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Key Points:

- 253,000 ha of additional land to the Earth's coastal surface in the 21st century, equivalent to an area the size of Luxembourg
- Coastal Reclamation is especially prominent in East Asia, the Middle East, and Southeast Asia, followed by Western Europe and West Africa
- We suggest that 70% of recent reclamation has occurred in areas identified as high risk to extreme SLR by 2100

Supporting Information:

Supporting Information may be found in the online version of this article.

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Mapping 21st Century Global Coastal Land Reclamation

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Abstract Increasing population size and economic dependence on the coastal zone, coupled with the growing need for residential, agricultural, industrial, commercial and green space infrastructure, are key drivers of land reclamation. Until now, there has been no comprehensive assessment of the global distribution of land use on reclaimed space at the coast. Here, we analyze Landsat satellite imagery from 2000 to 2020 to quantify the spatial extent, scale, and land use of urban coastal reclamation for 135 cities with populations in excess of 1 million. Findings indicate that 78% (106/135) of these major coastal cities have resorted to reclamation as a source of new ground, contributing a total 253,000 ha of additional land to the Earth's surface in the 21st century, equivalent to an area the size of Luxembourg. Reclamation is especially prominent in East Asia, the Middle East, and Southeast Asia, followed by Western Europe and West Africa. The most common land uses on reclaimed spaces are port extension (>70 cities), followed by residential/commercial (30 cities) and industrial (19 cities). While increased global trade and the rapid urbanization have driven these uses, we argue that a city's prestigious place-making effort to gain global reputation is emerging as another major driver underlying recent reclamation projects to create tourist and green spaces Meanwhile, the study suggests that 70% of recent reclamation has occurred in areas identified as potentially exposed to extreme sea level rise (SLR) by 2100 and this presents a significant challenge to sustainable development at the coast.

Plain Language Summary Coastal regions face enormous pressure from growing human footprints, especially given the current rates of sea-level rise. It is now recognized that seawards extension of the land through land reclamation and infrastructure development, at least partly in response to increased vulnerability induced by extreme storm surge events, is also a feature of recent coastal dynamics, especially in the world's coastal megacities Despite its growing global importance and reach worldwide, coastal reclamation is regarded as a local issue. Subsequently, the scale, intensity, and justification are not globally known, rather they are documented through localized case studies. By leveraging advanced satellite and cloud computing technology, this study aims to map the global state of 21st coastal land reclamation and to highlight the risk of such an anthropogenic footprint at the coast in the era of SLR.

1. Introduction

Coastal regions face enormous pressure from the burgeoning human footprint (Doney, 2010; Halpern et al., 2019; Smart et al., 2021). Population living in the Low Elevated Coastal Zone (LECZ), which was approximately between 750 million and 1.1 billion people in 2015 (MacManus et al., 2021a, 2021b), is estimated to increase by up to 71% by 2050 (Kulp & Strauss, 2019). Urban expansion in the coastal zone, creating multi-purpose spaces including ports, industry, commerce, housing, and places for entertainment and leisure, has resulted in "ocean sprawl" (Firthet al., 2016). This pressure, along with the emergence of the blue economy (Bugnot et al., 2021), has prompted the phenomenon whereby many of the world's coastal cities assertively extend their boundaries seaward by filling in coastal wetlands and shallow seas (Sengupta et al., 2018). However, the spatial characteristics, magnitudes, and drivers of this "coastal reclamation" have been quantified mostly at national, regional

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or local levels (Jiang et al., 2021; Koh & Khim, 2014; Martin-Anton et al., 2016). Filling this gap, this paper conducts a global quantitative analysis of coastal reclamation with high accuracy and precision.

We define coastal reclamation as the civil engineering activity that converts coastal wetlands or shallow seas into dry land or enclosed shallow water bodies. Coastal reclamation involves a range of processes, including seawall construction, draining seawater, and infilling the enclosed space with various materials such as sand, gravel, and rocks (Chapman, 1984). Existing studies suggest the prominence of urban reclamation over agricultural reclamation over the recent decades (Alexander, 2019; Meng et al., 2017). We, therefore, begin our quest by examining cities. Specifically, we present an account of globally distributed land reclamation between 2000 and 2020 through an analysis of 135 major coastal cities (population of at least 1 million) by leveraging the cloud computing and satellite remote sensing technology of Google Earth Engine (GEE). Additionally, we use data from Open Street Maps (OSM) to evaluate land use types on reclaimed land. We address the local-global data gap by focusing on the following objectives: (a) to quantify and map the global spatial distribution and magnitude of coastal land reclamation at the city scale between 2000 and 2020, (b) to evaluate how the reclaimed space is being used, and (c) to identify and critically discuss key drivers underlying large-scale urban coastal land reclamation projects.

