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Land reclamation and artificial islands: Walking the tightrope between development and conservation

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ABSTRACT

Coastal developments worldwide have put entire shoreline ecosystems at risk. Recently, land reclamation has been extended to the construction of whole new islands; a phenomenon that is particularly common in Asia and the Middle East and is recognised as a global conservation issue. Using Penang Island, Malaysia as a case study, we illustrate the relationship between rapid population growth and the simultaneous increase in urbanisation, land reclamation and extent of artificial shorelines; and decrease in the quality and extent of natural coastal habitats. Our goal was to provide an up-to-date assessment of the state of coastal habitats around Penang, identify knowledge gaps and identify locations that may be potentially suitable for eco-engineering. Comparisons of historical and current topographic maps revealed that land formerly consisting of coastal swamp and forest, mangrove forests, sandy beaches, and rubber and oil plantations have been lost to large-scale land reclamation and urbanisation. Between 1960 and 2015, there were increases in urbanised area, reclaimed land, and artificial shoreline extent. The total extent of mangrove forests has remained relatively stable but this balance is characterised by significant losses on the east coast coupled with increases on the west coast. Coastal development on the island is still on-going with plans for the construction of five artificial islands and another two coastal reclamation projects are either underway or scheduled for the near future. If the plans for future land reclamations are fully realized, 32.3 km^2 of the 321.8 km^2 island (10%) will be reclaimed land and the associated negative effects on the island's natural coastal habitats will be inevitable. This study highlights sections of the coast of Penang Island in need of effective monitoring, conservation and management and explores the possibility of incorporating ecological engineering into development projects, either prospectively or retrospectively, to create more environmentally-friendly urban environments and to promote educational, amenity and economic activities. With coastal development taking place on a global scale, opportunities to balance development needs with conservation strategies abound and should be integrated into present and subsequent projects to protect these coastal ecosystems for future generations.

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1. Introduction

1.1. Burgeoning coastal populations

Throughout history, people have settled and built cities in coastal zones due to the prevalence of natural resources, easy access to transport and trade and better defence opportunities (Small and Nicholls, 2003; Neumann et al., 2015). Consequently, coastal ecosystems support disproportionally higher densities of people, many of whom are urban dwellers (McGranahan et al., 2005). In relation to rapid population growth and high proportions of urban populations living in coastal areas (McGranahan et al., 2005; UNEP, 2016), Asia has shown some of the greatest intensification of coastal development (Jongman et al., 2012), with 20 of the top 30 (67%) most populated coastal cities located there (UNEP DESAP, 2014; Firth et al., 2016a).

To accommodate the rise in human population, coastal areas are becoming progressively saturated with high-rise buildings, and while this serves as a temporary solution in some cases, available land for development becomes scarcer in others. In the latter, land reclamation (the gain of land from the sea, wetlands, or other water bodies) is often one of the few solutions to provide space and counteract erosion (Charlier et al., 2005; Lai et al., 2015). Land reclamation can be extended to the construction of whole new islands; a phenomenon that is particularly common in Asia and the Middle East (e.g. the Palms, Dubai, Burt et al., 2010). The construction of artificial islands to support infrastructure and people is not a new concept but there is increasing concern about the environmental and political implications of these developments (Larson, 2015). For example, in a recent horizon scanning review paper, Sutherland et al. (2016) identified the construction of oceanic islands as a "global conservation issue".

As a result of land reclamation, natural habitats (e.g. mangrove forests, seagrass beds, saltmarshes and mudflats) are rapidly being replaced by artificial "habitats" such as seawalls, rock armour, breakwaters and marinas (Airoldi et al., 2009; Bulleri and Chapman, 2015; Dafforn et al., 2015a; Ng et al., 2015), with the loss of valuable ecosystem services and disruption to natural connectivity among terrestrial and marine systems (Airoldi et al., 2005, 2015; Bulleri and Chapman, 2010; Bishop et al., 2017). It is estimated that by the year 2030, up to 12.5 million km^2 of natural habitat will potentially have been replaced by artificial habitats (Seto et al., 2011; Browne and Chapman, 2014) and there is a pressing need to find ways to mitigate this loss.

1.2. Ecological engineering

Environmentalists have traditionally disfavoured city growth and urbanisation. Interestingly, in recent years, there has been a turnaround in environmental thinking (Martine, 2008) based on the recognition of urban biodiversity and the potential for landscapes to support valuable ecosystem services (Bolund and Hunhammar, 1999). Through appropriate planning and management, cities can be designed to have reduced ecological footprints and even promote urban biodiversity and conservation (McKinney, 2002).

Ecological engineering (eco-engineering) is an emerging field which integrates engineering criteria and ecological knowledge to create more environmentally-friendly urban environments (Schulze, 1996; Bergen et al., 2001; Chapman and Underwood, 2011). A recent surge of literature is calling for a shift in the way artificial environments (often referred to as "grey" spaces) are perceived and designed to become "green" and "blue" spaces (Goddard et al., 2010; Kong et al., 2010; Sutton-Grier et al., 2015; Firth et al., 2016a; Mayer-Pinto et al., 2017). A range of different eco-engineering trials have now been trialled in coastal regions globally, with the vast majority being implemented in a few key hotspots (e.g. Europe, USA, Australia, Toft et al., 2013; Strain et al., 2017; Perkol-Finkel et al., 2017). As a result, there is now an increasing number of "proof-of-concept" methods emerging for a range of different types of coastal infrastructure (e.g. see Dyson and Yocom, 2015; Firth et al., 2016a for comprehensive reviews).

In the past "hard" (i.e. physical manipulation of artificial structures, Chapman and Blockley, 2009; Martins et al., 2010; Loke et al., 2014; Evans et al., 2016; Firth et al., 2016b; McManus et al., 2017) and "soft" (i.e. the incorporation of natural habitats for coastal defence Hanley et al., 2014; Ondiviela et al., 2014; Willemsen et al., 2016) approaches were typically applied on a local scale and treated as two separate approaches to eco-engineering of coastal habitats. More recently, the combination of hard and soft approaches has been trialled and has been referred to a "hybrid stabilisation" (Hashim et al., 2010; Bilkovic and Mitchell, 2013), "ecosystem-based flood defence" (Temmerman et al., 2013) or "hybrid-infrastructure" (Sutton-Grier et al., 2015).

It is important to note that all management strategies will be context-dependent and what works in one location may not work (or indeed be desirable) in another location (Chapman and Underwood, 2011; Lai et al., 2015); and consideration of the environmental setting and management goals is advocated (Firth et al., 2014). The ecosystem approach may be feasible in locations where sufficient space between urban areas and the coastline is available (Sutton-Grier et al., 2015) to accommodate the creation of natural ecosystems (e.g. shellfish and coral reefs, seagrass beds, saltmarshes, mangroves), that have the natural capacity to attenuate waves (Gedan et al., 2011; Shepard et al., 2011; Zhang et al., 2012), and can keep up with sea level rise by natural accretion of mineral and biogenic sediments.

