Applied Geography 90 (2018) 229–238

Contents lists available at ScienceDirect

Applied Geography

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

Building beyond land: An overview of coastal land reclamation in 16 global megacities

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ARTICLE INFO

Keywords:
Coastal megacities
Land reclamation
Artificial land
Geo-engineering coastlines

ABSTRACT

The increase in global population has been accompanied by rising consumption of natural resources such as clean air, water and land. Demand for land has increased significantly over the past 30 years or so, both inland and at the coast. In coastal regions, reclaiming land from the sea has often been the preferred solution towards meeting the need for more land for urban development. Seaward land reclamation entails the formation of artificial land surfaces which are constructed in such a way as to extend outwards over the sea using advanced geo-engineering techniques. The process is driven by numerous underlying factors and has manifold impacts. Although this pattern of urban development is not new, the nature, scale and magnitude of land extension has changed dramatically for a range of underlying reasons involving both 'natural' geophysical, and anthropogenic factors. The overall aim of this paper is to evaluate the changing spatial extent of seaward land expansion in 16 selected coastal megacities. Remote sensing data, spanning the time period mid-1980's to present, were obtained and used to determine the extent of spatial change due to new land construction in each of the cities. Landsat TM satellite imagery was used to calculate the percentage increase and area reclaimed since the mid-1980s. In addition, a systematic classification is proposed, based on the different geomorphic patterns that have been observed to characterize the process. Among 16 cities analyzed in this study, major land reclamation projects have been especially marked in China, most prominently in Shanghai, which has expanded its coastal area by more than 580 km^2 in the recent past.

1. Introduction

Widespread, rapid urbanization is arguably the most significant geographical manifestation of global population growth, as reflected in the rising number of megacities. Mounting population numbers and increasing levels of associated urban expansion, especially in coastal cities, have placed extreme pressure on land through construction and development (Li et al., 2016; Tan, Li, Xie, & Lu, 2005). This has resulted in major geo-engineering projects that have reclaimed or extended land by altering the surface morphology in many cities, in particular along and beyond the coastline. Key examples include the edifice of the Palm resorts of Dubai, construction of the new Hong Kong airport, artificial islands in the South China Sea and the development of "Baia de Luanda" in the capital city of Angola. Other examples include Flevoland, a province in the center of the Netherlands, home to 400,000 inhabitants, which was created by draining lakes, and the construction of a contiguous Mumbai from a group of seven islands which has evolved into the second most populous coastal megacity in the world more than 21 million inhabitants (UN, 2014). There are diverse geospatial consequences of such development that demand our attention.

Artificial structures may significantly alter the earth's surface, thereby strongly affecting geomorphic processes such as soil erosion, land subsidence, hydrology and sediment dynamics (Xue Hong et al., 2016). The Land Cover Classification System (LCCS) developed by the Food and Agriculture Organization (Di Gregorio, 2000) classifies and describes "artificial surface and associated areas" under "urban type" as non-vegetated dominated areas that have an artificial surface as a result of human activities such as construction (cities, towns, transportation, etc.), extraction (open mines and quarries) or waste disposal. (2.3.4.1 LCCS User Manual, FAO 2000). However, building infrastructure on existing natural surfaces is very different to constructing entirely new land in the sea, as this may require application of advanced geo-engineering technologies facilitating a completely artificial mode of sediment transport. This is the concept of 'artificial land' used in this study.

Construction of such artificial land is driven fundamentally by anthropogenic processes operating at several levels. At the global level

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https://doi.org/10.1016/j.apgeog.2017.12.015
Received 26 May 2017; Received in revised form 15 December 2017; Accepted 15 December 2017
Available online 22 December 2017

international geo-politics and economic interconnectedness drives many processes. Regionally, rapid economic development, and resultant urbanization have initiated land reclamation projects (Tian, Wu, Yang, & Zhou, 2016), whereas improvement in transport infrastructure for airports and harbours has contributed the same at a local level. Increased population and associated urbanization therefore are important factors in global environmental processes at all three spatial scales (Findlay & Hoy, 2000). Extending land along and beyond the shorelines of - for example Dubai (Bagaeen, 2007), Bahrain (Burt, Al-Khalifa, Khalaf, AlShuwaikh, & Abdulwahab, 2013), Hong Kong (Shen, Hao, Tam, & Yao, 2007) - has, on one hand, boosted the real estate industry, while on the other raised several questions regarding its environmental impact and sustainability(Grydehøj, 2015).

The dynamics and interconnected nature of coastal geomorphology, with both natural and anthropogenic elements means that the coast is highly susceptible to external disturbance. The coastal zone, covering ten percent of the earth's land surface, is estimated to contain over half of the world's population (Seto, Fragkias, Güneralp, Reilly, & Pidgeon, 2011) and, indeed, most global megacities are coastally located and vulnerable to change. In the lowest lying situations, sea level rise (Brown et al., 2013) and the resultant coastal inundation is widely reported potential hazard for coastal communities (Balica, Wright, & van der Meulen, 2012; Nicholls, Wong, Burkett, Woodroffe, & Hay, 2008). There has been rather less research, however, on the increasingly common pattern of building beyond the land as a feature of urban development in coastal cities.

1.1. Urban expansion at the coast

Rapid and sustained urbanization globally has resulted in both vertical and horizontal expansion of cities and exerted considerable pressure on environmental and socio-economic systems (Shukla &Panikh 1992). The global urban footprint has ballooned to accommodate the burgeoning population and its demands. This is particularly prevalent in Asian cities, including Shanghai (Zhang, Ban, Liu, & Hu, 2011), Hong Kong (Loo & Chow, 2008), Manila (Murakami, Medrial Zain, Takeuchi, Tsunekawa, & Yokota, 2005), Jakarta (Jones, 2002) and Mumbai (Moghadam & Helbich, 2015), where expansion has taken place at an unprecedented pace. In the present day, approximately three billion people now reside in urban areas within 200 km of the coastline and, by 2025, this figure is likely to double (Creel, 2003; UNEP, 2014) This pattern of urban settlement has led to economic benefits in coastal regions which include upgraded transportation links, economic returns from tourism development, and enhanced industry and trade, while at the same time it has also had negative consequences.

The effects of population pressure and improved technological ability to harness natural resources have combined to trigger significant environmental imbalance. Given the challenge of maintaining equilibrium between current economic (and social) development, and environmental sustainability, analyzing the future demand for urban land in terms of actual physical space becomes highly significant. In China for instance, the government has responded to urban population increase by turning to seaward - as opposed to landward - expansion as the major solution to the problem of growing demand for land (Yue, Zhao, Yu, Xu, & Ou, 2016). As megacities continue to emerge along the coastline, it becomes more and more important to compare landward and seaward expansion patterns. Coastal megacities are emerging as dominant drivers of environmental change due to their sensitive location and the magnitude of their influence on terrestrial, coastal and marine environments. (Glasow et al., 2013).

The present paper articulates the widespread nature of seaward land extension from the coast. Although coastal land reclamation has previously been studied (de Mulder et al., 1994; Riding, 2017), the scale and pace of construction have intensified for particular regions (Tian et al., 2016; Chee et al., 1994). While such regional perspectives are important, it is imperative to assess the globally widespread nature of land reclamation. Such an assessment may ultimately provide a platform for a systematic coastal land reclamation monitoring system which can track such coastal constructions. Moreover, the geomorphological classification of land extension pattern is only possible through a global assessment. Further to this, understanding (at a global level) how anthropogenic activities, especially land reclamation, alter coastal geomorphology may provide a perspective on the degree to which humans have influenced ocean-human-land interactions in general.