2. Materials and Methods

The study is based on an analysis of all the coastal cities globally (135) that have populations exceeding 1 million in 17 global regions based on the United Nations World Cities in 2018 and United Nations World Urbanization Prospect 2018 database (UN, 2018). For all 135 cities, we processed more than 50,000 Landsat images between 2000 and 2020 using the Aqua Monitor database and applied the Automatic Water Extraction Index (AWEI) (Feyisa et al., 2014) along with Ostu's method of adaptive and automatic thresholding technique (Ghorai & Mahapatra, 2020) in GEE platform to quantify the global distribution of coastal reclamation. AWEI was specifically used due to its better performance compared to other indices in distinguishing land and water (Vinayaraj et al., 2018). Finally, land use over reclaimed land was mapped for the largest sites in each of the 17 regions by extracting data from the OSM database (Yang et al., 2017). We supplemented our research with an in-depth literature search to yield relevant recent coastal reclamation information coupled with field validation and scrutiny of high-resolution images where available. Table S1 in Supporting Information S1 lists data and materials used in this study.

2.1. Data and Definitions

2.1.1 Coastal Cities

We examined all the major coastal cities (population >1,000,000) globally to ascertain whether they have engaged or not in reclamation between 2000 and 2020. We followed World Urbanization Prospects (UN, 2018) to classify regions. We identified 135 coastal cities with the characteristics of a "Metropolitan area" as defined in the United Nations Report of Expert Group Meeting on Sustainable Cities, Human Mobility, and International Migration (https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/unpd_egm_201709_s2_paper-moreno-final.pdf) Data on population were obtained from the World Cities in 2018 booklet (https://www.un.org/en/development/desa/population/publications/pdf/urbanization/the_worlds_cities_in_2018_data_booklet.pdf), and location for cities was extracted from OSM (https://www.openstreetmap.org/). According to this data source, there are 548 coastal cities defined as metropolitan areas of populations >1,000,000. Additionally, we used the LECZ definition to delineate coastal extent using a global DEM to create a buffer zone of 10 km "coastal strip," and we select cities that lie within this zone. Moreover, from LECZ definition, we considered the distance from the coast rather than elevation above MSL. After applying the 5 km LECZ coastal mask, our study extent was reduced to 197 cities. After processing cloud and cloud shadow for approximately 30,000 Landsat images, only 135 had suitable satellite image records to enable analysis.

2.1.2 Pre-Reclamation Elevation

The Multi-Error-Removed Improved Terrain digital elevation model (MERIT-DEM) is a high accuracy global DEM at three arc-second resolution (~90 m at the equator) produced by removing the error from present DEMs (Yamazaki et al., 2017). MERIT DEM splits absolute bias, stripe noise, speckle noise, and tree height bias utilizing compound satellite products and filtering methods. This data product was used in this study to showcase the distribution of pre-reclaimed land-based on elevation figures for the year 2000 (Starting point of this study) as well as to create a land-ocean mask for coastal zone delineation.

2.1.3 Coastal Reclamation

As this was calculated based on annual changes in surface water, reclamation of tidally controlled wetlands and marshes were not considered. In addition, yearly temporal resolution of imagery also limited accounting for tidal changes within the reclamation process. Although coastal defense structures or fixtures (e.g., breakwaters, bridge foundations) were not considered land reclamation as they were not discernible given the 30 m image resolution, there were examples where land expansion occurred due to significant active sedimentation up-drift of such structures. Where this occurred above the high water mark; these cases were included in the study, for example, Dar es Salaam (Tanzania) and Maputo (Mozambique). A detailed list of what types of coastal reclamation was considered in this study can be found in Table S2 Supporting Information S1.

2.1.4 Land Use

In this study, we used land use POI as defined in NJDEP modified Anderson system 2002 (https://www.state.nj.us/dep/gis/digidownload/metadata/lulc02/anderson2002.html) and geotagged in OSM database. S3 provides information on land use abstraction. Additionally, we define land "under construction" as reclaimed land without any visible or mapped land use, current dredging or land building activities.