1.3. The case of Malaysia and Penang Island

Malaysia has the highest urban population and is one of the fastest growing countries within Southeast Asia (World Bank, 2016a,b). Urbanisation in Malaysia began during the British administration in the Straits Settlements of Penang and Malacca during the 18th century (Hadi et al., 2010). Since 1900, the population of Malaysia has increased from 2 million to >30 million people. The vast majority of these people live in the coastal zone on the west coast of Peninsular Malaysia where mega urban regions are found in Kuala Lumpur, the Klang Valley, Putrajaya and Penang Island (Fig. 1). Despite coastal land reclamation dating back to the 8th century, it wasn't until the 1990s - in response to a vibrant economy, that coastal reclamation became a serious development option in Malaysia (Ghazali, 2006). Since 1988 at least 31 land reclamation projects have been approved

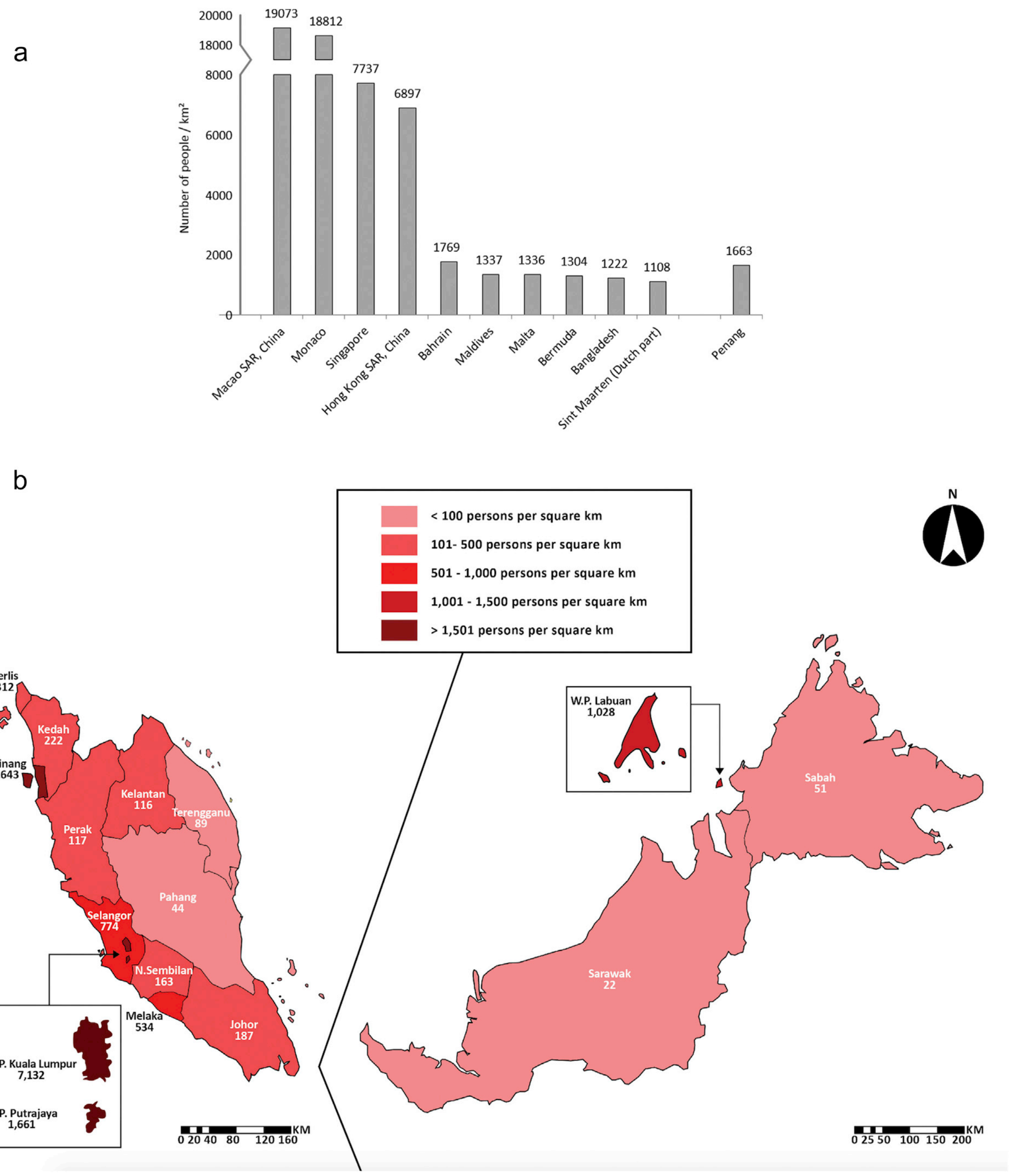

Fig. 1. (a) The population densities of the top ten most densely populated countries. Data for Penang included for comparison. Data taken from the World Bank (2016c). (b) Population density of Malaysia by state, 2016. Map Redrawn from Department of Statistics (2010) and data taken from Department of Statistics, Malaysia (2015).

with megaprojects including the reclamation of entire coastlines of federal states (e.g. Kedah and Negeri Sembilan) and the construction of 18 artificial islands (Table 1).

Nowhere is this development more intense than on the small Island of Penang (Pulau Pinang) off the northwest coast of Peninsular Malaysia (Fig. 1). Penang Island is one of the fastest-growing and most densely populated places in the world with a population of 752,800 (Department of Statistics Malaysia, 2015) and a density of 1663/km^2 (Penang Institute, 2016; Fig. 1). The population on the 299 km^2-island has increased by more than 40% since 1970 (Department of Statistics Malaysia, 2015 data) and is projected to rise exponentially over the next 15 years (Penang Transport Masterplan Study, 2013). Land reclamation in Penang began in the early 1800s (City Council of Georgetown, 1966) during the British administration but recent large-scale coastal development projects have contributed to the alteration of the coastline of Penang to make way for transportation and infrastructure (City Council of Georgetown, 1966; Khoo and Wade, 2003).

At the time of writing, construction had just begun on the first of a series of five artificial islands (three still pending approval) and large-scale coastal reclamation projects around the coast of Penang. In a recent paper that quantified past and proposed changes to the coastline of Singapore, Lai et al. (2015) advocated that coastal cities in the early stages of expansion quickly establish monitoring efforts to establish baselines and track changes. Although Penang is not necessarily in the early stages of expansion, it is recognised that there is a paucity of baseline data available and with the large-scale coastal developments that are currently underway, there is serious scope for eco-engineering to be incorporated into the planning and design of urban waterfronts to reduce the ecological footprint and factor in urban biodiversity and conservation targets. In this paper, Penang Island is used as a case study to highlight the mega urban development that is an existing or future reality for many countries throughout the developing world. Our goal is to emphasise that eco-engineering should be considered during the planning stage in order to attempt to mitigate the impacts of such developments. In particular, when developments are on such large scales and/or when coastal vegetation is being cleared, we advocate that the hybrid-approach be given serious consideration.