2. Aim and objectives

The aim of this study is to assess the extent of anthropogenic seaward coastal land expansion globally, using examples from 16 coastal megacities over the period from approximately 1985 to 2017 and, in so doing, highlight the widespread nature of this phenomenon and its potential environmental impact. The objectives of this paper are as follows:-

- To produce 30m resolution maps of the coastline of 16 of the world's largest megacities from the mid-1980s and compare these to the situation in 2017
- To calculate the absolute and percentage area extended in each of the selected coastal megacities over the period under consideration.
- To develop a classification of the types of geomorphic patterns produced by geo-engineering of the additional coastal land.
- To briefly consider the possible driving forces and environmental impacts of land extension

3. Study areas, data and method

In order to asses coastal land reclamation, population figures were taken as the primary element to select cities for this study. Megacities, i.e. those with population greater than 10 million were selected, as per The World's Cities in 2016" (UN 2014). According to this report, there are 31 megacities globally, of which 16 are situated at the coast (Small and Nicholls, 2003); ten of these are located in Asia, of which three are in China and two each in Japan and India, see Table 1 & Fig. 1. Remotely sensed satellite imagery of the earth's surface is widely used in geospatial research due to its coverage, quality and accessibility. For this study, satellite data from the Earth Resource Observation System, in particular from Landsat were employed. Images from two time periods were obtained and analyzed to illustrate coastal seaward construction. Landsat Thematic Mapper 5 has a database from 1984 onwards, depending on the city in question, while Landsat 8 covers the most recent period (January 2017). For each of the selected cities, the absolute and percentage area increases were calculated, firstly, by delimiting the administrative boundary according to a range of different sources (Table 1) and overlaying the polygon indicating the current boundary on Landsat TM 5 imagery. Secondly, Band 4 (Landsat TM 5) and band 6 (Landsat 8) were utilized for digitization of the coastline due to its capability on distinguishing between built-up land and water. The difference in the area between the two images was then calculated both in terms of area and percentage values. The satellite imagery was then examined to develop a classification of types of spatial pattern created as a result of the seaward land extension.

4. Results[1]

4.1. Mapping “building beyond land”

Analysis of the satellite imagery facilitated visualization and calculation of the spatial distribution of new land constructed in each of the cities (Fig. 2a to 2p).

[1] New York City is not included due to errors in calculating appropriate coastal area because of changes in the city's administrative boundaries.

Table 1
Coastal megacities analyzed in the study, including source of administrative boundary and the most recent population estimates (UN, 2014)}.

Coastal megacity	Landsat TM 5Month/Year	Population in 2016 (thousand)	(Source) Administrative Boundary
Tokyo, Japan	May 1987	38 140	OSM
Shanghai, China	May 1987	24 484	Google Earth
Mumbai, India	October 1988	21 357	Diva GIS
Osaka, Japan	May 1989	20 337	OSM
Karachi, Pakistan	October 1989	17 121	OSM
Buenos Aires, Argentina	March 1986	15 334	Google Earth
Istanbul, Turkey	June 1884	14 365	Diva GIS
Lagos, Nigeria	December 1984	13 661	OSM
Manila, Philippines	April 1993	13 131	OSM
Rio de Janeiro, Brazil	August 1985	12 981	OSM
Los Angeles-Long Beach-Santa Ana, USA	April 1987	12 317	OSM
Tianjin, China	September 1986	11 558	Google Earth
Shenzhen, China	October 1988	10 828	OSM
Jakarta, Indonesia	May 1989	10 484	Google Earth
Chennai, India	August 1991	10 163	OSM
Lima, Peru	May 1989	10 072	OSM

4.2. Area reclaimed

According to the data (Table 2), between the mid-1980s and 2017, there was a total addition of 1249.78 km^2 of land reclaimed in the 16 megacities under scrutiny (see Table 3). Shanghai (Fig. 2a) has expanded by adding 587 km^2 of land to its coastline since 1987, representing a reclaimed land percentage increase of 6.46 percent over the mid-1980s land area. Shanghai is followed by the other two coastal megacities in China i.e. Tianjin (Fig. 2b) and Shenzhen (Fig. 2c), which have reclaimed 86.38 km^2 and 488.9 km^2 respectively. Coastal land extension employing geo-engineering projects appear to be especially prominent in East Asian cities (Shanghai, Tianjin, Shenzhen, Tokyo and Osaka). More than one million km^2 of artificial lands have been created in the region since the mid-1980s.

Artificial shoreline construction has been very rapid in coastal cities in developing nations; examples include Istanbul, Turkey (Fig. 2(p)), Jakarta, Indonesia (Fig. 2d), Karachi, Pakistan (Fig. 2i), Manila, Philippines (Fig. 2g), Chennai, India (Fig. 2f) and Mumbai, India (Fig. 2m). The ongoing land development project at Jakarta has already reclaimed 18.93 km^2 of land out of planned total 50.87 km^2 (Jeffreys & Kuncinas, 2014). The ports of Karachi, Istanbul and Chennai have expanded seaward mainly through the creation of artificial land (Fig. 2i, p, and 2f). As a result, 8.76 km^2, 9.23 km^2 and 6.59 km^2 respectively, have been reclaimed through to March 2017 (Table 2). Manila, which has already increased its land area by 4.66 km^2, plans to add a further 4.27 km^2 of land for the central part of Manila Bay (news.mb.com.ph/2017/02/07/erap-approves-manila-bay-reclamation-project/). There are notable differences in reclamation rates between cities. For instance, Shanghai (China), with a population now exceeding 24 million has added 587 $km^2$of land since 1987, whereas Mumbai (India) has reclaimed less than 1 km^2 over the same period, despite increasing its population by more than 3 million during that time.

More than 16 km^2 have been reclaimed in the remaining five coastal megacities, *viz.* Lagos, Nigeria (Fig. 2l), Los Angeles-Long Beach-Santa Ana, USA (Fig. 2.n), Rio de Janeiro, Brazil (Fig. 2k), Lima, Peru (Fig. 2) and Buenos Aires, Argentina (Fig. 2j). Lagos, with its highly ambitious project to accommodate the headquarters of the region's major financial institutions {www.ekoatlantic.com/} had reclaimed 6.66 km^2 as of January 2017 (Table 2). Buenos Aires has reclaimed 1.33 km^2 of land along its shoreline, including the international airport runway extension. Los Angeles-Long Beach-Santa Ana and Rio de Janeiro have expanded in order to enhance their port capacity by reclaiming 4.12 km^2 (since 1987) and 2.6 km^2 (since 1985)respectively.

4.3. Spatial classification of geo-engineered artificial land

Interactions between the various natural and anthropogenic drivers at different levels ultimately lead to alteration on the earth's surface. The relationship between waves, currents, storms, changing sea levels

Fig. 1. Map of coastal megacities analyzed in this study.

