. 2009). Despite their ecological-economic values, around half of total global mangrove coverage has been lost since pre-industrial times (Giri et al. 2011). Mangrove forests are currently disappearing at an alarming annual rate of 1 to 2% globally. This article is written to highlight the critical importance of mangrove forests in: providing essential ecosystem services, mitigating the impacts of coastal disturbances such as tsunamis and extreme storms, reducing the adverse impacts of climate change by way of carbon sequestration, and supporting the implementation of the United Nations Sustainable Development Goals (UN-SDG, 2016−2030). It provides an overview on the resilience and vulnerability of mangroves to natural and anthropogenic disturbances, including sea-level rise and extreme storms. It is hoped that the paper will promote awareness and education on the importance of mangroves that would lead to improving mangrove replanting, restoration and resilience worldwide. Further research is needed to address several knowledge gaps. The economic valuation of ecosystem services provided by mangroves needs to be adequately and systematically quantified for inclusion in policy decision beyond mere advocacy. The role of mangroves in protecting coastal areas from tsunamis and other extreme storm surges such as hurricanes and typhoons should be properly quantified to facilitate policy debates leading to rational integrated coastal zone development plans. In the context of UN-SDG implementation, mangroves, despite their critical importance in mitigating climate change impacts, appear to have received little attention from the diverse and diffuse stakeholders. This undesirable situation can be improved by a coordinated integration of various social-ecological-economic dimensions that requires further research.

Mangroves provide essential ecosystem services

These highly productive mangrove ecosystems provide vital habitats for diverse fauna such as fish, birds, reptiles and shellfish. Moreover, mangrove forests have high carbon burial efficiency, helping to regulate climate change (Donato et al. 2011, McLeod et al. 2011). Mangroves have been shown to buffer shorelines from damage by tidal currents (Mazda et al. 1997), waves (Massel et al. 1999, Mazda et al. 2006, Vo-Luong & Massel 2008, Bao 2011, Horstman et al. 2014) and tsunamis and cyclones (Danielsen et al. 2005, Wolanski 2007, Alongi 2008, Deb & Ferreira 2016). Mangroves enhance water quality by removing organic and inorganic nutrients from the water column, thereby inhibiting eutrophication (Ewel et al. 1998). They play an important role in flood defence against lower category hurricanes by dissipating incoming wave energy (Hong & San 1993, Wu et al. 2001). Because of the protection afforded by mangroves, yachts and ships in the Caribbean and Florida are often moved behind these ecosystems before or during hurricanes. Their dense root-trunk systems inhibit flow and enhance sediment deposition (Blasco et al. 1996). Mangrove forests currently occupy 14.6 million ha of coastline globally (Wilkie & Fortuna 2003), with an estimated ecosystem service value in the order of USD200,000–900,000 ha^{-1} $year^{-1}$ (UNEP-WCMC 2006). Comparing the results of de Groot et al. (2012) with Costanza et al. (1997), Costanza et al. (2014) noted an increase in the estimated value of tidal marsh/mangroves from USD13,786 ha^{-1} $year^{-1}$ in 1997 to USD193,843 ha^{-1} $year^{-1}$ in 2011. Although the estimated area of tidal marsh/mangroves decreased from 165 million ha in 1997 to 128 million ha in 2011, the recognition of new functions of these coastal wetlands increased the unit values of these ecosystems.

Mangrove resilience and vulnerability

Mangrove forests worldwide have been threatened by many forms of disturbances such as conversion to agriculture and aquaculture and unsustainable harvesting for timber, food, fuel, and medicine (Saenger 2002). Indonesia had lost more than 200,000 ha of its mangroves by the 1960s, the largest losses of which were reported from Java and Sumatra. In the next three decades, another 800,000 ha were lost, mainly in Kalimantan and Sulawesi. Shrimp farming ('tambak') and the timber industry cleared 600,000 ha more over the following two decades. However, the net loss of mangroves in the coming two decades could be reduced to around 23,000 ha (Ilman et al. 2016). Serious environmental stress, anthropogenic impacts, metal pollution, and a heavy influx of sewage and industrial effluents affect the health of the mangrove ecosystem (Satheeshkumar et al. 2012a, b). In the face of these threats, the persistence and resilience of mangroves to disturbances of different characteristics and over different time scales remains an open question. Persistence refers to relative constancy over time, regardless of environmental perturbations. Here, resilience refers to the ability to recover from disturbances back to persistent state and is coined as engineering resilience (Holling 1996, Mumby et al. 2014). Another type of resilience is ecological resilience that refers to the ability of an ecosystem to shift towards one or more community types with or without disturbances. The duration, frequency, intensity and size of disturbances play a crucial role in determining the persistence and resilience of mangroves, facilitating or denying adaptive change to disturbances (Odum & Barrett 2004).