In this paper we aimed to quantify the past and future transformations of the coastline of Penang, as well as describe proposed changes to the coastline based on the Penang Transport Master Plan. We also identify the potential to incorporate ecological engineering into the design of coastal infrastructure. Using a combination of historical maps and Google Earth, we collated information on past and present trends of land use change and extent of artificial shoreline on the island of Penang from 1960 to 2015. We hypothesised that the extent of urban areas, reclaimed land and artificial shoreline would increase and that the extent of natural barriers to coastal erosion (i.e. mangroves, seagrass beds and coral reefs) would decrease during this time. Furthermore, we also compared the efficacy of using Google Earth compared to ground-truthed walk-around surveying

Table 1
List of EIA-approved coastal reclamation projects in Malaysia (1988–2016). Source: Department of Environment (DOE), Malaysia. For artificial islands projects it is indicated in brackets whether they are at the proposal stage, underway or completed and how many islands are involved. All other land reclamation activities listed are either underway or complete and have been approved by the DOE.

State	Completed Project Location (Year of completion)	Artificial islands projects (stage of project × number of islands)
Kedah	Entire coast	
	Pulau Bunting, Daerah Yan	
Penang	Tanjung Tokong	Tanjung Tokong (underway × 2)
	Bayan Lepas	Permatang Damar Laut (proposed × 3)
Perak	Lekir Coastal Development, Pulau Pangkor, Daerah Manjung	Teluk Muroh (completed × 1)
	Perak Heavy Industries Park (PHIP), Bagan Datoh	Marina Island, Pangkor (completed × 1)
	Teluk Muroh	Lukut (proposed × 1)
	Bagan Datoh	
Selangor	Port expansion at Westport, Pulau Indah Kelang	
Negeri Sembilan	Entire coast	
Melaka	Pantai Kundur	Malacca City (completed × 2)
	Malacca City	Off Melaka (proposed × 3)
	Pulau Panjang, Daerah Melaka Tengah	
Johor	Southern International Gateway Project and Tanjung Puteri	Forest City Island Reclamation and Mixed Development (underway, × 4)
	Lido Boulevard, Johor Bahru	
	Independent Deepwater Petroleum Terminal, Pengerang	
	Mersing Laguna	
	Phase III Dredging and reclamation works at Pelabuhan Tanjung Pelepas	
	Marine and Riverine Facilities on Lot PTD 504 and Lot 1668, Sungai Batu Pahat	
	Integrated Hub and Maritime Industrial Park, Tg. Piai	
	R&F Tanjung Puteri	
	Lot PTD 220207 and Part of Lots PTD 194792, PTD 194794-PTD194797, Mukim Plentong, Johor Bahru	
Kelantan	Jetty and Industrial zone constrution, Tumpat	
Sabah	Kudat	Kudat (completed × 1)
Federal Territory of Labuan	Integrated Port, Ranca-Ranca	
	Oil and gas industrial base, Kg. Ranca-Ranca	

as methods for quantifying the extent of artificial shoreline. The walk-around surveys also served the purpose of identifying potential locations for eco-engineering trials.

2. Materials and methods

Estimates of urbanised areas, reclaimed land, mangroves, seagrass beds and coral reefs were obtained from a combination of existing literature, historical maps and Google Earth. Unfortunately, due to a paucity of information, no data were available for coral reefs and seagrass beds, thus we only report on changes in mangrove cover. Due to the availability of historical maps from 1962 (Surveyor General of Malaya) and 1975 (Director of National Mapping) we arbitrarily selected years of 1960, 1980, 2000 and 2015 for comparison to illustrate changes in land use over the period of 1960–2015 for Penang Island and its associated islands (Jerejak, Tikus, Betong, Kendi and Rimau). Additional information on the distribution, areal extent and percentage of overall land area for reclaimed land prior to 1960 was also sourced from the City Council of Georgetown (1966). The boundaries of Penang Island and associated islands, its urban areas, reclaimed land and mangrove forests were traced, and planar areas calculated for each time period using ArcView 3.3 (ESRI®, 2002). The extent of artificial shoreline characterised by seawalls, rock revetment and jetties in 2015 was determined and mapped based on satellite images from Google Earth (Google, 2015) and available maps in the Penang Geographical Information System (PEGIS).

As a separate exercise, we were interested in testing the reliability of using Google Earth for estimation of the extent of artificial shorelines (see Waltham and Sheaves, 2015). In order to do this, we compared data collected from Google Earth with ground-truth data obtained through walk-around surveys where the linear extent of stretches of artificial shoreline were identified using handheld global positioning system (gps). The entire shoreline of Penang Island was surveyed once in August 2015 and the extent of natural (beach, mangrove) and artificial (reclaimed land, seawalls, piers/jetties, breakwaters/groynes) shorelines were recorded from point to point using the handheld gps. Besides that, the number of slipways, piers/jetties and breakwaters/groynes were also recorded. In areas where walking was not possible, locations were accessed using a boat and exact co-ordinates were estimated using a combination of handheld gps and Google Earth (just to pin-point the start and end points of different coastline types). All ground truth data was collected during low water periods. All seawalls, rock armouring and jetties were grouped together as “artificial shoreline” and were traced onto the 2015 topographic map using ArcGis 3.3 (ESRI®, 2002). The dual purpose of the walk-around surveys was to provide a quantifiable comparison with the Google Earth method, and also to identify locations that were potentially suitable for eco-engineering trials. There were no specific selection criteria applied but decisions were made based on previous proof-of-concept trials from the growing body of published literature (see Firth et al., 2016a; Strain et al., 2017 for reviews).

3. Results

The period between 1960 and 2015 was characterised by dramatic land use changes and extensive land reclamation on Penang Island. During this time two bridges were constructed in 1985 and 2014 linking Penang to the mainland. Areas of oil palm and rubber tree plantations, low-lying-forests, mangroves as well as rocky and sandy beaches have been largely replaced on the east coast and to a lesser extent on the north and south coasts by urban infrastructure, erosion control structures and highways. The west coast remains largely undeveloped, primarily due to the presence of mangroves along the central west coast and Penang National Park in the northwest corner (Fig. 2).

3.1. Urbanised areas

The extent of urbanised area increased from 29.5 km^2 (10.2%) in 1960 to 112.0 km^2 (37.4%) in 2015 (Fig. 3a, Table 2). In 1960, the urbanised area was concentrated in the northeast corner of the island around Georgetown (Fig. 3a, Table 2) because this is where the initial settlement began in the 18th century (City Council of Georgetown, 1966). By 1980, this had spread along the north coast to Tanjung Bungah and Batu Ferringhi and also westwards to Air Itam in the valley between Batu Lanchang Hill, Penara Hill and Penang Hill. Furthermore, small urbanised areas had developed at Bayan Baru to the south of Georgetown and Balik Pulau in the centre of the island. By 2000 significant development in the southeast led to a doubling of urbanised area from 37.8 km^2 (13.0%) in 1980 to 79.3 km^2 (26.7%). By 2015, continued development on the east and north coasts in addition to new development in the west drove the urbanised area of Penang to 112 km^2 (37.4%, Fig. 3a, Table 2).