2.2. Data Processing

2.2.1 Image Processing

Coastal land reclamation was mapped using a three-step approach that mainly includes identification of reclamation, extraction of reclaimed land in GIS shapefile format and validation using high resolution images (See Section S4.1 in Supporting Information S1)

1. Identification: First, by using the LECZ definition, we divided the coastal zone of individual cities into 0.02 × 0.02-degree geometric grids after masking 10 km of coastal land and ocean zones using the MERIT DEM. Second, to locate land expansion in the form of reclamation between 2000 and 2020, we used Deltares Aqua Monitor (DAM) Donchyts et al., 2016 (https://aqua-monitor.appspot.com/, GEE code 1). This applies the Normalized Difference Water Index (NDWI) over inter-annual composites of Landsat Top-of-Atmosphere images. DAM calculates percentiles to estimate average cloud-free reflectance values and the slope of linear regression to identify NDWI pixels where long-term changes in surface water occurred. Using DAM and Google Earth images, surface water change, that is, land gain and land loss (for conversion of tidal flats into aquaculture ponds/lake/reservoirs) at the coast, was visually interpreted with coastal grids for all 135 selected coastal cities (See Section S4.2 in Supporting Information S1).
2. Extraction: Only the land expansion portion of the annual coastline was extracted for individual cities for the annual median composites of 2000 and 2020 by applying the AWEI (1) and Ostu adaptive and automatic thresholding technique for Landsat TM/ETM+/OLI atmospheric corrected surface (SR) images in GEE cloud computing platform (Gorelick et al., 2017; Tamiminia et al., 2020) (GEE code 2). By using the automatic thresholding technique over AWEI we classified the annual composite image into two class land-water. Cloud and topographical shadow of the Landsat SR imagery were obtained from a "pixel_qa" band produced by means of the CFMASK algorithm to avoid cloudy images (Foga et al., 2017). Initially, in addition, reduce connected components function was applied to remove inland water and small objects from the image. Lastly, individual coastal zone raster images for each year (i.e., 2000 and 2020) were vectorized and then differentiated to get reclaimed land polygon using the ArcGIS Erase toolbox.

$$\mathrm{AWEI} = 4 \times (\mathrm{Green} - \mathrm{MIR}) - (0.25 \times \mathrm{NIR} + 2.75 \times \mathrm{SWIR}) \tag{1}$$

3. Zonal statistics of elevation and building footprints: Here, we calculated the zonal statistics of elevation values for 106 locations adjacent to current reclaimed land having the base year at 2000. We used MERIT DEM in GEE to extract point values for the raster image (GEE code 3). The average of adjacent pixels was calculated to estimate the central value, or "neighborhood" mean. This was done using the bufferPoints function, which returns a function to add a buffer to points and transform them to circular bounds. After that, the zonalStats

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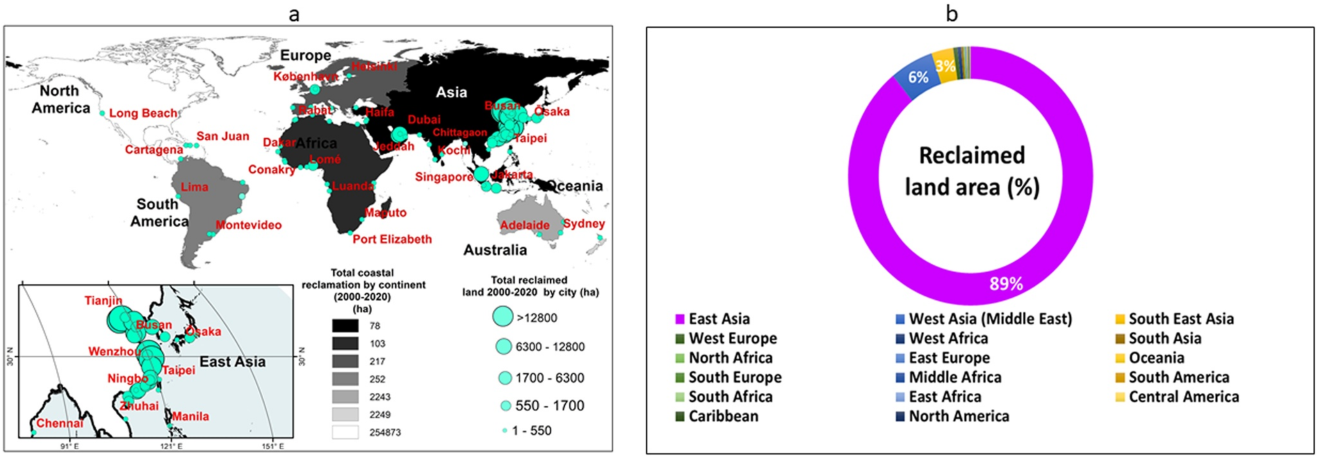

