Ocean & Coastal Management 103 (2015) 78–85

Contents lists available at ScienceDirect

Ocean & Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

The effects of urbanisation on coastal habitats and the potential for ecological engineering: A Singapore case study

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ARTICLE INFO

Article history:
Received 15 May 2014
Accepted 7 November 2014
Available online 22 November 2014

Keywords:
Coastal change
Coastal management
Ecological engineering
Intertidal habitats
Land reclamation
Seawalls
Singapore

ABSTRACT

Habitat loss associated with land reclamation and shoreline development is becoming increasingly prevalent as coastal cities expand. The majority of Singapore's mangrove forests, coral reefs and sand/mudflats disappeared between the 1920s and 1990s. Our study quantifies additional coastal transformations during the subsequent two decades, analyses the potential impact of future development plans, and synthesises the mitigation options available. Comparisons of topographical maps between 1993 and 2011 reveals declines in total cover of intertidal coral reef flats (from 17.0 km^2 to 9.5 km^2) and sand/mudflats has (from 8.0 km^2 to 5.0 km^2), largely because of extensive land reclamation. Conversely, mangrove forests have increased (from 4.8 km^2 to 6.4 km^2) due to restoration efforts and greater regulatory protection. However, 15 and 50-year projections based on Singapore's 2008 Master Plan and 2011 Concept Plan show that all habitats are predicted to shrink further as new reclamations are completed. Such decline may be counteracted, at least in part, if ecological engineering is used to help conserve biodiversity. The problems exemplified by Singapore, and the potential future solutions discussed in our paper, provide guidance for urban marine conservation in coastal cities that are experiencing rapid development and land use change.

1. Introduction

In 2003, approximately 3 billion people lived within 200 km of the sea—a number that is predicted to double by 2025 (Creel, 2003). As coastal cities expand, land reclamation is one of the few options available to provide space and counteract erosion (Small and Nicholls, 2003; Charlier et al., 2005), as evidenced by huge projects in the Netherlands, Tokyo, Taipei, Mumbai, Bahrain, New Orleans, Macau and Hong Kong (Craig et al., 1979; Al-Madany, 1991; Glaser et al., 1991; Luo, 1997; Yokohari et al., 2000; Murthy et al., 2001; Charlier et al., 2005; Hoeksema, 2007). Coastal armouring to protect newly-created shorelines is also increasing, with addition impetus provided by the threat of sea level rise and more frequent storms as a consequence of global climate change (Moschella et al., 2005). The resulting loss of natural shores—and gain in artificial ones—has profound implications for the conservation of marine ecosystems and species in urban settings. The highly urban environment represented by Singapore serves as an illustrative case study of the ecological future that many coastal cities, especially those in rapidly developing countries, may eventually face.

Singapore's coastal landscape has been altered extensively, starting with British colonial establishment in 1819. In parallel with its rapid development, its shoreline has been shifting seawards via land reclamation to accommodate ports, industries, infrastructure, parks, and homes. Hilton and Manning (1995) documented historical shoreline changes in Singapore up to 1993. From 1922 to 1993, areas of mangroves (75 km^2 reduced to 5 km^2), coral reefs (32 km^2 reduced to 17 km^2) and intertidal sand/mudflats (33 km^2 reduced to 8 km^2) shrunk dramatically. During this time, the percentage of natural coastline dropped from 96% to 40%. Hilton and Manning (1995) projected that by 2030 land reclamation would eventually increase the coastline to 532 km. They concluded that local resources could be better managed to protect biodiversity and achieve sustainable development.

As coastlines continue to be altered, both in Singapore and around the world, there is a need for paradigm shift in the way artificial habitats are perceived and designed. Internationally,

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http://dx.doi.org/10.1016/j.ocecoaman.2014.11.006
0964-5691/

there is growing interest in the potential to engineer these structures to improve their capacity to support more bio-diverse communities while still retaining their engineering function (Mitsch and Jørgensen, 2003; Köhler, 2008; Chapman and Underwood, 2011; Francis and Lorimer, 2011). This process of combining engineering and ecological principles to reduce the negative effects of artificial structures is an established form of ecological engineering (Bergen et al., 2001; Borsje et al., 2011) and has been applied to seawalls and other coastal infrastructure to mitigate their ecological impacts (Chapman and Blockley, 2009; Browne and Chapman, 2011). Ecological engineering of shorelines can broadly be categorised into "soft" and "hard" approaches (Charlier et al., 2005; Chapman and Underwood, 2011). Soft engineering employs the inclusion of natural elements such as marshes, mangroves, and sand dunes for coastal defence (Morris, 2007; Bouma et al., 2009). For instance, removing or re-arranging sections of seawalls while adding natural vegetation (Chapman and Underwood, 2011). Soft engineering approaches often result in the presence of both hard armament and natural habitats—sometimes called the "hybrid approach"—reflecting a gradient in the amount of natural habitat added (where the extreme end point would be complete restoration of the natural shore). The hard approach, on the other hand, involves the physical manipulation of artificial structures such as seawalls, usually by changing their slope angle or altering their topographic complexity (e.g. Martins et al., 2010; Loke et al., 2014). Even though both soft and hard ecological engineering have the same practical goals, they are not universal solutions that will work equally well in all situations. Soft and hard ecological engineering strategies are therefore context-dependent and lead to alternate outcomes as the resulting habitats usually support different assemblages of species. Creating a hybrid environment, e.g. combining natural vegetation with seawalls, might be feasible in certain cases (Chapman and Underwood, 2011) but not in others, for instance, in highly exposed shores.