3.2. Reclaimed land

The extent of reclaimed land increased from 0.4 km^2 (0.1%) in 1960 to 9.5 km^2 (3.2%) in 2015 (Fig. 3b, Table 2). The first area to be reclaimed was the land to the southeast of Beach Street in Georgetown. This began as a series of ghauts (alleys) running perpendicular to the sea some time before 1803; this was further extended to include what is the present-day Weld Quay by 1883 (City Council of Georgetown, 1966). By 1960 the areal extent of reclaimed land was 0.4 km^2 (<0.1%, Table 2). By 1980, a small reclaimed area consisting 0.9 km^2 (0.3%) had developed on the east by the location of the present-day Penang Bridge (Fig. 3b, Table 2). There was a seven-fold increase in the reclamation from 1980 to 2000 with the reclaiming of almost the entire east coast of the island (Fig. 3b, Table 2). The construction of Penang Island’s Free Trade Zone in the 1970s led to the

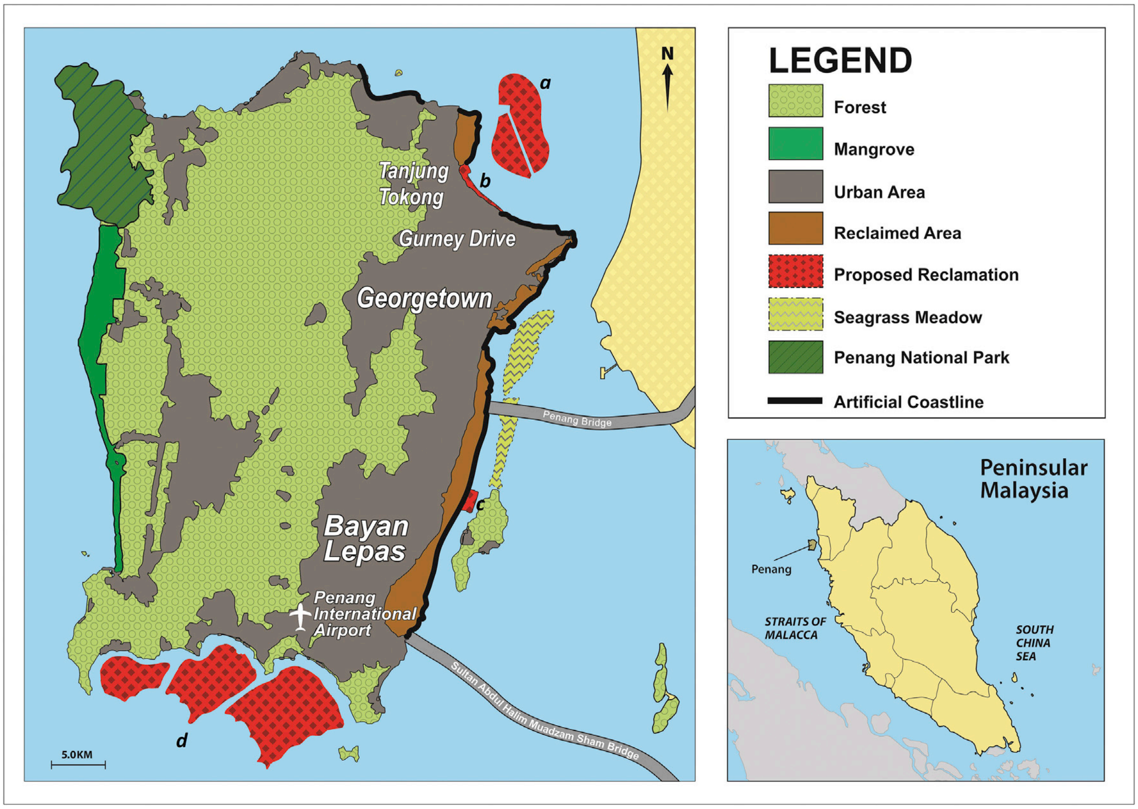

Fig. 2. Map showing present distribution (as of 2017) of natural habitats, reclaimed land and artificial shoreline on Penang Island and its associated islands. Also shown is the distribution and extent of the five proposed artificial islands and land reclamation projects. The reclamation and islands to the north and east began in 2016. It is not yet known when construction will commence on the southern islands. *a* – Sri Tanjung Pinang Phase II (proposed areal extent = 3.97 km^2), *b* – Gurney Wharf (proposed areal extent = 0.53 km^2), *c* – Queens Waterfront (proposed areal extent = 0.06 km^2), *d* – Penang South Reclamation Scheme (proposed areal extent = 18.21 km^2). All proposed land reclamation and islands will be protected with hard artificial structures such as seawalls and rock armouring.

reclamation of the entire bay north of Batu Maung on the southeast coast. By 2015, expansions from both existing and new projects on the northeast of the island (Straits Quay) had led to a slight increase in reclaimed land bringing the total reclaimed area to 9.5 km^2 (3.2%, Table 2).

The extent of reclaimed land is expected to dramatically increase between 2017 and 2030 with the construction of five new artificial islands on the northeast and south coasts (Fig. 2). At the time of writing, the construction of two artificial islands in addition to the extension of the existing coastline on the northeast coast (Seri Tanjung Pinang) had just begun (Fig. 4). This will lead to the reclamation of a further 3.97 km^2. Furthermore, the three islands proposed for the south coast (Penang South Reclamation Scheme, Fig. 2) under the Penang Transport Master Plan (PTMP) will lead to the reclamation of an additional 18.21 km^2. To the east of the island, reclamation (0.06 km^2) is underway for the construction of Queensbay Waterfront (Fig. 2), which will house residences, a marina, a waterfront promenade, and a sports centre. All of these developments will significantly add to the artificial shoreline extent of Penang Island. On completion of the five proposed artificial islands and additional land reclamation the total areal extent of Penang Island and its associated islands will be 321.8 km^2 and the area of reclaimed land will be 32.3 km^2 (10.0%) (Table 2).

3.3. Mangrove forests

Total areal extent of mangrove forest has remained relatively stable, decreasing very slightly from 6.9 km^2 (2.4%) in 1960 to 6.8 km^2 (2.3%) in 2015 (Fig. 3c, Table 2). In 1960, there was extensive mangrove forest on the central west side of the island with a smaller forest on the southeast coast downstream of Kluang River (Fig. 3c). The reclamation of the entire bay north of Batu Maung led to the loss of the only remaining mangrove forest on the east coast (Fig. 3c). Between 2000 and 2015, the extent of mangrove forest increased slightly from 6.0 km^2 (2.0%) to 6.8 km^2 (2.3%). Interestingly, following the reclamation of Straits Quay (Tanjung Tokong) on the north coast (Fig. 3b) a small patch of mangrove forest developed due to sedimentation and natural recruitment. At the time of writing, the majority of this urban mangrove forest had been removed to make way for the proposed land reclamation projects (Fig. 4).