Figure 1. It shows spatial and temporal distribution of 21st-century coastal land reclamation. (a) Map of 21st coastal reclamation showing the location of cities and continents with total land area reclaimed (in ha) between 2000 and 2020. (b) Pie chart showing the distribution of total reclaimed land area (in ha) between 2000 and 2020 for 17 regions. Most recent reclamation has been carried out by East Asian cities such as Shanghai, Incheon, Osaka etc. For the rest of the world, notable cities in Western Europe include Rotterdam (1,106 ha, Netherlands) and Amsterdam (337 ha, in Netherlands).

function was applied to reduce or aggregate images in an image collection by manual POIs with a radius of 90 m parallel to the 90 m pixel resolution of the DEM.

4. Building footprints: Data were extracted from OSM using the OSMNX python package (Boeing, 2017). OSMNX is a tool for collecting, creating and analyzing street networks and building footprints in a consistent and automatable manner. Additionally, QuickOSM plugin in QGIS was used to extract land use shapefiles from OSM database. Furthermore, cross verification of OSM data was done using high-resolution images from Google Earth and Sentinel-2 images.

2.3. Accuracy and Validation

2.3.1 Uncertainty Analysis of Area Calculations

The uncertainty is assessed using the number of unsystematic variations in an observation. This can be calculated by the difference of maximum and minimum value in a series of observations, divided by 2. Such uncertainties arise mainly due to observation error from the instrument or geographical fluctuations such as the tidal system.

2.3.2 Validation

This study's initial method uses the DAM (https://www.deltares.nl/en/software/aqua-monitor/) to identify surface water changes at the coast (land gain), which already has excellent precision and accuracy. Nevertheless, this study provides a validation method based on two UAV drone-based field inspections in 2018 (Figure S5 in Supporting Information S1). In addition, to validate the accuracy of the automatic extraction results, time series chips of Landsat images for five coastal cities were visually interpreted in GEE Landsat explorer app (https://github.com/jdbcode/ee-rgb-timeseries/blob/main/landsat-timeseries-explorer.js) (Figure S6 in Supporting Information S1). Additionally, high resolution time series Google Earth images were further interpreted to ensure accuracy of data derived from Landsat images. However, it is noteworthy that the complex geographic environment, vivid shoreline, and the quality of Landsat images in some cities lead to errors in automatic extraction results.

3. Results

3.1. Global Spatial Distribution of Coastal Reclamation by World Regions and Cities

Our results show that among the 135 major coastal cities in the world, 106 cities (78%) have participated in coastal reclamation between 2000 and 2020. The results underline that coastal reclamation is indeed a global-scale phenomenon in the 21st century. In total, more than 253,000 ha of land and enclosed water spaces (Figures 1a and S7 in Supporting Information S1)—equivalent to an area the size of Luxembourg—have been reclaimed by these cities. To break down the global data by world regions, more than 248,550 ha was reclaimed within

Asia, followed by Africa (2,277 ha) and Euorpe (2,233 ha) (Figure 1a) Using the classification system used in UN 2018, we further divided the world regions into 17 sub-regions. Figure 1b illustrates that coastal land reclamation has been especially prominent in East Asia (225,290 ha), West Asia (14,998 ha) and Southeast Asia (7,477 ha), followed by Western Europe (1,443 ha) and West Africa (1,290 ha). At the country levels, our results demonstrate that the countries of the Global South with rapidly growing economies, such as China, the United Arab Emirates (UAE), Indonesia, Nigeria, Ghana, and Angola have been particularly active in reclaiming the coasts over the past two decades. Among them, China, the UAE, and Indonesia account for approximately 90% of the total coastal area reclaimed in all 106 cities.

According to our analysis, many individual cities deserve particular attention, not all of which are known to the international audience for their reclamation efforts. Within the top-tier world regions with the highest reclamation profiles, East Asian cities include Shanghai (34,978 ha, China), Incheon (4,026 ha, South Korea) and Osaka (1,005 ha, Japan). In West Asia, notable cities are those in the UAE including Abu Dhabi (5,408 ha), Dubai (3,604 ha) and Sharjah (24 ha), followed by the cities in Saudi Arabia such as Dammam (3,287 ha) and Jeddah (171 ha). Kuwait (189 ha), Beirut (Lebanon) (103 ha), and Muscat (74 ha, Oman) also have participated in coastal reclamation. Southeast Asian cities such as Singapore (3,135 ha), and Jakarta (839 ha, Indonesia) and Da Nang (266 ha, Vietnam) have also reclaimed substantial areas of land at their coastal frontier.