Mangrove response to sea-level rise

Sea-level rise (SLR) may pose the greatest threat to mangroves where the mangrove sediment surface levels are not keeping pace with SLR. The greatest impact will be on those mangroves where the area for landward migration is limited (Gilman et al. 2008). The impact of sea-level change on mangroves is not yet fully understood. Sea-level change could be abrupt (Hull 2005), as recorded in the Indonesia Sunda Shelf where the sea level rose as much as 16 m within 300 years (Hanebuth et al. 2000). While data are lacking, some have speculated that mangroves may face collapse if confronted with SLR in the order of 1.0 to 1.2 mm $year^{-1}$ over an extended period (Ellison & Stoddart 1991). Mangroves in the Key West of Florida, for example, have shifted inland by 1.5 km since the mid-1940s under a SLR regime of 2.3 to 2.7 mm $year^{-1}$ (Ross et al. 2000). Mangroves will move inland if the pace of SLR and other environmental and hydrological conditions are suitable. He et al. (2007) classify the flooding tolerance of four species of mangroves in the following order (from most to least tolerant): *Avicennia marina* > *Aegiceras corniculatum* > *Rhizophora stylosa* > *Bruguiera gymnorrhiza*. Several studies suggest possible whole-forest changes (regime shifts) in community composition in relation to SLR. Globally however, mangroves appear to keep pace with SLR, because average sedimentation rates are in equilibrium with mean SLR rates. Not all mangrove forests accrete sediments (Semeniuk 1994). Most vulnerable to the impact of SLR are those mangroves occupying low-relief islands in carbonate settings, such as small islands and atolls in the Pacific, where rates of sediment supply and available upland space for migration are usually low. Also, most vulnerable are coastal forests where rivers are lacking or where the landform is subsiding. The least vulnerable are those mangroves located in macro-tidal estuaries, tropical coastal wetlands or shores adjacent to rivers. Mangroves that are likely to be resilient to SLR are those that occupy high-relief islands located in remote areas with minimal human interruptions to inhibit landward migration (Alongi 2008).

Mangroves are vulnerable to extreme storm surges

Mangroves were significantly impacted by the 2004 Andaman tsunami (Alongi 2008). In South Andaman, 30 to 80% of *Rhizophora* spp. trees died due to continuous inundation but mangroves of the species *Avicennia marina* and *Sonneratia alba* inhabiting the intertidal zone behind the *Rhizophora* spp. were not affected. In Middle Andaman, mangroves were not affected but in North Andaman the impact of the earthquake elevated the land mass to the extent that the *Rhizophora*-dominated stands are now no longer inundated by tides even at the highest astronomical tide. These stands are dying and are expected to be succeeded by terrestrial flora, having lost the competition to glycophytic vegetation in a bi-stable equilibrium bifurcation. In the 2010 Mentawai tsunami, almost all vegetation was destroyed by 10-m waves (Borrero et al. 2010) while in the 2011 Tohoku tsunami all coastal vegetation was completely uprooted by 20-m waves (Suppasri et al. 2011). Using remote sensing technology, Long et al. (2016) assessed the extent and severity of damage to mangroves in the Philippines after Super Typhoon Haiyan made landfall on 8 November 2013. The damage was greatest where the typhoon first made landfall on Eastern and Western Samar provinces, and lessened westward with decreasing storm intensity as Haiyan tracked from east to west across the Visayas region of the Philippines. However, within 18 months following Haiyan, mangrove areas initially classified as severely, moderately and minimally damaged decreased by 90, 81 and 57% respectively, indicating their recovery from that powerful typhoon. To enhance resilience, the Philippines' greenbelt laws require mangrove buffer zones of 50 to 100 m facing open seas and 20 to 50 m along riverbanks. Considering the future, we need to address the potential damage that natural coastal disasters can inflict on mangroves. The impacts of a potential Mw 9.0 rupture of the Manila megathrust and other earthquakes, volcanic activities and submarine landslides in the South China Sea margins are presently inadequately quantified. A major risk would come from the potential Brunei and Baiyun giant submarine mass failures of over-steepened sediment burden sliding from continental slopes into deep water, triggered by methane hydrate disassociation or local seismic activity (Tan et al. 2017, Terry et al. 2017). In the central South China Sea, near-surface carbonate platforms and coral atolls show evidence of a propensity for possible tsunami-genic lateral flank collapses. These potential tsunamis pose major threats to mangroves on the South China Sea coast.

MATERIALS AND METHODS

The systematic process of literature search used in this review paper consisted of four stages: identification, screening, eligibility and inclusion. In the identification stage, searches were performed in the Web of Science database using combinations of the following main keywords: mangrove and coastal forest; and supplementary keywords: mitigation, resilience, protection, tsunami, hurricane and storm surge. The titles and abstracts of articles brought up by the searches in the date range 1950–2017 were scanned for relevance. A total of 212 papers were downloaded from the database and screened to identify relevant research performed on mangrove forests, specifically their mitigating role and resilience to disturbances. Attention was given to current and prominent studies concerning mangroves' protection against and resilience to tsunamis, storm surges and hurricanes. From the 114 resulting papers found relevant and examined thoroughly in the eligibility stage, a final total of 90 papers were selected for inclusion in this review paper.

REVIEW OF APPROACHES USED FOR ASSESSING MANGROVE DISTURBANCE AND RESILIENCE

Role of mangroves in tsunami mitigation

Mangroves have an idealised association with the Andaman mega-tsunami of 26 December 2004, hereafter called the 2004 Andaman tsunami. Prior to 2004, Japan invested heavily on costly man-made coastal structures, known as hard engineering, to stop tsunami wave inundations but with limited success. As a viable alternative, can soft bio-engineering in the forms of mangrove greenbelts be built to offer protection? The 2004 Andaman tsunami destroyed large tracts of mangrove forests and agricultural areas including aquaculture ponds in Aceh, Indonesia, significantly reducing resilience of the coastal communities whose livelihoods rely on mangrove resources. It is highly likely that a tsunami of similar or higher intensity than that of the 2004 Andaman tsunami will happen again in the foreseeable future. Can mangrove greenbelts mitigate the tsunami's damage and loss then? Tsunami-impacted coastal communities must be prepared with a complete set of well-planned and adequately-financed mitigation measures to develop resistance and resilience to tsunamis. With a total area of 575,000 ha in Malaysia (Asian Development Bank 2014), mangroves can be utilised for effective mitigation against moderate tsunamis. Partially protected by Sumatra Island and located relatively far from tsunami sources, the states of Kedah, Penang, Perak and Selangor can be protected, to an extent, from tsunamis originating from the Andaman Sea, by dense and healthy mangrove forests of adequate width (Koh et al. 2009a, Spalding et al. 2014).