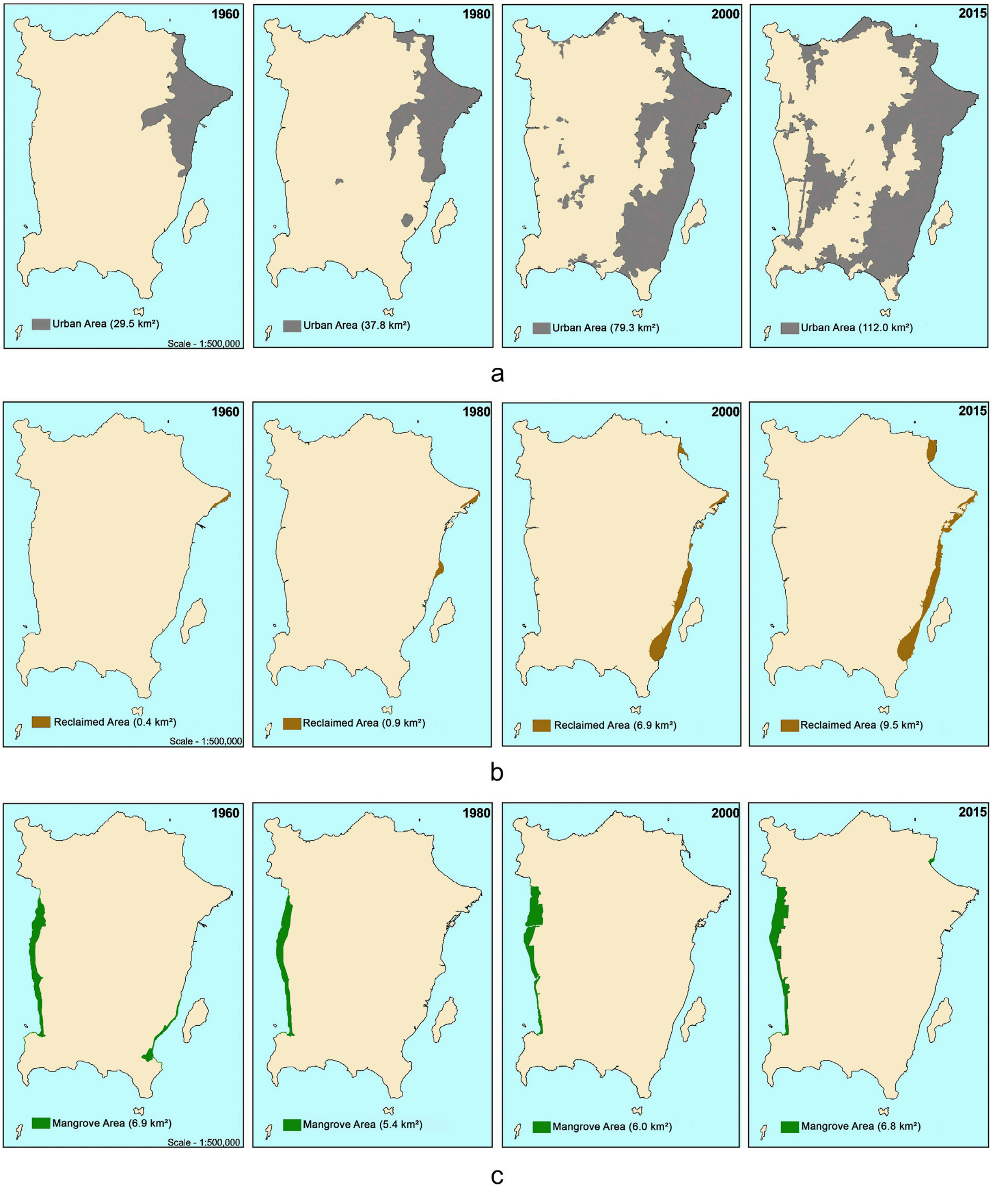

Fig. 3. Maps showing the distribution, areal extent (km^2) of overall land area for (a) urbanised areas, (b) reclaimed land and (c) mangrove forests on Penang Island for the periods of 1960, 1980, 2000 and 2015. No data were available for seagrass beds or coral reefs. Data for 1960 and 1980 obtained from historical maps. Data for 2000 and 2015 obtained from Penang Geographical Information System (PEGIS) and Google Earth.

Table 2
Areal and linear extent measurements of Penang Island from 1960 to 2015 and proportional change between years.

	Year					Proportional Change between years					
	1960	1980	2000	2015	After proposed reclamation	1960 −1980	1980 −2000	2000 −2015	2015-After	1960 −2015	1960-After
Total area (km^2)	290.6	290.9	296.9	299.1	321.8	1	1.02	1.01	1.08	1.03	1.11
Urban area (km^2)	29.5	37.8	79.3	112	*	1.28	2.1	1.41	*	3.8	*
Reclaimed area (km^2)	0.4	0.9	6.9	9.5	32.3	2.25	7.67	1.38	3.4	23.75	80.68
Mangrove forest (km^2)	6.9	5.4	6	6.8	6.7	0.78	1.11	1.13	0.99	0.98	0.97
Total shoreline (km)	103.5	114.7	117.2	106.5	*	1.11	1.02	0.91	*	1.03	*
Artificial shoreline (km)	2.4	2.7	11	31.8	*	1.13	4.07	2.89	*	13.25	*
Urban area (%)	10.2	13	26.7	37.4	*						
Reclaimed area (%)	<0.1	0.3	2.3	3.2	10						
Mangrove forest (%)	2.4	1.9	2	2.3	2.1						
Artificial shoreline (%)	2.3	2.4	9.4	29.9	*						

*Cannot be determined.

Fig. 4. Drone image indicating Pulau Jerejak, felled mangroves, and reclamation underway for both Gurney Wharf and an artificial island taken in April 2017. (Image by Hong Chern Wern).

3.4. *Artificial shoreline extent*

Due to extensive land reclamation between 1960 and 2015, the total area of Penang Island grew from 290.6 km^2 to 299.1 km^2 (Table 2). Furthermore, the extent of artificial shoreline also increased from 2.4 km (2.3%) in 1960 to 31.8 km in 2015 (29.9%, Fig. 2, Table 2). In response to the increasing area of the island, the total shoreline extent also experienced a steady increase between 1960 and 2000 (Table 2). Interestingly, there was a reduction in extent of the total linear extent of the shoreline from 117.2 km in 2000 to 106.5 km in 2015, probably due to the loss of complexity in shoreline configuration by replacing natural habitats with linear artificial structures (Table 2). Although the exact figures are unknown, the projected land reclamation and artificial island projects will dramatically increase both artificial and total linear extents of the coastline of Penang.

3.5. *Comparison of methods for calculating extent of artificial coastline*

Google Earth revealed that 19.8% of Penang Island's shoreline was artificial while ground-truthing produced a slightly higher percentage of 21.3% (Table 3). The Google Earth method proved fairly reliable along stretches of shoreline that were predominantly natural (i.e. the north, south and west coasts). However, along the highly altered east coast the method proved less reliable with much lower estimates (65.4%) than those obtained using ground-truthing (88.3%, Table 3). It is reasoned that

Table 3a
Shoreline extents of Penang Island obtained from Google Earth and ground-truthing.