In West Africa, Lagos (924 ha, Nigeria), Luanda (200 ha, Angola), and Abidjan (119 ha, in Côte d'Ivoire), Accra (88 ha, in Ghana), Lomé, (48 ha in Togo) and Conakry (28 ha, in Guinea) have extended their coastlines. In addition, more than 300 ha of land areas have been collectively reclaimed in the Caribbean, Central America and South America. They include cities such as Port-au-Prince (Haiti), Panama city (Panama), Buenos Aires (Argentina) and Rio de Janeiro (Brazil). In the region of Eastern Europe, Saint Petersburg (300 ha, Russia), Copenhagen (119 ha, Denmark) and Helsinki (65, Finland) is particularly notable. The phenomenon of coastal reclamation has been less widespread in Oceania, where 160 ha of the coastal area was reclaimed in Brisbane (Australia), followed by 50 ha in Auckland (New Zealand) and 48 ha in Sydney (Australia). Lastly, cities across North America have not recently engaged in reclamation, with the exception of the Los Angeles Port, which has reclaimed 29 ha in the past 20 years.

Furthermore, coastal reclamation in the last two decades is much more globally widespread than was the case in the previous century (Figures S8.1 and S8.2 in Supporting Information S1) when reclamation was carried out in only relatively few countries, most notably the Netherlands, the United States, and some East Asian countries (China, South Korea, Singapore, and Japan). While 20th century reclamation was concentrated mainly in the global north, rapid urbanization and development in the global south have witnessed a marked shift to coastal cities in the Middle East, West Africa, Southeast Asia, and East Asia (Solarz, 2019). Interestingly, the purposes of land reclamation twentieth century have varied spatially. For example, New York's Manhattan and San Francisco Bay were reclaimed to create land for development, while in the Netherlands, Dutch engineers originally drained coastal marshes and lagoons for flood control and to counteract shrinking organic soils (Hoeksema, 2007; VanKoningsveld et al., 2008). In East Asian countries, reclamation has often been undertaken for salt production and aquaculture (Chio, 2014; Ding et al., 2019).

3.2. SLR Impact on Reclaimed Land at the Coast

1. Our analysis highlights that reclamation is typically found in low-lying coastal areas which are especially vulnerable to SLR. Figure 2 shows projected SLR (RCP 4.5) from 2046 to 2100 along with locations of coastal cities graded with their pre-reclamation elevation figures (base year-2000). More than 50 coastal cities that engaged in recent reclamation are located in zones that are predicted to experience marked sea level rise by the end of the century, with values ranging from +0.7 m to +0.47 m. Moreover, prior to reclamation, these cities, located mainly in East Asia (e.g., Shanghai, Jakarta) and West Africa (e.g., Abidjan, Lagos, and Luanda) were characterized by elevations of between −0.26 and 2.13 m amsl. Pre-reclamation elevation data also reveal that more than 70% of these coastal geoengineering projects are potentially exposed to a high risk of extreme SLR by 2100 (Oppenheimer et al., 2019). Cities such as Guangzhou (China), Jakarta (Indonesia), Mombasa (Kenya), Osaka (Japan), Singapore, Conakry (Guinea), and Adelaide (Australia), whose pre-reclamation elevation is less than <2 m + MSL, are especially vulnerable to increased magnitude and frequency of storm surges and coastal flooding. Furthermore, the scale of land subsidence over reclaimed land may exceed 15 cm/year in some localities and will clearly accentuate exposure to rising sea levels (Sengupta