Cautionary note on mangroves for mitigating tsunami

The 2004 Andaman tsunami inflicted a disaster of epic proportions on millions of people worldwide. An event of that magnitude is bound to create illusions regarding the magic and wonders of mangrove greenbelts that are the front line of defence. After the tsunami, much attention focused on the role of natural barriers such as coral reefs, mangroves and sand dunes in protecting vulnerable coastlines and populations. The dense network of mangrove roots and trunks that appeared capable of dissipating wave energy intrigued the idealists. The lowered human casualties and reduced damage in areas of Tamil Nadu that were hit by the 2004 tsunami were attributed to the protective effects of dense mangrove forests (Kathiresan & Rajendran, 2005). However, this assertion has been vigorously challenged by many authors (e.g. Dahdouh-Guebas et al. 2005, Kerr et al. 2006, Kerr & Baird 2007, Chatenoux & Peduzzi 2007) purporting incorrect statistical analysis used by Kathiresan and Rajendran (2005). A post-tsunami survey of coastal fishermen in Sri Lanka indicated these communities had traditional ecological awareness of the protective role played by mangroves against tsunami impacts (Venkatachalam et al. 2009). However, a modelling study that considered combinations of factors including the way tsunami impacts were measured (e.g. wave travel distance from shore), household damage and human deaths inflicted, concluded that mangroves were not a significant ameliorative factor in mitigating the impact of the tsunamis (Venkatachalam et al. 2012). In Malaysia, areas with intact and dense mangrove forests, such as Pantai Acheh in Penang Island, suffered less damage during the 2004 Andaman tsunami, because the dense forests dissipated wave energy and reduced wave heights where runup heights did not exceed 4 m (Koh et al. 2009b). Where tsunami waves exceed 4 m, mangrove trees could be uprooted to form dangerous debris flows that might inflict even more damage (Shuto 1987). The complete destruction of coastal forests in the 2010 Mentawai tsunami and 2011 Tohoku tsunami mentioned earlier, attest to the inability of these forests to withstand the impact of extreme waves. Hence, we should not harbour any false sense of security that bio-shields such as mangroves and other greenbelt vegetation are able to protect against extreme coastal hazards (Wolanski 2007, Yanagisawa et al. 2009). Further, the presence of forest gaps, such as roads that run perpendicular to the shore, can intensify the force of tsunami waves by channelling them into narrow constrictions (Tanaka 2009, Thuy et al. 2009). In Tamil Nadu during the 2004 Andaman tsunami, the maximum velocity at a gap exit in a vegetation belt was recorded as 1.7 times greater than that at a belt of land with no vegetation cover (Mascarenhas & Jayakumar 2008). Along the gaps, wave heights increased monotonically with distance travelled, posing increasing risks further into the forest gaps. Coastal vegetation intended for wave attenuation should therefore not have significant and continuous gaps perpendicular to the shoreline (in the direction of tsunami flow).

The science of tsunami mitigation by mangroves

Analysing Japan's historical record of tsunamis, Shuto (1987) reported a moderate role of coastal forests in buffering against tsunami waves. He suggested that if wave heights exceed 4 m, coastal trees may be snapped or uprooted, creating floating tree debris that could heighten tsunami damage. Subsequently, numerous researchers investigated the effects of coastal vegetation on tsunami mitigation by means of field investigations, laboratory experiments and numerical simulations (e.g. Hamzah et al. 1999, Harada & Imamura 2000, Hiraishi & Harada 2003, Kathiresan & Rajendran 2005, Mazda et al. 2006, Tanaka et al. 2007, Vo-Luong & Massel 2008). A laboratory-scale coastal forest model was used to analyse the effectiveness of artificial trees in reducing wave heights (Irtem et al. 2009). The study found that runup height was negatively correlated with slope, sand grain diameter, distance from still water level, beachfront water depth, tree height, number of trees per unit area and tree volume. Runup height was positively correlated with the horizontal and perpendicular gaps between trees and specific gravity of sand. Artificial mangroves in that study reduced wave heights by 20−45% due to absorption of wave energy by the artificial trees. As reviewed by Alongi (2008), the magnitude of energy absorbed or dissipated by mangroves depends strongly on three factors: (a) the mangroves' structure (density, height, and stem and root diameter), (b) bathymetric-topographic features (slope and elevation) and (c) the spectral characteristics (wave length and wave period) of incident waves. The dissipation of wave energy within mangrove forests is caused mostly by wave-trunk interactions and wave breaking (Vo-Luong & Massel 2006). This basic understanding of how mangroves interact with tsunami waves is critically important to anyone interested in tsunami risk reduction using mangroves. In India, post-tsunami surveys of a dense mangrove forest (1400−2600 trees per ha) reported low damage overall (Danielsen et al. 2005). Wave height reduction by drag force due to the mangroves' dense root-trunk systems was reportedly 5 to 7 times better than that by bare soil bottom friction alone (Quartel et al. 2007). However, Das and Vincent (2009) observed that mangroves saved fewer lives in Orissa, India, than an early warning issued by the government.