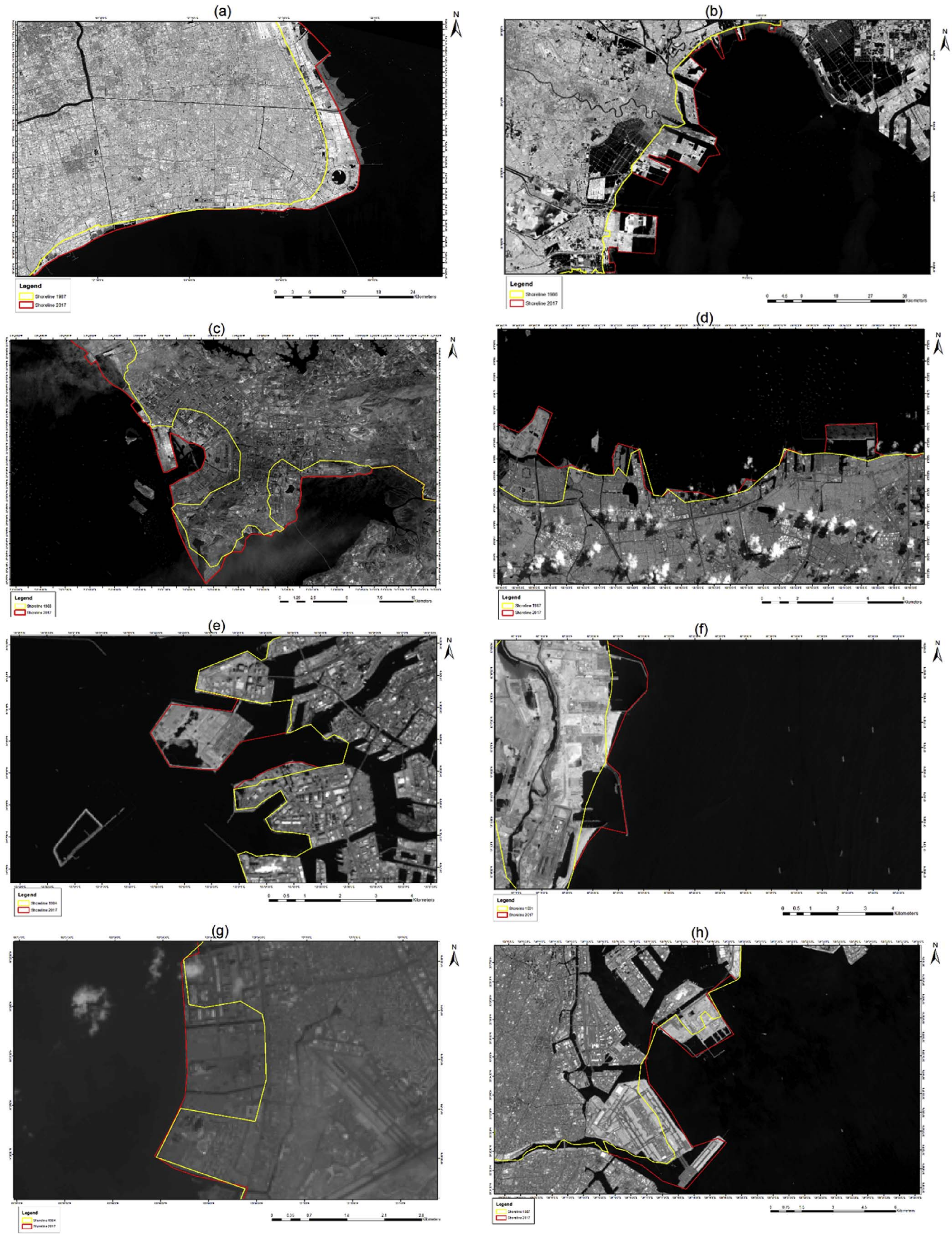

Fig. 2. (a) Shanghai; (b) Tianjin; (c) Shenzhen; (d) Jakarta.(e) Osaka; (f) Chennai; (g) Manila; (h) Tokyo. (i) Karachi; (j) Buenos Aires; (k) Rio de Janeiro; (l) Lagos.(m) Mumbai; (n) Los Angeles-Long Beach-Santa Ana; (o) Lima; (p) Istanbul.

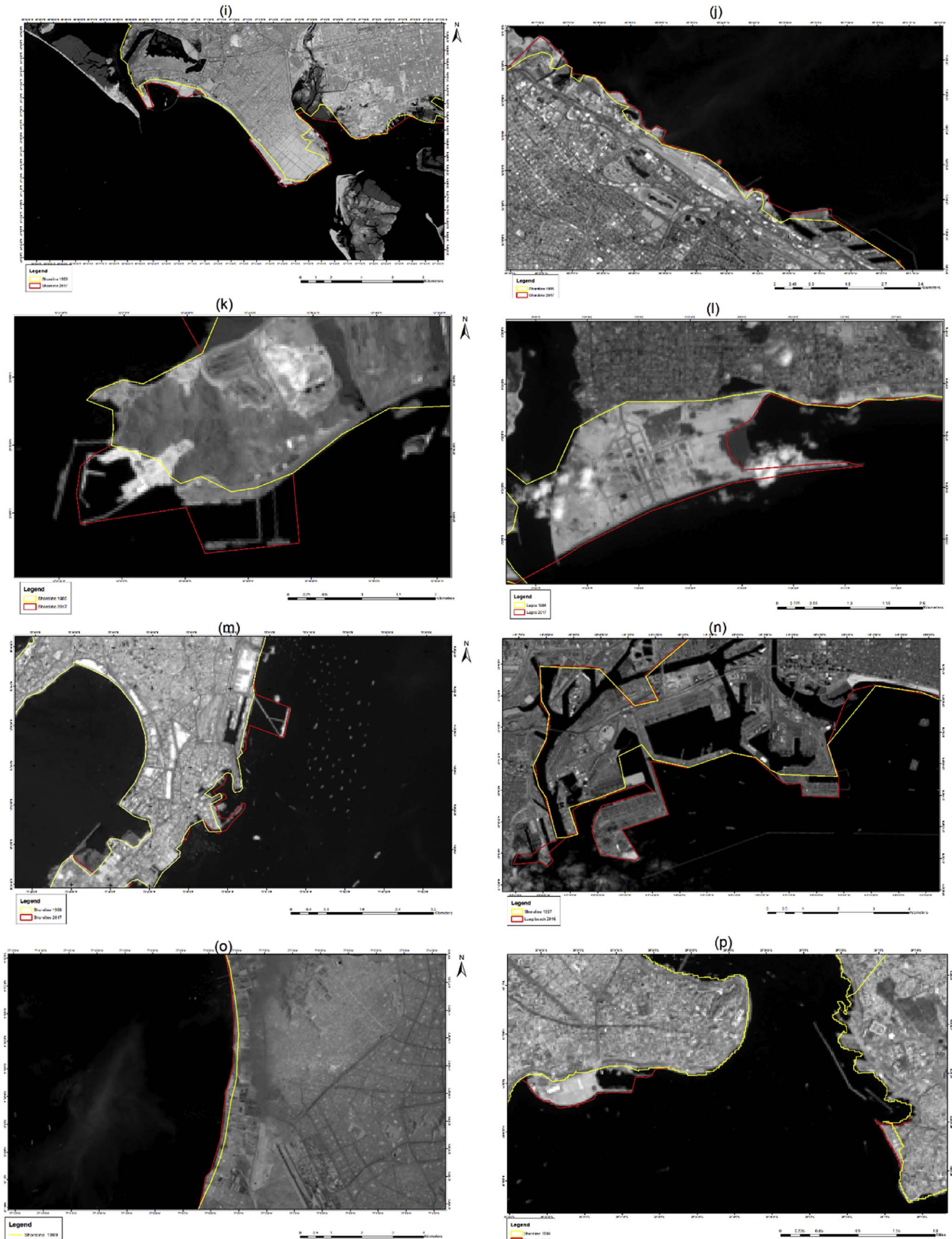

Fig. 2. (*continued*)

Table 2
Area reclaimed by 16 megacities (Area in square kilometers; Increase in percent).