	Google Earth		Ground-truthing
Total length (km)	106.5	>	98.3
Length rocky/natural	34.8	>	20.2
Length beach (km)	26	>	20.5
Length mangrove (km)	14	<	16
Length artificial/seawall (km)	21	<	23.8
Artificial/seawall (%)	19.8	<	24
Length reclaimed (km)	2.4	<	22.1
Total extent piers/jetties	6.9	<	7.8
Total extent breakwaters/groynes (km)	1.4	<	1.6
Number of slipways	5	<	6
Number of piers/jetties	55	<	57
Number of breakwaters/groynes	19	=	19

the discrepancy between the figures is as a result of the fact that it is not easy to tell from Google Earth whether land has been reclaimed or not (unless it has been captured in the preceding aerial photos), leading to an underestimation of artificial coastline. This is probably exacerbated by the fact that we employed a conservative approach; when in doubt coastline was considered natural over artificial.

4. Discussion

The results from this study revealed that there was a rapid increase in urbanisation, land reclamation and extent of artificial shoreline on Penang Island between 1960 and 2015. As a result of these changes natural habitats have become increasingly fragmented or have completely disappeared over time. On many parts of the island, fragments of forest are now completely surrounded by urbanised areas, while mangroves are now restricted to the west coast only. Despite the lack of historical data for seagrass and coral reefs, it is assumed that both habitats were historically widespread around Penang. Today, one of two seagrass beds remain on the east coast at Middle Bank, stretching from Georgetown to Pulau Jerejak (Fig. 2). These seagrass beds have been around since at least 1884 when they appeared on historical maps of Penang. Whilst no information at all is available on corals, live reefs can be observed on the uninhabited Pulau Kendi and small colonies have been found living on the rock revetment and outfall structures on Gurney Drive (Chee, pers. obs.), highlighting the potential for their presence prior to mass development on the island.

4.1. Urbanisation and reclaimed land

37% of land on Penang Island has been lost to urbanisation (Fig. 3a). This has largely been attributed to industrialisation, economic growth and better standard of living (Abdul-Majdeed and Ismail, 2013). Urbanisation is particularly pronounced on the east coast (Fig. 3a) and is coupled with major land reclamation projects (Fig. 3b). Upon completion, the proposed and on-going reclamation projects will triple the reclaimed land from 9.5 km^2 to 32.3 km^2 (Table 2). The Seri Tanjung Pinang Project around Tanjung Tokong on the north coast comprises not only the construction of two artificial islands but also the reclamation of land immediately in front of what is now Gurney Drive, iconic to residents and visitors alike. This new strip of land will be called Gurney Wharf and will be given over to "green" space, perceived to be a way of "giving back" to the city and its residents. Furthermore, an even larger project under the South Reclamation Scheme has been proposed on the south coast which proposes the construction of three artificial islands (total area of 18.21 km^2). At the time of writing, no Environmental Impact Assessment (EIA) had yet been performed but it is expected that this scheme will also be approved; the goal of which will be to redistribute traffic pressure on the existing infrastructure, in addition to the construction of residential and commercial property and amenities such as golf courses.

It was expected that there would be a positive relationship between the increasing areal extent and total shoreline extent of Penang Island. However, despite the extent of artificial shoreline increasing from 2.4 km in 1960 to 31.8 km in 2015, the total shoreline only increased by 3 km. A 10.7 km decrease in the total length of shoreline was also observed between 2000 (117.2 km) and 2015 (106.5 km). The replacement of complex natural shorelines with straight seawalls, marinas and jetties can sometimes lead to the linearisation of the coastline which can be coupled with an overall reduction in shoreline extent (Firth et al., 2016a). More often however, land reclamation gives rise to an increased area and extent of shorelines as evidenced from Dubai (Burt et al., 2009), Singapore (Lai et al., 2015), Qatar (Wiedmann et al., 2012) and the Maldives (Caprotti, 2014).

Conversely, 62.6% of Penang Island remains undeveloped. Development on the hilly centre of Penang is largely restricted by topography, geotechnical and environmental factors (Fig. 2; Barrow, 1981; Yahaya et al., 2013) although media reports on logging activities are on the rise. Development on the northwest tip of Penang Island, on the other hand, is limited by the gazetting of Penang National Park in 2003 (Fig. 2). This 25.6 km^2 park (the world's smallest national park) boasts a variety of habitats such as coastal hills, mangroves, mudflats, coral reefs, beaches and a meromictic lake (Hong and Chan, 2010a). The

Table 3b
Percentage of artificial coastline on each coast based on direction.

Direction	Google Earth (%)	Ground-truthing (%)
East	65.4	88.3
North	23	26.9
South	1.9	1.8
West	0	0

park supports many commercially important tree species (e.g. Seraya, *Shorea curtesii*), ferns, orchids and threatened pitcher plants (Hong and Chan, 2010a). The beaches of Penang National Park are also important sites for nesting green (*Chelonia mydas*) and Olive Ridley (*Lepidochelys olivacea*) turtles (Hong and Chan, 2010b), and are considered to be the only place on the island inhabited by the trochid button snail, *Umbonium vestiarium* (Berry and Zamri, 1983), which is threatened by collection for curios and handicrafts.

4.2. Mangroves and other coastal habitats

The west coast of Penang Island is less developed compared to the east coast. The “lack” of development on the west coast is primarily due to the fact that muddy soil is considered unstable by developers, therefore, not suitable for development. Mangroves, thrive in the shallow coastal waters here. Aquaculture activities like shrimp, oyster and cockle farming take advantage of the sheltered, brackish environment in the mangroves and generate a substantial sum of income for the residents. The mangroves have played a vital role in the mitigation of tsunami and storm surges. They were being credited with reducing wave heights and velocities in the 2004 tsunami which resulted in 52 deaths (Teh et al., 2009, 68 in total in Malaysia (Koh et al., 2009)) and more than USD 2.4 million in property losses in Penang alone (Siwar et al., 2006). Despite this, it has been reported that the west coast has experienced an 80% increase in urbanised areas and a 23% decrease in agricultural land between 1992 and 2002 (Mohammed et al., 2015).

Our results indicated that despite the total areal extent of mangroves remaining relatively stable between 1960 and 2015, there were substantial changes in distribution and abundance of mangroves (Fig. 3c; Table 2). The most prominent decrease occurred between 1960 and 1980 (6.9–5.4 km^2) in the southeast of the island at Bayan Lepas. An entire mangrove forest was felled to make way for the construction of Malaysia’s first Free Trade Zone (now known as Free Industrial Zone) which was completed in 1972 (Yeow and Ooi, 2009). Remnants of these trees can still be found at river mouths in this area. Despite the decreasing trend observed throughout 1960–2015, there was a 13% increase between 2000 and 2015 (6.0–6.8 km). Beh et al. (2012) attributed this increase to constant monitoring, conservation and reforestation efforts conducted by the state government. Similarly, the mangrove forests in Singapore has also increased recently due to restoration efforts and greater regulatory protection (Lai et al., 2015).