A controlled field study of over 32 mangrove plots in Vietnam showed that wave height decays exponentially with distance travelled through the mangrove forest (Bao 2011). This measured exponential decay in wave heights had also been previously derived mathematically and verified numerically by Teh et al. (2009). A simple wave decay law provides a quick and easy way to assess the potential reduction of wave heights through mangrove forests, once the critical parameters regarding forest structures, wave characteristics and topo-bathymetric features are known. This exponential decay is caused by bottom friction and drag forces posed by the dense network of trunks, branches, canopy and aerial roots of the mangrove trees (Quartel et al. 2007). Bao (2011) derived exponential regression equations to express the exponential decay law:

$$\eta = \alpha e^{-\beta x} \qquad (1)$$

where η (m) is the wave height at distance travelled x (m), α (m) is the wave height at initial point x = 0.0 m, and β (m^{-1}) is the wave decay rate. The mangroves there have high tree density (2000 to 13000 trees ha^{-1}) and a high canopy closure of more than 80%, resulting in good wave decay rates. Wave decay rates estimated by Bao (2011) were 0.0055, 0.0067, 0.0068 and 0.0100 m^{-1}. In comparison, the wave decay rate for Pantai Acheh in Penang Island, Malaysia was about 0.00428 m^{-1} (Teh et al. 2009). The wave decay rate is a function of average tree height, H (m); tree density, N (number of trees per ha); and canopy cover (%). The wave decay rate increases with increases in H, N and canopy cover.

Mangrove-fluid interaction

A good understanding of tsunami wave propagation dynamics within mangrove forests is essential in the modelling of wave attenuation by mangroves. The hydraulic characteristics of tsunamis are quite different from those of short-period wind waves and long-period tidal waves (Latief & Hadi 2007). Tsunamis have periods that range between 10 and 60 minutes while normal tidal waves have a period of 12 to 24 hours and wind waves have a period of 10 to 20 seconds (Mazda et al. 2007). A tsunami propagates like a tidal bore in that its momentum increases with movement upstream into shallower water. Longer period (60 minute) tsunami waves can move more water inland than shorter period (10 minute) waves (Edward 2008). A bore can move a large volume of water more quickly than a normal tide. In a laboratory set up similar to that employed by Teh et al. (2009), Ismail et al. (2012) assessed the drag resistance to fluid flow, of the canopy, trunk and root components of a model *Rhizophora* mangrove forest. Their experimental results showed a strong influence of forest density and width (wave travel distance) on wave damping and attenuation. Several studies have pointed out various limitations and gaps that require further research to resolve problems relating to scaling effect, vegetation parameterisation, flow conditions representation and vegetation horizontal distribution. The interaction between mangroves and fluid flow can be modelled numerically and simulated in the laboratory using solitary waves impinging on emergent rigid cylinders. Huang et al. (2011) conducted laboratory experiments in a 32 m long and 0.55 m wide wave flume using emergent 0.01 m cylinders made of Perspex. Following that, adopting two different approaches, Maza et al. (2015) conducted 3-D numerical simulations to investigate mangrove-fluid interactions. The first micro approach used a direct simulation of the 3-D flow fields that incorporated the actual geometry of the array of cylinders using Unsteady Reynolds-Averaged Navier−Stokes (URANS) equations. The second macro approach introduced a drag resistance to model the momentum damping created by the cylinders. The experimental results of Huang et al. (2011) were used by Maza et al. (2015) to validate both micro and macro URANS numerical models with very high agreement for wave height evolution. However, wave forces acting on the cylinders calculated with the macro approach by means of the drag coefficient yielded clear underestimations. Both macro and micro URANS numerical approaches provided an accurate wave height evolution along the cylinder array but the micro model incurred high computational costs. While macro modelling needed the calibration of the drag coefficient, the direct micro simulation approach was free of parameterisations. The macro approach produced satisfactory results for the prediction of wave height evolution along the mangrove path with the momentum damped by vegetation if the appropriate damping coefficient C_D was found. However, maximum wave-exerted forces on the cylinders were not well reproduced by the macro model. In another study, wave attenuation by artificial vegetation consisting of flexible and solid pipes, was evaluated using experimental and numerical approaches (Tar et al. 2017). The dimensions of the tsunami wave basin were 44 m x 0.7 m x 0.9 m (length x width x depth) with two slopes: 1/40 and 1/100. Numerical results showed good agreement with experiments for flow velocity and hydrodynamic forces. The flexible and solid pipes reduced the maximum hydrodynamic force by 30 and 44% respectively.