Coastal megacity	Area in Mid 1980s	Area in 2017	Increase in Area	Area Reclaimed
Shanghai	6432	6876	6.46	587
Shenzhen	1880	1962	4.18	86.38
Tianjin	11553	12026	3.93	488.91
Jakarta	627	641	2.18	18.23
Osaka	227	232	2.16	7.12
Chennai	482	489	1.43	6.59
Manila	562	569	1.23	4.66
Tokyo	1522	1538	1.04	15.17
Karachi	3824	3851	0.70	8.76
Buenos Aires	206	207	0.48	1.33
Rio de Janeiro	1205	1209	0.33	2.66
Istanbul	5351	5360	0.16	9.22
Lagos	3925	3938	0.33	6.66
Mumbai	703	704	0.14	0.68
Los Angeles-Long Beach-Santa Ana, USA	2233	2236	0.13	4.12
Lima	2854	2856	0.07	1.68
Total	**43,586**	**44,694**	**24.96**	**1249.78**

Table 3
Classification of 16 megacities based on geo-engineering construction pattern.

Types of Model	Coastal megacities
Expanded Land Construction	a) Shanghai, China b) Tianjin, China c) Shenzhen, China d) Chennai, India e) Mumbai, India f) Buenos Aires, Argentina g) Lima, Peru h) Karachi, Pakistan i) Rio de Jeniero, Brazil j) Long Beach-Santa Ana, USA k) Lagos, Nigeria l) Istanbul, Turkey
Off-shore construction	a) Jakarta, Indonesia b) Osaka, Japan c) Tokyo, Japan
Merged construction	a) Manila, Philippines b) Mumbai, India*

and barrier island response is complex and rendered more so when people manipulate coastal processes (Smith et al., 2015). The physical environment therefore influences the precise spatial pattern of artificial land construction, suggesting that the development of a typology could prove to be a useful means of understanding the process. Remote sensing satellite images enable detection and monitoring of this manipulation and provide a platform to observe and classify particular patterns of construction. The types of construction along the coastline of the 16 selected megacities are arranged into three distinctive geomorphic models on the basis of their physical appearance. The categories are identified as follows: (1) expanded land construction, which involves extension of artificial land from the existing land surface; (2) offshore construction whereby new land is created leaving open water between the coastline and the artificial land; (3) merged construction, in which individual separated landmasses are fused together by landfill (see Fig. 3). The selected coastal megacities can be classified on the basis of these three distinctive types of construction. Mumbai can also be classified under merged construction because of its history of land reclamation whereby colonial authorities merged seven island to build today's Bombay (Mumbai) (Pacione, 2006), although this was of course not a recent development by comparison with most of the other coastal megacities.

5. Discussion

5.1. Understanding driving forces

It is pertinent to consider why this form of urban development at the coast has been so widespread and so rapid. Cities act as a catalyst for rapid socio-economic development. In this context, coastal cities have experienced accelerated spatial and economic growth due to several factors. Topographically, coastal regions usually provide abundant flat surfaces which offer ease of accessibility compared to more hilly or mountainous terrain.

The coast lies at the land-sea intersection and acts as a crucial resource base supporting various development activities. Due to the availability of appropriate technological interventions, human interaction at the coast has therefore intensified in the form of building harbors, airports and real estate development. This has led coastal megacities to emerge as prominent examples of how a particular combination of physical environmental attributes facilitates economic growth. In addition, there are several factors, such as population growth, economic development, institutional action and cultural intervention which should be considered as potential drivers of seaward land reclamation.

Population growth drives alterations in land-use and land-cover patterns (Lambin et al., 2001). This poses serious challenges to the management and planning of urban zones, especially in the face of global environmental change (Lambin, Geist, & Rindfuss, 2006). In 1990, 43 per cent (2.3 billion) of the world's population resided in urban areas; by 2015 this proportion had risen to 54 per cent (4 billion) (UN, 2014). These statistics suggest that the global urban population increased by almost 80 million people annually from 2010 to 2015 (UN, 2014) and is projected to continue to rise in the future. As a result, the proportion of people living in cities globally is set to reach 66 per cent by 2050 (UN, 2014; UN-Habitat, 2016). A substantial proportion of this growth has been (and will continue to be) in the low-elevation coastal zone (LECZ), commonly defined as “the contiguous and hydrologically connected zone of land along the coast and below 10 m of elevation” (Mcgranahan, Balk, & Anderson, 2007) which is home to a total population of 734 million comprising 243 cities (UN, 2014).

Globally, the urbanized coast is a focus of economic and real estate development coupled with population growth (Small and Nicholls, 2003). In this context, artificial land expansion is increasingly a feature of urbanization at the coast and therefore its underlying forces need to be considered (Fig. 4). Anthropogenic drivers are dominant, but are also affected by natural processes such as soil-sediment dynamics and sea level rise that can influence the urban planning process. For example, *Eko Atlantic*, a massive land reclamation project in Lagos, Nigeria, was initiated in response to the need to establish additional land due to coastal retreat {http://www.ekoatlantic.com/about-us}. In Jakarta, the anticipation of sea level rise and the consequent threat of coastal flooding led the authorities to develop a plan to build 17 artificialislands{http://www.indonesiainvestments.com/news/newscolumns/construction-of-jakarta–island-reclamation-project-can-resume/item7180}.

Economic drivers play a significant role in initiating seaward urban expansion due to construction of artificial coastal land. For example, Tian et al. (2016) show that GDP per capita in China is positively correlated with coastal land reclamation; between 1985 and 2010, 754,697 ha.of land was reclaimed nationally and that there was a six-fold increase in GDP over the period. In addition, Zhou, Hubacek, and Roberts (2015) identify strong correlations between economic growth and urban expansion in South Asian megacities. The expansion of Mumbai for example, is directly related to its economic growth (Shafizadeh-Moghadam & Helbich, 2015), although in this case colonial policies were initially responsible for fashioning the land reclamation project that ultimately created a megacity (Pacione, 2006).