Ironically, the increase in mangrove areas in Penang was partly due to the side effects of coastal development involving land reclamation. The mangroves between Tanjung Tokong and Gurney Drive for instance was an unexpected side effect (or “happy accident”, Rosenzweig, 2003) of extensive land reclamation. The development caused siltation and sedimentation along Gurney Drive which made it conducive for the development of a natural mangroves forest. Since then, the mangroves have become rest stops for migratory birds and habitat to myriad coastal, marine and terrestrial organisms (Chee, pers. obs.). At the time of writing, the mangroves had just been cleared to make way for the reclamation of Gurney Wharf (Fig. 4).

There were initial plans for the South Reclamation Scheme to be located on the east coast between Penang Island and the mainland. This would have led to a substantial negative impact on the extensive seagrass beds at Middle Bank (Fig. 2). Continuous scientific monitoring of one of the two seagrass beds on the west coast of Peninsular Malaysia here provided evidence for the protection of these seagrass beds from development; as they are known to provide habitat, feeding and breeding grounds for a variety of marine organisms including fan shells, sea cucumbers, razor clams, sponges, sea anemones, octopuses and cockles (Ooi and Quek, pers. comm.). Horseshoe crabs and dugongs which are considered vulnerable species on the IUCN Red List can also be found at Middle Bank (Ooi, pers. comm.). This valuable ecosystem, together with the mangroves and protected forests, not only conserve the biodiversity of flora and fauna of Penang but also provide for the local community, encourage tourism, and educational value. This highlights the need for consistent research, management and conservation efforts with appropriate solutions to maintain these coastal ecosystems' functions and services. This study provides a suitable platform for future explorations of these solutions.

4.3. The potential for eco-engineering as an adaptive management tool

Recently, there has been growing interest in ecological engineering to design sustainable ecosystems for the mutual benefit of both humans and nature (Mitsch, 2012). Ecological engineering has been used increasingly as a solution to mitigate the ecological impacts caused by the hardening of shorelines in many parts of the world (see Firth et al., 2016a for review). The building of whole islands in Penang serves as a unique opportunity to trial large-scale ecological engineering works. Ideally, adopting an ecosystem or hybrid approach, such as the building of shellfish reefs in combination with other valuable habitats like mangroves, could be used to help restore ecosystem functions and services on the artificial coasts of the new islands

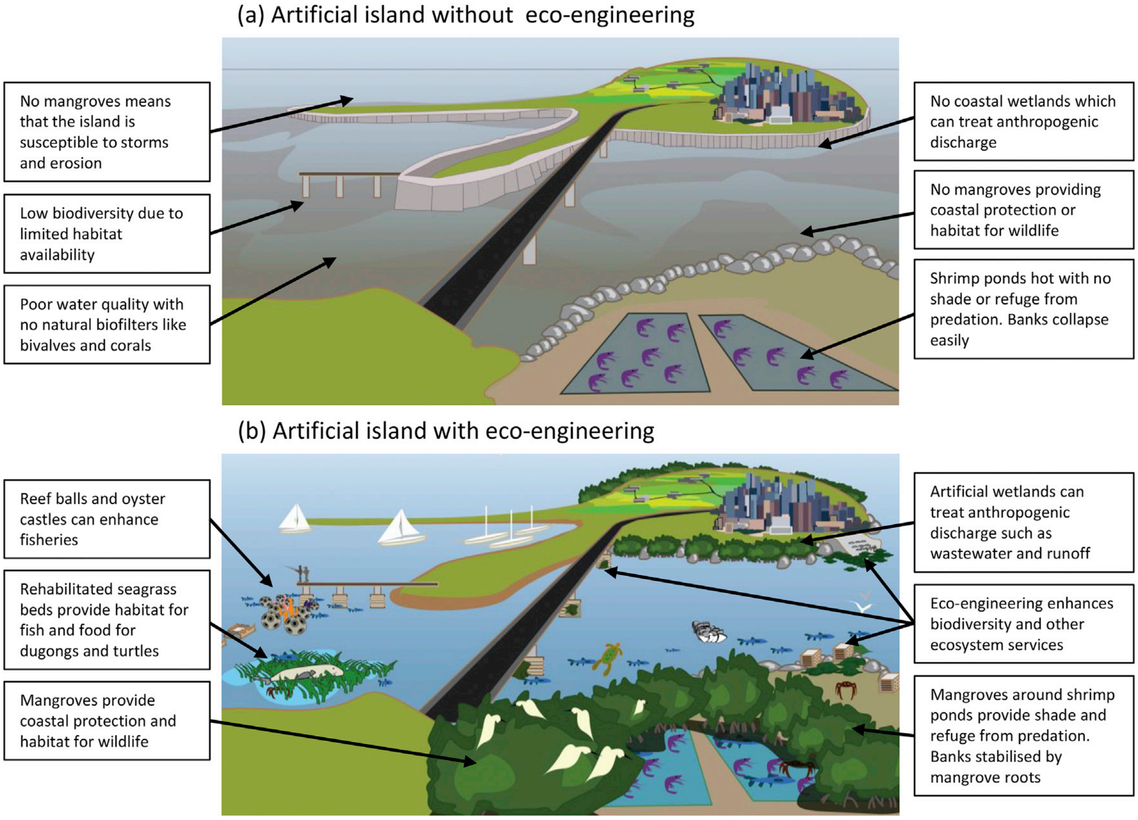

Fig. 5. Conceptual diagram, providing examples of (a) an artificial island without eco-engineering, and (b) the way in which eco-engineering can be applied on an artificial island as a management solution. Figure produced by by Shaun Lewin (Plymouth University).

(Fig. 5). Despite mangroves being perceived to be undesirable places to live in or near to (Rönnbäck et al., 2007), we do advocate that they be considered along sections of the coast that are less urbanised and/or be considered as an adaptive management approach to stretches of coast with shrimp and fish farms through “aquasilviculture” (Fig. 5, Dieta and Dieta, 2015; Flores et al., 2016). Shellfish reefs, perhaps a more likely contender for the ecosystem approach, are known to protect the area under their footprint against erosion and through sediment accretion and wave attenuation (Scyphers et al., 2011; Walles et al., 2015). Shellfish reefs have also been known to play an important role in mangrove rehabilitation by attenuating strong waves thus protecting vulnerable mangrove propagules (Chowdhury and Maiti, 2014). This “soft” approach could also be combined with artificial structures (i.e. the “hybrid” approach) to achieve similar goals (Temmerman et al., 2013; Sutton-Grier et al., 2015). In Bangladesh, oysters were transplanted onto concrete substrates in order to encourage the oysters to build reefs. By adding the hybrid concrete-oyster reef structure onto the coasts there, erosion was controlled, mudflats were stabilized (supporting the growth of seagrass plants and mangrove trees); biodiversity was increased, and food/income for local communities was enhanced (Chowdhury and Maiti, 2014). Interestingly, the ecosystem approach has already been applied in a mangrove restoration experiment in Sungai Haji Dorani, Malaysia. Hashim et al. (2010) planted mangroves behind a suite of rock armour breakwaters; the outcomes were advantageous ranging from wave energy reduction and beach elevation to favourable sapling survival and erosion mitigation.