It has been almost two decades since Hilton and Manning's (1995) paper was published, during which time Singapore's physical as well as social landscape has changed significantly. The resident population has swelled by over 40% to 3.8 million and the land area has increased by 14% to 714 km^2 (Singapore Department of Statistics, 2013). The length of Singapore's artificial coastlines has concomitantly increased, while natural shoreline has further decreased. Reclamation is so extensive along the southern coast of Singapore that the only remaining natural stretch is a 300 m long rocky shore (Todd and Chou, 2005), yet little research has been conducted to quantify these changes and their impacts. By designing future seawalls or modifying existing ones according to ecological principles, these structures may eventually host a greater diversity of native coastal species and hence contribute to the conservation management plans of this tropical city-state. The present paper aims to quantify the transformations of Singapore's coastline since 1993, as well as predict future changes based on the Singapore Government's 2008 Master Plan and 2011 Concept Plan (URA, 2008). We also evaluate the environmental problems arising from shoreline development, and highlight the potential to incorporate ecological engineering in the design of seawalls.

2. Materials and methods

Estimates of mangrove, coral reef and intertidal sand/mudflats were obtained from the 2002 and 2011 1:50,000 topographic maps published by the Singapore Armed Forces Mapping Unit. The boundaries of each fragment of habitat were traced in ArcGis 10.0 (ESRI®, 2012) which was also used to calculate planar areas. The original 1993 estimates by Hilton and Manning (1995) were made using the squares method, but differences between the two techniques are likely to be minor. Areas of remaining mangroves marked on the topographic maps include remnant patches that once lined two estuaries along the northern coastline, both of which have now been converted into freshwater reservoirs. These remnants are no longer connected to the marine environment, and were therefore not calculated within the total area of mangroves. On the other hand, some fragments not recorded in the topographic maps were included based on a contemporary publication by Yee et al. (2010) which documented the extent of mangroves in 2010. Accessible areas were ground-truthed by the first author to confirm their presence in 2013. Our estimates of the intertidal coral reef and sand/mudflat areas were based solely on the topographic maps. The coral reef areas marked out on the topographic maps used here represented intertidal reef flats only. The sub-tidal reef slopes were excluded, as they were in Hilton and Manning (1995).

The present (i.e. 2012) length of seawalls was determined based on satellite images from Google Earth (Google, 2009), data collected from ground-truthing, and observations from various researchers who have conducted studies around Singapore's coasts. Seawalls were traced onto the 2011 topographic map using ArcGis 10.0 (ESRI®, 2012) and grouped into three categories: sloping and un-grouted, sloping and grouted, and vertical. Sloping walls generally have a slope between 14 and 35° (Lee and Tan, 2009) and consist of granite rip rap that is often grouted with mortar to fill in the crevices between rocks. Vertical walls are typically made of concrete and are usually found in port areas. Categorisation was based on the satellite images (the resolution was high enough to discern between sloping and vertical walls), personal observations, or inferred from the use of the area (e.g. walls in docks were assumed to be vertical). The total area covered by sloping seawalls was obtained by multiplying the total length by 10.54 m, i.e. the average width of seawalls calculated from seawall measurements derived from Lee and Tan (2009). It was not possible to calculate the average width of vertical seawalls as these data are not published and the ports and docks where they are found have restricted access. The total length of the coastline around Singapore (combining both mainland and offshore islands) was obtained by adding the non-armoured and natural lengths of the coastline (the latter was also digitised using ArcGis 10.0, ESRI®, 2012).

The predicted conversion of coastal habitats over the next decade, including changes in mangrove, coral reef and sand/mudflat areas, as well as seawall length, were determined using the 2008 Singapore Urban Redevelopment Authority's (URA) Master Plan and 2011 Concept Plan. The Master Plan is a statutory land use plan that directs development over the subsequent 10–15 years while the longer-termed Concept Plan guides development over the subsequent 40–50 years (URA, 2008). Natural habitats in areas that are marked for development were considered to be built over, and the new resultant coastlines were assumed to be protected with seawalls. Habitats not directly affected by the developments were presumed not to have increased or decreased in area.

3. Results

3.1. Mangrove forests

Our estimates from the 2002 topographical map showed that total mangrove area in Singapore increased to 6.26 km^2 relative to the 4.87 km^2 recorded in 1993 (Hilton and Manning, 1995). Comparing the distributions of mangroves in Hilton and Manning's (1995) 1993 map (Fig. 1), it is clear that the bulk of the increase has occurred at S. Buloh and P. Ubin. Mangroves in areas that remained undisturbed also expanded, such as on the military training islands of P. Pawai (0.26 km^2 in 1993 to 0.48 km^2 in 2002), P. Tekong