In a globalized world, trade and commerce play dominant roles in

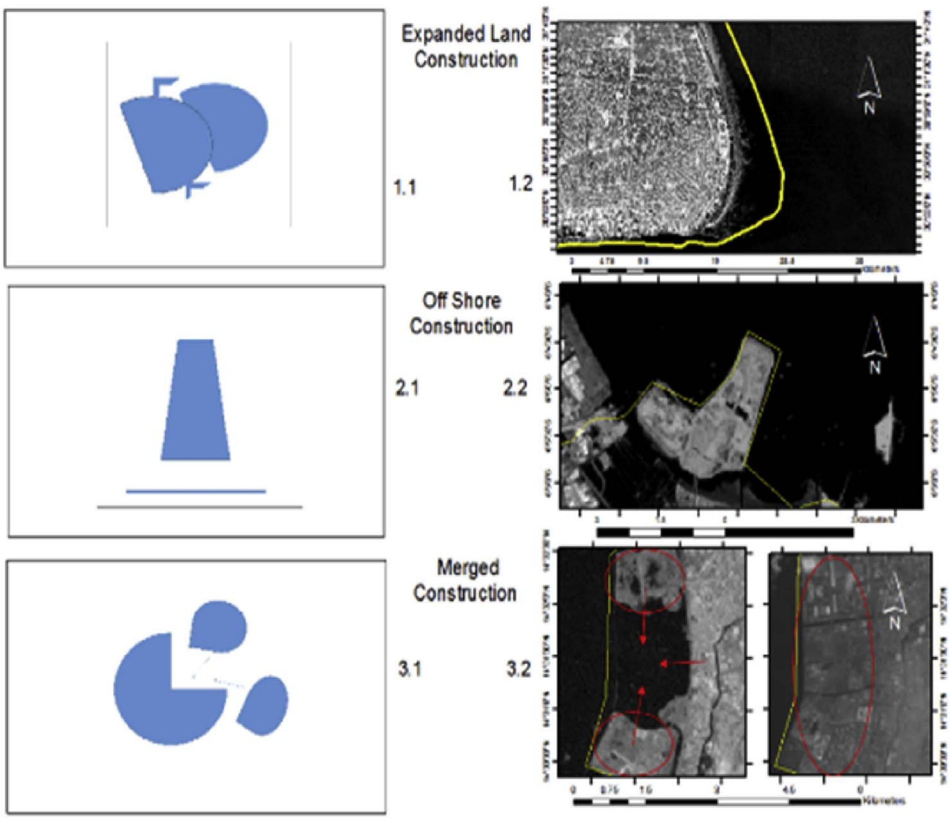

Fig. 3. Classification of the types of geomorphic pattern produced by geo-engineering of the additional coastal land. 1. Expanded land construction, 2. Offshore construction, 3. Merged construction.

keeping cities connected. In doing so, implementation of suitable technology is central to the development of the associated infrastructure. This requires an investment in transportation and, in coastal cities, shoreline infrastructure to facilitate the movement of goods and services. Megacities, such as Tianjin (China), Shenzhen (China), Osaka, (Japan) Tokyo (Japan) – all major port cities - have initiated substantial seaward land extension (Fig. 2(b), (c), 2(e) 2(h)) to support growing local, regional and global demand. Examples from the Middle East demonstrate how economic policies coupled with technological advancement drive coastal land alteration and the construction of artificial land. Advanced coastal dredging machines used to construct the Palm resorts in Dubai (Moussavi and Aghaei, 2013) and Amwaj Island in Bahrain (Fowler, Stephens, Santiago, & De Bruin, 2002) are two prominent examples. Overall, this rapid process of coastal land reclamation has been facilitated by technological revolution which has precipitated massive geo-engineering of the coastline (Smith et al., 2015).

Increasing harbor and airport capacity appears to be a common motivation for seaward land expansion. This is, in turn, economically driven, since as the consumption of goods and services increases, the physical capacity of these transport terminals needs to be expanded. As is apparent in the satellite images (Fig. 2h, m,f,k and j), Tokyo,

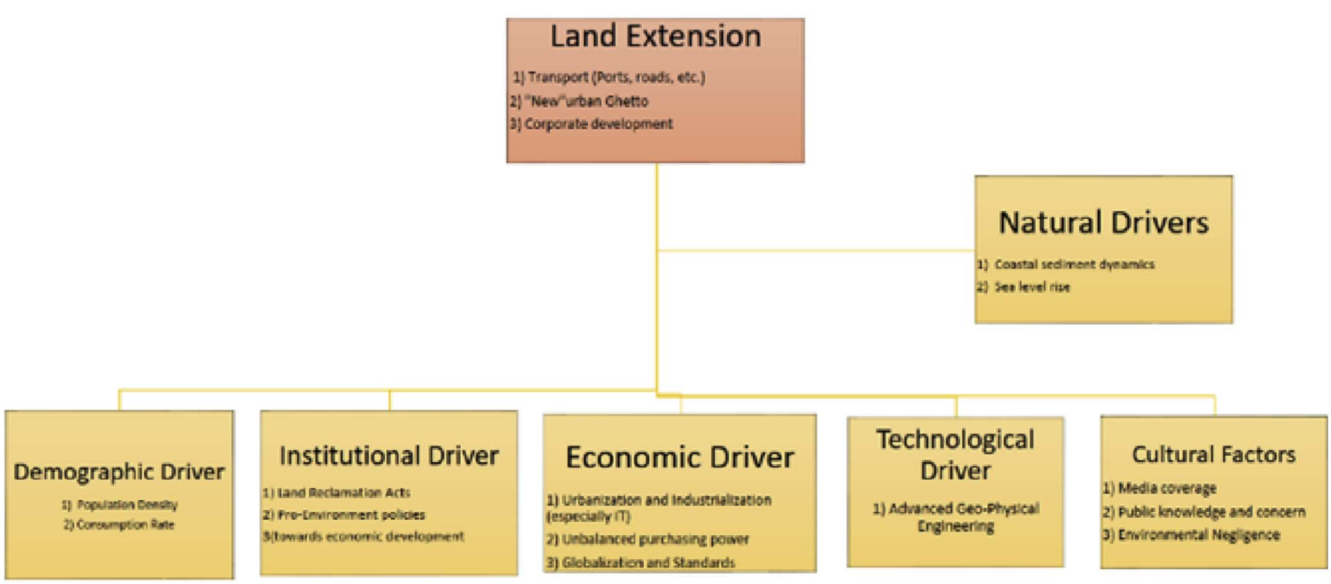

Fig. 4. Flow chart showing possible driving forces.

Mumbai, Chennai, Rio de Janerio and Buenos Aries have all undertaken substantial land alteration and construction to accommodate transport infrastructure in order to maintain their ongoing growth. Bearing in mind that the creation of new land represents an enormous financial challenge, sometimes the newly emerged residential spaces are targeted preferentially towards the economically elite who have the financial capacity to afford the plots. This can be observed in cities such as Shanghai, Jakarta, Lagos and Dubai, where huge investment has been made with a view to reaping the economic benefits in due course. The growing demand for additional urban land for various purposes such as transport, agriculture and settlement has prompted the implementation of appropriate urban planning policies and legislation (Kourtit, Nijkamp, & Reid, 2014). For instance, the increasing number of private and commercial vehicles has forced the authorities to develop the transport infrastructure by constructing more roads and associated bridges and flyovers (Wu, Li, Ding, Li, & Sun, 2016). In most cases, seaward urban expansion is a clear reflection of population and economic growth, whereby the development of artificial land is considered as a form of investment to support and enhance economic growth (Liu, Wu, Cao, & Wu, 2017). However, in some cases, especially in China, government planned to build on lands which are now "ghost cities" (Sorace & Hurst, 2016; Yu, 2014) wherein huge multi-storied buildings await occupation both by residential and commercial clients (Moreno & González Blanco, 2014).