Impact of bathymetry and topography

Tsunami runup and inundation is highly sensitive to mangrove forest structure, topographic-bathymetry features and wave characteristics. As the leading edge of a tsunami wave propagates towards the shore, decreasing water depth causes the wave to slow down and the wave height to increase, a process called shoaling. However, the waves' energy, and hence height, will dissipate exponentially due to bottom friction and mangrove drag resistance. The flooding waves interact with complex onshore morphology, including natural (Mazda et al. 1997) and man-made (Ikeno et al. 1988) barriers such as mangroves, dunes, coastal forests, seawalls, dikes and buildings. These coastal structures act as barriers to flow and as dissipaters of energy via hydraulic resistance, resulting in a reduction in wave height and velocity known as wave attenuation (Goto & Shuto 1983). These structures or barriers must be incorporated into tsunami simulations for accurate simulation of tsunami run-up and inundation. Mangrove stem density and stem diameter are important features in determining hydraulic resistance or drag. To quantify the effectiveness of coastal forests in reducing wave heights, we adopted a similar macro approach using (a) Morison's drag coefficient term, C_D, and (b) Manning's bottom friction coefficient, n, to represent the resistance of mangrove vegetation to fluid flow.

Morison's equation

This approach to estimating energy dissipation due to vegetation-induced flow resistance acting on the fluid, conceptualises the coastal vegetation as a collection of cylinders (Dalrymple 1984, Vo-Luong & Massel 2008, Teh et al. 2009). Harada and Imamura (2000) modelled this hydraulic resistance force as drag and inertia forces based on Morison's equation (Morison et al. 2000). The resistance coefficients of coastal vegetation against tsunamis may be derived from laboratory hydraulic tests, numerical simulations or field observations (Ohira et al. 2012). Experimental and numerical results have been found to agree well in general, indicating that Morison's equation can mimic the frictional resistance of coastal vegetation if the correct drag coefficient, C_D, is used. Kh'ng et al. (2017) have used Morison's equation to assess the attenuation of tsunami waves by mangroves in Pantai Acheh.

Manning's equation

A second approach is to use Manning's friction law to parameterise the frictional resistance F_x, where n is Manning's roughness coefficient, g is gravity, U is discharge flux and H is water depth (Kh'ng et al. 2017).

$$F_x = \frac{gn^2U|U|}{H^{7/3}} \qquad (2)$$

The selection of the appropriate n value is based on the flow resistance of the mangrove forest and the roughness of the terrain or seabed. For large-scale roughness elements such as buildings and tree vegetation, equivalent n values have been derived through hydraulic theory, laboratory experiments and calibration of numerical models to fit field measurements from actual flood events (Chow 1959, Leschka et al. 2011). Several land use cover datasets are available in the scientific literature that can be used to derive estimations of n values. These include the US National Land Cover Dataset (NLCD) and the state-by-state dataset from the Gap Analysis Program (GAP) study, courtesy of the United States Geological Survey (USGS; Hartley et al. 2000, Vogelmann et al. 2001). Selected datasets are available from Bunya et al. (2010). The GAP data are preferred because of their detailed levels of classification, particularly for wetlands. The nonlinear friction term is discretised using the Crank-Nicolson method to ensure numerical stability (Kristofer & Laurent 2014).

RESULTS

Mangrove wave reduction in the tsunami inundation model TUNA-RP

Most of the numerical models simulating tsunami propagation are based on shallow water two-dimensional vertical-averaged nonlinear equations. Teh et al. (2009) introduced the Morison equation in an in-house 2-D model known as TUNA-RP based on the Boussinesq equations, considering the drag and the inertia coefficients as calibration parameters. They used the formulas proposed by Harada and Imamura (2003) for these coefficients, which were based upon data collected on coastal pine forests in Japan. Formulations were quantified as a function of the volume of trees under the water surface within a chosen control volume, appropriate for the Pantai Acheh study site. The 2-D runup model TUNA-RP (Tan et al. 2017) was enhanced to incorporate both Morrison and Manning equations. TUNA-RP was validated against a set of standard benchmark test problems known as OAR-PMEL-135 compiled by the US National Oceanic and Atmospheric Administration (NOAA) for verifying reliable and accurate simulations of tsunami wave evolution (Koh et al. 2017). Wave attenuation by mangroves was then investigated using these two simulation methods to assess the impact of various forest configurations in reducing wave heights subject to several wave structures. Wave height reduction depended significantly on three factors: (a) forest structure (forest width, forest type, age, size and density), (b) wave characteristics (wave period, height and water depth) and (c) bathymetric-topographic features (slope and elevation). Both Morison and Manning models were used to assess the wave attenuation of the mangrove forest at Pantai Acheh, which was hit from a north westerly direction by the 2004 Andaman tsunami (Kh'ng et al. 2017). The simulation study suggested that the hydraulic resistance provided by that mangrove forest had an equivalent Manning roughness coefficient, n, of 0.1 to 0.12 $sm^{-1/3}$ and effectively reduced the extent of inundation by slowing down wave velocity (Figure 1).

The Manning approach to hydraulic resistance of mangroves is more convenient to use. Moreover, the Manning formulation of friction allows a simplification that leads to a simple exponential decay law for wave attenuation. Because of its simplicity, the exponential wave decay is further deliberated upon in the next section to provide useful insights.