In addition to adopting the ecosystem approach to coastal protection, impacts of coastal development on fisheries can also be mitigated through the construction of artificial reefs away from the affected site (Fig. 5). Depending on the fishery that is being threatened, artificial reefs can be designed to attract particular species (Sherman et al., 2002; Hackradt et al., 2011; Noh et al., 2017). Malaysia is the 6th biggest consumer of fish globally (FAOSTAT, 2013) and was one of the first countries in southeast Asia to develop an artificial reef programme as part of the Fifth Malaysia Plan (1986–1990) (Chou, 1997). Reef designs and materials vary considerably with the use of tyres, scrap metal, natural materials and concrete; each with varying degrees of success depending on the environmental situation (Chou, 1997). Interestingly, artificial reefs in Singapore and Brunei Darussalam have reported fish yields higher than those on natural reefs (Chou et al., 1991; Chou, 1994). Artificial reefs not only attract fish but can also provide important habitat for the settlement of benthic invertebrates (Jensen et al., 1994) in addition to important biogenic species such as algae, bivalves and corals (Fariñas-Franco and Roberts, 2014; Cummings et al., 2015) which can enhance the nursery function of artificial reefs (Pastor et al., 2013; Kent et al., 2017). This process can be expedited through direct transplanting of desired species using glues, epoxies or tiles containing fragments or juveniles

(Perkol-Finkel et al., 2012; Young et al., 2012; Ng et al., 2015; Ferrario et al., 2016). In addition to artificial reefs serving the primary function of habitat provision for fish and other benthos, they may also serve the secondary function of protection of the seabed through the prevention of bottom trawling and other damaging activities through the *de facto* marine reserve effect (see Inger et al., 2009; Ashley et al., 2014; Pearce et al., 2014). It must be noted though that like all artificial structures placed in the sea, artificial reefs require risk assessment, planning and long-term management; without which they typically fail and become nothing more than pollutants that contribute to the further degradation of the marine environment (Chou, 1997). For example, Baine (2001) assessed the performance of artificial reefs globally and found that case studies only met their requirements 50% of the time, with the remainder having little or limited success. This highlights the economic and environmental risks associated with artificial reefs.

The practices of eco-engineering of coastal infrastructure and artificial reefs could also be used to promote educational activities (Burcharth et al., 2007; Bulleri and Chapman, 2010). Newly-created habitats on seawalls, jetties and rock revetment or artificial reef exhibits in public areas could play a role as free educational marine resources and provide valuable learning experiences. Rock-pooling activities have been incorporated into educational programs in countries like Australia, Japan, and the United States, with the main objective of creating awareness among users of the marine environment of the importance of protecting the marine environment for future generations. Furthermore, the establishment of ecosystem approaches like building of oyster reefs could result in engagement projects educating the public about the ecological value of preserving ecosystems as a whole. For instance, in the United States, the rehabilitation of oyster reefs have engaged hundreds of thousands of school children in a program called the Billion Oyster Project (www.billionoysterproject.org) that links public school teaching and learning to ecological engineering in New York Harbour (Janis et al., 2016). This project also produces oysters, constructs and monitors reefs, and collects oyster shells, promoting both rehabilitation and public education.

4.4. The importance of sustained observations

One major finding from the present study was that baseline data on land use changes is largely lacking and there is also scarcity of publicly available EIA reports or scoping studies. Without these critical data, not only is it impossible to know what has already been lost, but it undoubtedly impedes management plans for conservation and eco-engineering initiatives (Sievanen et al., 2012; Hawkins et al., 2013). Baseline information is crucial to inform these management, conservation and monitoring programs, increase their chances of success and maximise their benefits. In saying this, monitoring should not just be done for the sake of monitoring and it is advisable that any monitoring programme should be goal-oriented and designed to yield good quality data for formal statistical analyses (Legg and Nagy, 2006).

This study has brought to attention sections of the coast of Penang Island in need of effective monitoring, conservation and management. Parts of the north coast such as Tanjung Tokong and Gurney Drive now have in place depauperate rock revetments instead of sandy and rocky beaches that lined the coast five decades ago. Natural rocky shores around Penang are characterised by complex substrata with a combination of rock pools, crevices, pits and overhangs providing essential refuge from insolation and temperature stress in this challenging environment (Chee, pers. obs.). These habitats support a plethora of invertebrates such as oysters, fishes, shrimps and algae (Loh, pers. comm.). The rock revetments and seawalls that characterise much of the coastline of Penang however, lack this complexity and are depauperate of biota as a result. Eco-engineering such as the creation of surface roughness, pits, crevices and rock pools could create habitat heterogeneity on the rock revetments to encourage biotic colonization. Such techniques have worked well in temperate areas (Chapman and Blockley, 2009; Browne and Chapman, 2011; Martins et al., 2010; Evans et al., 2016; Firth et al., 2016b) but few studies exist from the tropics (but see Loke et al., 2014, 2015). Due to severe temperature stress, it may be expected that the results obtained in tropical areas may be more pronounced than in temperate areas, however this is likely to vary by habitat. For example, environmental conditions in rock pools in Hong Kong can become very stressful for marine organisms (Chan, 2000; Firth and Williams, 2009) and may not represent the kind of refuge habitats that they represent in temperate areas (Chapman and Blockley, 2009; Firth et al., 2013; Evans et al., 2016). In smaller coastal developments, creating habitat complexity by drilling or using concrete may represent cost-effective and flexible techniques.

5. Conclusion

Human uses of marine environments have been known to alter global seascapes and ecosystem functions (Dugan et al., 2011; Dafforn et al., 2015b) and ecological consequences can range from local-scale effects including habitat destruction, loss of associated assemblages, increased water turbidity, water flow alteration and sediment deposition (Dugan et al., 2011; Heery et al., 2017) to regional-scale effects including habitat fragmentation and changes to regional connectivity (Airoldi et al., 2015; Dafforn et al., 2015b; Bishop et al., 2017). Whilst many are not supportive of land reclamation and the construction of artificial islands, others (i.e. the developers, state government and, to a certain extent, members of the public) deem these as “necessary evils” to create space for the rising human population as well as to modernize and develop the island further. With appropriate planning and long-term management (Mayer-Pinto et al., 2017), eco-engineering represents a valuable adaptive management tool to mitigate the impact of harmful coastal development for the island of Penang, and indeed elsewhere.

In this paper Penang Island is used as a case study to highlight the potential environmental impacts of mega urban development that is an existing or future reality for many countries throughout the developing world. If the plans for future land reclamations on Penang Island are fully realized, the further destruction of coastal ecosystems will be inevitable.

Therefore, it is important to look beyond artificial structures as precursors to ecosystem destruction but rather devise adaptive management solutions that create opportunities for marine conservation in locations where inevitable coastal development is taking place (Evans et al., 2017). The wide range of eco-engineering studies that have now been trialled show its flexibility and ways it can be suited to prospective or retrospective development projects (see Firth et al., 2016a), conducted on large- or small-scales, and used to promote educational, amenity or economic activities. With inevitable coastal development taking place globally, opportunities to attempt the delicate balance between development and conservation abound and indeed, should be incorporated into present and subsequent projects to safeguard precious coastal ecosystems for future generations.

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