Lai et al., (2014) applied price theory to understanding the role of governance in coastal land extension and show how local governments pursue ways to create land through reclamation in order to achieve their planning goals. In China, the land use classification system adopted by the Ministry of Land and Resources (MLR, 2007) focuses on the production function of land. Government policy is aimed at managing increased demand for resources, especially in cities which fall under higher administrative ranks, and acts as the prevailing driver of urban expansion (Li, Wei, Liao, & Huang, 2015). In addition, public awareness and behavior may be an agency in relation to coastal land reclamation. For example, in a recent study on public awareness about the U.K. coastal environment in the UK, it was noted that citizens are generally aware of the threats, but ominously less informed about governmental management policies (Easman et al., 2017). In this sense, institutional and cultural elements play joint roles as drivers of seaward land expansion.

5.2. Potential impacts and risks

It is broadly accepted that construction related to coastal land reclamation has various environmental consequences (Gagain, 2012; Ghaffari, Habibzadeh, Mortaza, & Mousazadeh, 2017; Riley, 1976). These consequences are not always accounted for and sometimes such developments are highly controversial. The construction of the island chain in the South China Sea, where dredging of the ocean floor is severely damaging coral reefs and other components of the local marine ecosystem is a case in point (Hutchings & Wu, 1987). Loss of biodiversity in the Chinese coastal region due to building artificial land has been widely reported (Yang, Chen, Barter, & Piersma, 2011; Duan et al., 2016). In Hong Kong, sea water has been seriously polluted due to the inflow of construction waste and effluent released during the process of building artificial land. (Chan. et al., 2017). Several other environmental issues have been reported arising from the offsite extraction of the building material (Padmalal, Maya, Sreebha, & Sreeja, 2008; Thornton et al., 2006; de Leeuw et al., 2010). It is clearly critical to investigate the more thoroughly than has been the case the potential ecological and geomorphological consequences emerging as a result of landfill material transfer, both at the source and destination.

Aside from biodiversity loss, geo-engineering of the coastline and coastal land expansion poses a significant threat to existing wetlands. Such ecosystems are diverse but vulnerable transition zones between terrestrial and aquatic biomes. Coastal land reclamation has reduced the land area covered by wetlands; since 1949, the loss of coastal wetlands in China is estimated to have been of the order of 22,000 km^2 (Tian et al., 2016; Wang, Liu, Li, & Su, 2014). During the operation of geo-engineering construction techniques, coastal wetland vegetation may be converted to tidal mudflats and sub-tidal zones (Zhu, Xie, Xu, Ma, & Wu, 2016). The rapid rate of seaward land expansion may result in irreversible damage to coastal wetland ecosystems, which ultimately puts pressure on the overall sustainability of coastal resources, a situation exacerbated by sea level rise. Coastal megacities are already exposed to serious risk, whereby projected future increasing sea levels pose a significant challenge (UN-Habitat 2016).

6. Conclusion

The paper demonstrates the global extent to which humans are using and transforming coastal morphology through the application of advanced geo-engineering. The narrative of coastal expansion illustrated by the 16 selected megacities provides stark evidence of the magnitude and rate of building beyond the land and raises some critical questions to prompt further analysis:

1. What material is used to construct such artificial land and where are the sources?
2. What are the possible geomorphic and other environmental consequences, both in the material source area and at the construction site?
3. How will such construction respond in the context of climate change and sea level rise?
4. What are the drivers of such development and how and why do they differ between cities?

In addition, the results of this study emphasize the scale of the process in Asia, where most coastal megacities have adopted large scale land reclamation projects. The pattern of development is also common in urban centres that are not classified (according to population numbers) as megacities, for example, Palm Island in Dubai, Flovoland in Netherlands and reclaimed islands of Maldives and Bangkok. Building beyond the land is undoubtedly a widespread global phenomenon. Population pressure clearly acts as one of the major drivers underlying the creation of new lands over sea, (Liu et al., 2017), although it is certainly not the only one. Further study of regional variations in terms of drivers, processes and potential impacts of land reclamation is needed.

The geomorphic classification of patterns constructed as a result of geoengineering at the coast presented here offers scope for further research as to the motives for developing such differentiated structures. For example, the type of land extension in Shanghai is different to that in Jakarta but similar to that of Lagos. Further consideration of the factors underlying these differences and similarities is clearly warranted. A comprehensive understanding of this requires an interdisciplinary approach which should include both engineering and geophysical perspectives in order to reveal what is driving the demand, what factors determine the particular pattern of land extension and what are its environmental effects.

Finally, in recognizing that both environmental and anthropogenic drivers act are at work in the rapid growth of artificial coastal lands, future studies should aim to identify the relative roles played by these critical driver(s). Through the availability of remote sensing data, it is now possible to estimate, monitor and showcase the ongoing changes in both marine and coastal ecosystems. Against a backdrop of sea level rise and other environmental and economic changes, it will be interesting to explore what will be the "geomorphic capacity" of these evolving artificial offshore spaces in terms of their future sustainability.

Acknowledgements

This study has been conducted with the support from the National Natural Science Foundation of China [grant number 41401094 & 41771119], and the Research Fund of the Laboratory of Marine Ecosystem and Biogeochemistry [grant number LMEB201713]. We are grateful for the insightful and constructive comments of the anonymous reviewers. There are no conflicts of interest among the researchers.

References

Bagaeen, S. (2007). Brand Dubai: The instant city; or the instantly recognizable city. *International Planning Studies, 12*(2), 173–197. http://dx.doi.org/10.1080/13563470701486372.

Balica, S. F., Wright, N. G., & van der Meulen, F. (2012). *Natural Hazards, 64*, 73. http://dx.doi.org/10.1007/s11069-012-0234.

Brown, S., Nicholls, R. J., Woodroffe, C. D., Hanson, S., Hinkel, J., Kebede, A. S., et al. (2013). *Sea-level rise impacts and responses: A global perspective (117–149).* Netherlands: Springerhttp://dx.doi.org/10.1007/978-94-007-5234-4_5.

Burt, J. A., Al-Khalifa, K., Khalaf, E., AlShuwaikh, B., & Abdulwahab, A. (2013). The continuing decline of coral reefs in Bahrain. *Marine Pollution Bulletin, 72*(2), 357–363. http://dx.doi.org/10.1016/j.marpolbul.2012.08.022.

Chan, J. T. K., Leung, H. M., Yue, P. Y. K., Au, C. K., Wong, Y. K., Cheung, K. C., et al. (2017). Combined effects of land reclamation, channel dredging upon the bioavailable concentration of polycyclic aromatic hydrocarbons (pahs) in Victoria Harbour sediment, Hong Kong. *Marine Pollution Bulletin, 114*, 587–591. http://dx.doi.org/10.1016/j.marpolbul.2016.09.017.

Chee, S. Y., Othman, A. G., Sim, Y. K., Adam, A. N. M., & Firth, L. B. (1994). Land reclamation and artificial islands: Walking the tightrope between development and conservation. *Global Ecology and Conservation,* 2351-9894*12*, 80–95. http://dx.doi.org/10.1016/j.gecco.2017.08.005.

Creel, L. (2003). Ripple effects: Population and coastal regions. Retrieved from http://pdf.usaid.gov/pdf_docs/Pnadd169.pdf.