Mangrove-induced exponential wave decay

We recall that wave height decays exponentially with distance travelled through the mangrove forest given by the simple exponential equation $\eta = \eta_0 \exp(-\beta x)$ where x (m) is the distance travelled and β (m^{-1}) is the decay rate. The ratio η / η_0 measures the degree of wave reduction. While Bao (2011) derived β from field experiments, Teh

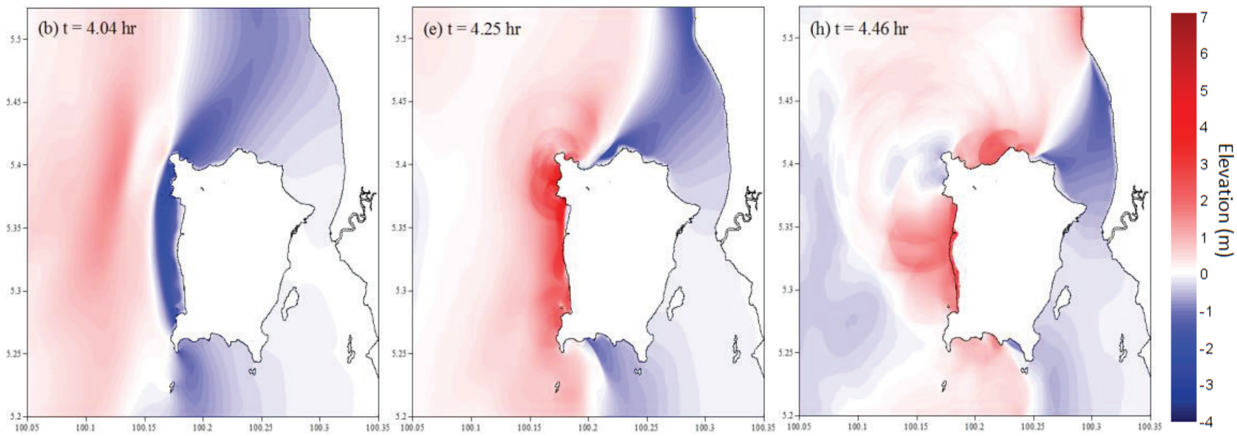

Figure 1 TUNA-RP simulated runup and inundation of the 2004 Andaman tsunami along the coast of Penang; t = number of hours after the earthquake that triggered the tsunami; wave heights above and below mean sea level (elevation = 0 m) are illustrated in shades of red and blue respectively

et al. (2009) mathematically derived the values of β as:

$$\beta = \frac{n}{H}\sqrt{\frac{2v_0}{TH^{1/3}}} \qquad (3)$$

where n = Manning's roughness coefficient, T = wave period, H = mean water depth and v_0 = incident velocity.

The half distance, X (m) is defined as the distance it takes the wave height to reduce by half and is given in equation (4).

$$X = -\frac{1}{\beta}\ln(0.5) \qquad (4)$$

For the tsunami that propagated through the Pantai Acheh mangrove forest in 2004, we prescribed values of H = 2 m, v_0 = 0.44 ms^{-1}, n = 0.1 $sm^{-1/3}$ and T = 60 minutes. The resulting value calculated for β was 0.00428 m^{-1}, while X was 162 m, indicating that a forest width of 162 m should reduce wave height by half. In the southern Andaman region of Thailand by comparison, mangrove forest fringes sparsely vegetated with *Avicennia* and *Sonneratia* species yielded a β value of 0.002 m^{-1} while β was calculated as 0.012 m^{-1} for the dense swath of *Rhizophora* behind those forests (Horstman et al. 2014).

Predicting regime shift under sea-level rise

Mangrove forests and hammocks compete along the salinity gradient to maintain bi-stability in a common habitat often exhibiting a sharp ecotone boundary as seen in south Florida, USA. There are three major wetlands in Florida, namely the Everglades, the Big Cypress Swamp and the Florida Bay coastal mangroves, which occupy a total area of 34,000 km^2. Sawgrass dominates the Everglades landscape, interspersed by deeper water sloughs and tree islands. The Big Cypress Swamp is dominated by cypress interspersed with pine flatwoods and wet prairies. Mangroves dominate the areas where the sawgrass and cypress swamps meet the saline waters of the coastlines. About half of the original Everglades has been lost to agriculture in the north and to urban development in the east. The natural sheet flow through the Everglades was drained to meet the demands of expanding agricultural and urban development activities. This human-induced change of hydrology disrupted the Everglades ecosystem and deprived wading birds, fish and animals of their natural water habitat. Further, the reduced freshwater flow facilitated seawater intrusion that stifled the growth of salt-intolerant plants, allowing salt-tolerant plants to dominate. Polluted waters that flowed in from neighboring farms and cities worsened water quality by fueling algae growth. The Everglades is currently undergoing the largest restoration effort in the US. All major federal and state environmental agencies and universities in the region are involved in this 30-year Comprehensive Everglades Restoration Project (CERP) with an initial commitment of USD8 billion by the US federal government and the Florida state government. The main objective of CERP is to restore the quantity and quality of the water flowing through the Everglades to revive its hydrology and ecosystem. With climate change and SLR, CERP has taken on a new urgency (Epanchin-Niell et al. 2017). If the rise in sea level is not accompanied by equivalent vertical accretion of marsh sediments (Smoak et al. 2013), then there will be a gradual disintegration of the coastal ecosystem due to increased inundation, erosion and saltwater intrusion (Crosby et al. 2016). The low-lying southernmost portion of the Everglades is already exhibiting SLR stress signs with major shifts in ecotones and animal communities (DeSantis et al. 2007). This extent of saltwater intrusion will be amplified during periods of prolonged drought induced by climate change. Hence, developing methodology to detect early signs of ecosystem shifts followed by mitigation measures is highly desirable for sustainable management of Everglades (Sternberg et al. 2007) and other wetlands. A recent study by Zhai et al. (2016) reported the promising use of the stable isotope composition of plant stem water to detect early indicators of shifts from hardwood hammock to mangrove. Prior to this, MANHAM was developed (Teh et al. 2008) to simulate vadose zone salinity changes assuming constant ground water boundary conditions. MANHAM was subsequently coupled with the USGS's Saturated-Unsaturated TRAnsport (SUTRA) groundwater model to form MANTRA (Teh et al. 2013) to improve simulations of hydrological systems and salinity dynamics. Currently, MANTRA is undergoing further improvement by incorporating the findings of Zhai et al. (2016) to enhance its ability to provide early warning regarding potential changes in stable oxygen isotope ($\delta^{18}O$) and salinity. Preliminary simulations using MANTRA-O18 suggest that the shift from hammock to mangrove can be detected a decade or two before the actual shift occurs. This encouraging result will lay the foundation for the development of a system that can provide early warning of sudden shifts in ecosystems.