Di Gregorio, A. (2000). *Land cover classification system (LCCS): Classification concepts and user manual for software version 1.0.* FAOhttps://fao.org/3/a-i5232e.pdf.

Duan, H., Zhang, H., Huang, Q., Zhang, Y., Hu, M., Niu, Y., et al. (2016). Characterization and environmental impact analysis of sea land reclamation activities in China. *Ocean & Coastal Management, 130*, 128–137. http://dx.doi.org/10.1016/j.ocecoaman.2016.06.006.

Easman, E.,S., Abernethy, K. E., & Godley, B.,J. (2017). Assessing public awareness of marine environmental threats and conservation efforts. *Marine Policy, 87*, 234–240. http://dx.doi.org/10.1016/j.marpol.2017.10.030.

Findlay, A. C., & Hoy, C. (2000). Global population issues: Towards a geographical research agenda. *Applied Geography, 20*, 207–219. http://dx.doi.org/10.1016/S0143-6228(00) 00008–4.

Fowler, J., Stephens, T. C., Santiago, M., & De Bruin, P. (2002). *Amwaj islands constructed with geotubes,Bahrain*, *Vol. 20*, 4–11. Geotec https://geotec.biz/publications/AmwajIslands Constucted with Geotubes.pdf.

Gagain, M. (2012). Climate change, sea level rise, and artificial islands: Saving the Maldives' statehood and maritime claims through the constitution of the oceans. *Colorado Journal of International Environmental Law and Policy, 23*(1), 78–120. https://www.colorado.edu/law/sites/default/files/GAGAIN%20_correctedv2_.pdf.

Ghaffari, K., Habibzadeh, T., Mortaza, A. N., & Mousazadeh, R. (2017). Construction of artificial islands in southern coast of the Persian Gulf from the viewpoint of international environmental law. *Journal of Politics and Law, 10*(2), 263–275. http://dx.doi.org/10.5539/jpl.v10n2p264.

Glasow, R.,V., Jickells, T.,D., Baklanov, A., Carmichael, G.,R., Church, T.,M., Gallardo, L., et al. (2013). Megacities and large urban agglomerations in the coastal Zone: Interactions between atmosphere, land, and marine ecosystems. *The Rolyal Swedish Academic of Scniences, 42*, 13–28. http://dx.doi.org/10.1007/s13280-012-0343-9.

Grydehøj, A. (2015). Making ground, losing space: Land reclamation and urban public space in island cities. *Urban Island Studies, 1*, 96–117. http://www.urbanislandstudies.org.

Hutchings, P. A., & Wu, B. L. (1987). Coral reefs of Hainan island, South China sea. *Marine Pollution Bulletin, 18*(1), 25–26. http://dx.doi.org/10.1016/0025-326X(87)90652-7.

Jeffreys, A., & Kuncinas, P. (2014). *The report : Indonesia, 2014: Economy, banking, real estate, insurance, energy, tourism, infrastructure, construction, telecoms & it, industry, capital markets, transport, interviews*Oxford Business Group (Retrieved from books.google.com.hk/books).

Jones, G. W. (2002). Southeast Asian urbanization and the growth of mega-urban regions. *Journal of Population Research, 19*(2), 119–136. http://dx.doi.org/10.1007/BF03031973.

Kourtit, K., Nijkamp, P., & Reid, N. (2014). The new urban world: Challenges and policy. *Applied Geography, 49*, 1–3. http://dx.doi.org/10.1016/j.apgeog.2014.01.007.

Lai, L. W. C., Lu, W. W. S., & Lorne, F. T. (2014). A catallactic framework of government land reclamation: The case of Hong Kong and Shenzhen. *Habitat International, 44*, 62–71. http://dx.doi.org/10.1016/j.habitatint.2014.04.013.

Lambin, E. F., Geist, H., & Rindfuss, R. R. (2006). Introduction: Local processes with global impacts. *Land-use and land-cover change* (pp. 1–8). Berlin, Heidelberg: Springer Berlin Heidelberg. http://dx.doi.org/10.1007/3-540-32202-7_1.

Lambin, E. F., Turner, B. L., Geist, H. J., Agbola, S. B., Angelsen, A., Bruce, et al. (2001). The causes of land-use and land-cover change: Moving beyond the myths. *Global Environmental Change, 11*(4), 261–269. http://dx.doi.org/10.1016/S0959-3780(01)00007-3.

de Leeuw, J., Shankman, D., Wu, G., de Boer, W. F., Burnham, J., He, Q., et al. (2010). Strategic assessment of the magnitude and impacts of sand mining in Poyang Lake, China. *Regional Environmental Change, 10*(2), 95–102. http://dx.doi.org/10.1007/s10113-009-0096-6.

Liu, D. C., Wu, D. X., Cao, D. X., & Wu, D. G. (2017). Analysis of coastline changes and the socio-economic driving mechanism in Shenzhen, China. *Marine Geodesy, 40*(6), 378–403. http://dx.doi.org/10.1080/01490419.2017.1319447.

Li, H., Wei, D. Y., Liao, F.,H., & Huang, Z. (2015). Administrative hierarchy and urban land expansion in transitional China. *Applied Geography, 56*, 177–186. http://dx.doi.org/10.1016/j.apgeog.2014.11.029.

Li, Y., Zhang, X., Zhao, X., Ma, S., Cao, H., & Cao, J. (2016). Assessing spatial vulnerability from rapid urbanization to inform coastal urban regional planning. *Ocean & Coastal Management, 123*, 53–65. http://dx.doi.org/10.1016/j.ocecoaman.2016.01.010.

Loo, B. P. Y., & Chow, A. S. Y. (2008). Changing urban form in Hong Kong: What are the challenges on sustainable transportation? *International Journal of Sustainable Transportation, 2*(3), 177–193. http://dx.doi.org/10.1080/15568310701517331.

Mcgranahan, G., Balk, D., & Anderson, B. (2007). The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *International Institute for Environment and Development (IIED), 19*(1), 17–37. http://dx.doi.org/10.1177/0956247807076960.

Ministry of Land and Resources (MLR)TD/T (2007). *The technological standard for the second national land survey.* 1014-2007,(In Chinese).

Moghadam, H. M., & Helbich, M. (2015). Spatiotemporal variability of urban growth factors: A global and local perspective on the megacity of Mumbai. *International Journal of Applied Earth Observation and Geoinformation, 35*(B), 187–198. http://dx.doi.org/10.1016/j.jag.2014.08.013.

Moreno, E. L., & González Blanco, Z. (2014). Ghost cities and empty houses: Wasted prosperity. *American International Journal of Social Science, 3*(2), 207–215. http://www.aijssnet.com/journals/Vol_3_No_2_March_2014/23.pdf.

Moussavi, Z., & Aghaei, A. (2013). The environment, geopolitics and artificial islands of Dubai in the Persian Gulf. *Procedia - Social and Behavioral Sciences, 81*, 311–313. http://dx.doi.org/10.1016/j.sbspro.2013.06.434.

de Mulder, E. F. J., van Bruchem, A. J., Claessen, F. A. M., Hannink, G., Hulsbergen, J. G., & Satijn, H. M. C. (1994). Environmental impact assessment on land reclamation projects in The Netherlands: A case history. *Engineering Geology,* 0013-7952*37*(1), 15–23. http://dx.doi.org/10.1016/0013-7952(94)90078.

Murakami, A., Medrial Zain, A., Takeuchi, K., Tsunekawa, A., & Yokota, S. (2005). Trends in urbanization and patterns of land use in the Asian mega cities Jakarta, Bangkok, and Metro Manila. *Landscape and Urban Planning, 70*(3), 251–259. http://dx.doi.org/10.1016/j.landurbplan.2003.10.021.

Nicholls, R. J., Wong, P. P., Burkett, V., Woodroffe, C. D., & Hay, J. (2008). Climate change and coastal vulnerability assessment: Scenarios for integrated assessment. *Sustainability Science, 3*(1), 89–102. http://dx.doi.org/10.1007/s11625-008-0050-4.

Pacione, M. (2006). Mumbai. *InCities,* 0264-2751*23*(3), 229–238. http://dx.doi.org/10.1016/j.cities.2005.11.003.

Padmalal, D., Maya, K., Sreebha, S., & Sreeja, R. (2008). Environmental effects of river sand mining: A case from the river catchments of Vembanad lake, Southwest coast of India. *Environmental Geology, 54*(4), 879–889. http://dx.doi.org/10.1007/s00254-007-0870-z.

Riding, T. (2017). "Making Bombay island": Land reclamation and geographical conceptions of Bombay, 1661–1728. *Journal of Historical Geography, 59*, 27–39. http://dx.doi.org/10.1016/J.JHG.2017.08.005.

Riley, J. G. (1976). The construction of artificial islands in the Heaufort Sea. *Journal of Petroleum Technology, 28*(4), 365–371. http://dx.doi.org/10.2118/5464-PA.

Seto, K. C., Fragkias, M., Güneralp, B., Reilly, M. K., & Pidgeon, A. (2011). A meta-analysis of global urban land expansion. *PLoS ONE, 6*(8), e23777. http://dx.doi.org/10.1371/journal.pone.0023777.

Shen, L.-Y., Hao, J. L., Tam, V. W.-Y., & Yao, H. (2007). A checklist for assessing sustainability performance of construction projects. *Journal of Civil Engineering and Management, 13*(4), 273–281. http://dx.doi.org/10.1080/13923730.2007.9634471.

Shukla, V., & Parikh, K. (1992). The environmental consequences of urban growth: Cross-national perspectives on economic development, air pollution, and city size. *Urban Geography, 13*(5), 422–449. http://dx.doi.org/10.2747/0272-3638.13.5.422.

Small, C., & Nicholls, R. J. (2003). A global analysis of human settlement in coastal zones. *Journal of Coastal Research, 19*(3), 584–599. http://dx.doi.org/10.2307/4299200. Retrieved from www.jstor.org/stable/4299200.

Smith, M. D., Murray, A. B., Gopalakrishnan, S., Keeler, A. G., Landry, C. E., Mcnamara, D., et al. (2015). Geoengineering coastlines? From accidental to intentional. *Coastal zones: Solutions for the 21st century*Elsevier Press9780128027592. Retrieved from http://ssrn.com/abstract = 2403945.

Sorace, C., & Hurst, W. (2016). China's phantom urbanization and the pathology of ghost cities. *Journal of Contemporary Asia, 46*(2), 304–322. http://dx.doi.org/10.1080/00472336.2015.1115532.

Tan, M., Li, X., Xie, H., & Lu, C. (2005). Urban land expansion and arable land loss in China—a case study of Beijing–Tianjin–Hebei region. *Land Use Policy, 22*(3), 187–196. http://dx.doi.org/10.1016/j.landusepol.2004.03.003.

Thornton, E. B., Sallenger, A., Sesto, J. C., Egley, L., McGee, T., & Parsons, R. (2006). Sand mining impacts on long-term dune erosion in southern Monterey Bay. *Marine Geology, 229*(1), 45–58. http://dx.doi.org/10.1016/j.margeo.2006.02.005.

Tian, B., Wu, W., Yang, Z., & Zhou, Y. (2016). Drivers, trends, and potential impacts of long-term coastal reclamation in China from 1985 to 2010. *Estuarine, Coastal and Shelf Science,* 0272-7714*170*, 83–90. http://dx.doi.org/10.1016/j.ecss.2016.01.006.

UN-Habitat (2016). *Urbanization and development: Emerging futures*. UN Habitat World

Cities Report http://wcr.unhabitat.org/main-report/.
UNEP (2014). Assessing global land use: Balancing consumption with sustainable supply. *A Report of the working group on land and soils of the International Resource Panel. 2014*. Retrieved from http://wedocs.unep.org/handle/20.500.11822/8861.
United Nations (2014). *World urbanization prospects: The 2014 revision.* highlights (ST/ESA/SER.A/352). New York, Unitedhttp://dx.doi.org/10.4054/DemRes.2005.12.9.
Wang, W., Liu, H., Li, Y., & Su, J. (2014). Development and management of land reclamation in China. *Ocean & Coastal Management, 102*, 415–425. http://dx.doi.org/10.1016/j.ocecoaman.2014.03.009.
Wu, J., Li, R., Ding, R., Li, T., & Sun, H. (2016). City expansion model based on population diffusion and road growth. *Applied Mathematical Modelling, 43*, 1–14. http://dx.doi.org/10.1016/j.apm.2016.08.002.
Xue Hong, C., Xin, C., An Ping, L., Li Jun, C., Shu, P., Miao, L., et al. (2016). Science China special topic: Global mapping of artificial surfaces at 30-m resolution. *Science China Earth Sciences, 59*(59), 2295–2306. http://dx.doi.org/10.1007/s11430-016-5291-y.
Yang, H.-Y., Chen, B., Barter, M., & Piersma, T. (2011). Impacts of tidal land reclamation in Bohai bay, China: Ongoing losses of critical Yellow sea waterbird staging and wintering sites. *Bird Conservation International, 21*(3), 241–259. http://dx.doi.org/10.1017/S0959270911000086.
Yu, H. (2014). China's "ghost cities.". *East Asian Policy, 6*(2), 33–43. http://dx.doi.org/10.1142/S1793930514000142.
Yue, Q., Zhao, M., Yu, H., Xu, W., & Ou, L. (2016). Total quantity control and intensive management system for reclamation in China. *Ocean & Coastal Management, 120*, 64–69. http://dx.doi.org/10.1016/j.ocecoaman.2015.11.026.
Zhang, Q., Ban, Y., Liu, J., & Hu, Y. (2011). Simulation and analysis of urban growth scenarios for the Greater Shanghai Area, China. *Computers, Environment and Urban Systems, 35*(2), 126–139. http://dx.doi.org/10.1016/j.compenvurbsys.2010.12.002.
Zhou, N., Hubacek, K., & Roberts, M. (2015). Analysis of spatial patterns of urban growth across South Asia using DMSP-OLS nighttime lights data. *Applied Geography, 63*, 292–303. http://dx.doi.org/10.1016/j.apgeog.2015.06.016.
Zhu, G., Xie, Z., Xu, X., Ma, Z., & Wu, Y. (2016). The landscape change and theory of orderly reclamation sea based on coastal management in rapid industrialization area in Bohai Bay, China. *Ocean & Coastal Management, 133*, 128–137. http://dx.doi.org/10.1016/j.ocecoaman.2016.09.016.