DISCUSSION

Mangroves reduce hurricane and cyclone flooding

Mangroves and other wetland vegetation can play a key role in reducing flood water heights and flood areas caused by hurricanes, typhoons and cyclones. For hurricanes and cyclones, forward-moving speed is the most important determinant of the extent of flooding and flood reduction. Based on limited field observations for Hurricane Wilma, Krauss et al. (2009) suggested that the wetlands along the Gulf Coast reduced peak water levels at rates of 4.2 to 18.9 cm^{-1} km^{-1}. The coastal areas of Bangladesh are recognised by the United Nations as the most vulnerable in the world to tropical cyclones. Cyclone Sidr (2007) in Bangladesh caused 10,000 deaths and USD1.7 billion in damage. The Sunderban mangrove ecosystem, the world's largest at 7900 square miles, is increasingly being degraded for a variety of reasons such as agriculture, fishing, farming and settlement. To quantify the effects of mangrove degradation on spatial flood inundation and storm surge magnitude, storm surge was calculated using the coupled SWAN + ADCIRC model at six separate locations along the Bangladesh coast using Cyclone Sidr meteorological inputs (Deb & Ferreira 2016). In that study, simulation results for category 3 cyclones showed that mangrove degradation to grassland could raise the surge elevation by 57% and increase the velocity of the flood wave by 2730%. Inland penetration of the inundation and total flooded area could increase by 10 km and 18% respectively for low intensity cyclones, and slow-moving cyclones imparted more severe flooding than fast-moving ones. Numerical experiments were performed by Liu et al. (2013) by means of the numerical model Coastal and Estuarine Storm Tide (CEST), using Manning's coefficient based on the 2001 National Land Cover Data set (NLCD). CEST was verified by comparing the results of that model with field observations in south Florida for Hurricane Wilma. Storm surge reduction by mangroves is sensitive to the intensity, size, approach direction, and forward-moving speed of a hurricane. The effect of the mangrove zone in reducing flooding areas and peak storm surge heights is most sensitive to hurricane forward-moving speeds. Mangroves are more effective in reducing the water levels and inundation areas of fast-moving, small and weak hurricanes than those from slow-moving, large and strong hurricanes. A slow-moving hurricane can deliver more precipitation than a fast-moving one, in much the same way as a tsunami of longer period can move more water over land than a tsunami with a shorter period.

Mangrove replanting and rehabilitation

Following the 2004 Andaman tsunami, coastal greenbelts have received increasing acceptance as environmental-friendly and cost-effective coastal defences. After that tsunami, many started planting mangroves and other vegetation belts along coastal areas as a natural bio-shield against tsunamis and other natural disasters (Paphavasit et al. 2007, Feagin et al. 2010). Mangrove replanting has had mixed success and has been affected by several technical and social-economic issues discussed below for three sites in Malaysia, south Florida and Thailand.

The Malaysian Federal Government allocated RM40 million under the Ninth Malaysian Plan (2006−2010) for the restoration of mangroves and other coastal vegetation. The choice of the appropriate mangrove species to protect coastlines is crucial. Mangrove species differ in their drag force and hydraulic resistance in relation to tsunami height, e.g. *Pandanus odoratissimus* (a palm) and *Rhizophora apiculata* are more effective than *Avicennia alba*. Mangrove species also differ in their ability to recolonise new or degraded habitats. This observation underscores the importance of preserving or selecting appropriate species that: (a) are viable and robust to recolonise the zones intended for them, and (b) can act as wave barriers to offer sufficient shoreline protection. Mangrove replanting in Malaysia achieved limited success. Innovative mangrove replanting efforts require technical inputs from several specialists from various fields, e.g. engineers, hydrologists, ecologists and botanists, to plan bio-technical options for initial ground stabilisation and subsequent mangrove replanting work. It usually requires the construction of both a hard and a flexible breakwater that: (a) facilitates seawater flushing of the restoration area at high tide, and (b) promotes sediment accretions at low tide (Tamin et al. 2011). At about USD142,000 per ha, the cost of constructing a hard breakwater is substantial and therefore requires justification. Innovative pre-planting trials, species selection and enrichment planting are crucial for the success of the restoration efforts. *Rhizophora apiculata* was the favourite choice due to its commercial value as poles, and logs for charcoal. *Avicennia* spp. have limited commercial value as firewood, but are suitable as protective green shelterbelts and coastal bio-shields against wave surges and tsunamis. Of note, in the Philippines, *Rhizophora* spp. were also the preferred choice for mangrove restoration but *Avicennia* spp. are now widely planted in degraded mangrove sites (Primavera & Esteban 2008). The hugely variable performance of each species has made the selection process complicated. Within the restoration area in Sungai Haji Dorani, Selangor, Malaysia, sedimentation remains an ongoing problem. *Avicennia marina* appears to show greater tolerance to root burial than does *Rhizophora apiculata*. Nevertheless, within a year after the hard breakwater was constructed, attempts to establish *Avicennia marina* failed due to active accretion that buried the roots of planted seedlings and killed them (Tamin et al. 2011). At that site, seedling mortality 90 and 120 days after planting was 75 and 93% respectively, due to root burial by sediment at depths of 9.3 and 11.5 cm respectively (Affandi et al. 2010). Much needs to be done before sustained rehabilitation becomes the norm rather than the exception.

In southwest Florida, an experimental program was initiated in 2016 for early detection of mangrove forest degradation (Lewis et al. 2016). This involves development of a rehabilitation monitoring project for 220 ha of dead and stressed mangrove forest, which has succumbed to slow degradation over the last three decades. The clear associations between the observed mangrove die-offs and modifications to local hydrology have generated great interest among residents. The coastal management plan intends to stop further mangrove losses through preemptive action. This prototype mangrove 'heart attack' prevention model is needed globally to rehabilitate vast areas of dead or stressed mangroves over the coming decades. Prevention begins with monitoring for early detection of small degrees of degradation, identifying the thresholds that may trigger acute losses, and ameliorating those stresses before acute losses occur.

In Thailand, mangrove rehabilitation is costly and time-consuming and requires justification, motivation and community cooperation for its sustained success. Communities need to feel that their contributions will benefit them directly or indirectly. In a survey conducted in Thailand, individual household responses to mangrove replanting were based on maximising an underlying utility function, i.e. the household will contribute some of its adult labour to the public goods program only if it benefits them (Barbier 2008). The decision to participate is mostly influenced by household awareness of the importance of community conservation programs. However, the decision to contribute is sensitive to the degree to which the household derives mangrove-based income. According to Thai law, forest concessionaires are required to replant but reforestation has never taken place, and replanting must depend on community willingness on a voluntary basis.

CONCLUSIONS

The role of mangroves and other greenbelts in mitigating impacts of tsunamis remains an area of intense debate. Nevertheless, the economic value of mangrove ecosystem services is now better appreciated, leading to potentially new management strategies and policies for integrated coastal zone management that incorporates mangrove ecology as a core component. In additional to providing protection from hazards, coastal mangroves and other greenbelts have been given credit for providing many ecosystem services, such as wood for fuel, fish breeding habitats, pollution mitigation, coastline stabilisation and scenic amenity enhancement. The 2004 Andaman tsunami led to increased appreciation of and dedicated efforts to replant or rehabilitate mangroves (Barbier 2006), despite the myriad obstacles encountered. However, in view of the limited coastal livelihood recovery in Acheh, Indonesia 10 years post-tsunami, it is doubtful whether it is possible, or even desirable, to attempt to fully rehabilitate coastal greenbelts and livelihoods to their pre-disaster state (Daly et al. 2017). Despite its important contribution to ecological services, coastal tsunami greenbelts should not dominate other equally crucial agendas of improving community risk awareness and education and implementing an effective and robust early warning system. Recent findings suggesting that a large tsunami may hit Aceh soon (Sieh et al. 2015) serve as a key incentive and mandate to build resilience in Aceh and elsewhere, noting that the human impact of coastal hazards can be felt beyond the area of inundation. Greenbelt proponents need to have a good basic understanding of mangrove-fluid interaction dynamics during a tsunami runup over a greenbelt, and clearly acknowledge the limitations of greenbelts in mitigating extreme tsunamis. Modelling specialists should appreciate the many ways mangroves and greenbelts contribute to ecosystem services and correctly incorporate into their models important factors such as the landscape and hydraulic resistance of different types of coastal forests and morphology (Cochard et al. 2008). Efforts devoted to early warning systems, community education and awareness should be complemented by efforts to address the daily needs of communities in coastal areas. Environmental greenbelt reconstruction can complement early warning systems and community awareness. Integrating greenbelt components into landscape ecosystems would enhance the performance of the overall system. Effective risk management clearly requires an integrated approach that embraces valuable contributions of various exponents from many disciplines.

Mangrove forest rehabilitation should begin much earlier than at the tipping point of catastrophic loss. Vulnerability is set decades earlier when seemingly innocuous hydrological modifications are made, for example by road construction (Lewis et al. 2016). Reduced river-tidal flows and exchanges can compromise flushing that result in higher salinity and impaired sedimentation, which is detrimental to some mangrove species. Long-term chronic degradation of mangrove ecosystem functions can lead to unexpected acute mortality prompted by acute events, but created by a systematic long-term neglect of mangroves. The need for 'mangrove forest heart attack prevention' can be addressed by embedding mangrove rehabilitation within integrated coastal zone management plans.

Numerous studies show that mangroves provide nursery habitats for juvenile coral reef fishes of many species. Many economies, particularly the Wider Caribbean Basin economy, are heavily dependent on tourism, fisheries and other coastal resources provided by essential coastal ecosystem services created by mangroves, seagrasses and coral reefs. However, legislation in most countries does not currently integrate interdependent habitats such as coral reefs, sea grasses and mangroves, into a unified entity for effective management and protection from human disturbances. Proactive and dedicated research on this aspect of coastal resources integration will narrow existing knowledge gaps and pave the way towards more effective management in the future.

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