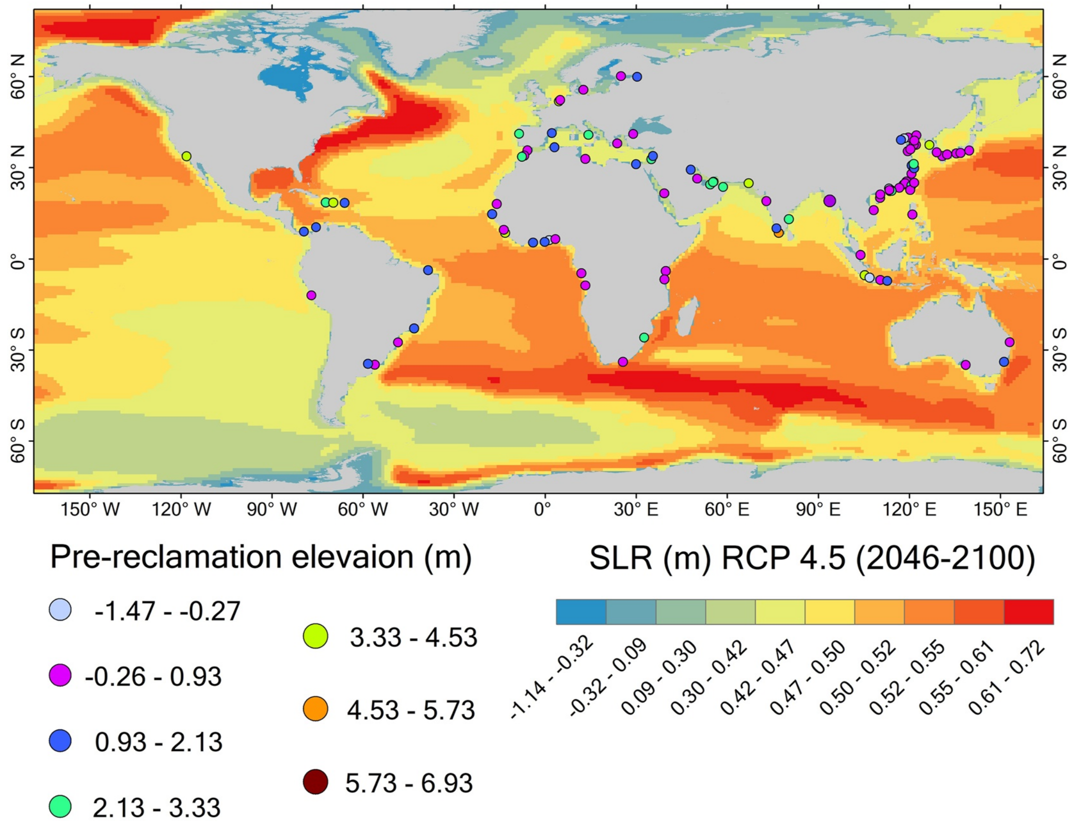

Figure 2. Map showing the location of cities as graded with their pre-reclamation elevation figures having RCP 4.5 projection of sea-level rise 2046–2100 at the backdrop. Pre-reclamation elevation data for 106 cities were derived from MERIT DEM and plotted against SLR projections under RCP 4.5 to show that more than 70% of coastal cities who have taken up reclamation at their coastal frontier are at high risk from coastal flooding between 2046 and 2100.

et al., 2020). Considering the physical environmental and natural setting of the reclaimed areas, coastal reclamation has mostly been associated with estuaries, for example, Shanghai, Rotterdam, Sydney, Mumbai, Chittagong (Bangladesh). Coastal cities such as Luanda (Angola), Maputo (Mozambique), Incheon, and Rio de Janeiro have reclaimed land from lagoons, while 10 coastal cities in the Middle East, characterized by arid, sandy coastlines, have also been prime locations for large-scale reclamation. Therefore, such large scale reclamation at the coast Kuşçu Şimşek, 2021 in areas of high exposure to SLR raises questions on to better investigate the state of anthropogenic coasts.

3.3. Uses of Coastal Reclamation Land

Our analysis indicates that land reclaimed at the coast is typically used for a limited range of purposes, including transport (especially ports), industry, residential/commercial, agriculture (including aquaculture ponds), tourism, and recreation in the form of wetland parks, greenways and leisure gardens (Figure S9 in Supporting Information S1). Figure 3a shows that the primary land use of coastal reclamation is for port development or expansion and is directly related to the functioning of transport. Of the 106 cities in this study, 78 have engaged in port development or expansion, including strategically important sites in Singapore, Tianjin (China), Mombasa (Kenya), Alexandria (Egypt), and Tangier (Morocco). It is noteworthy that reclamation for port development is especially common in the Middle East, Southeast and East Asia, along with West Africa (Figure 3b). Reclamation for residential/commercial land is the second most common land use and is found in 31 of the cities globally, many of which are located in East Asia (Figure 3b), although examples elsewhere include Tunis (Tunisia), St Petersburg (Russia), Rotterdam (Netherlands), Port-au-Prince (Haiti). A further 19 cities have opted for reclamation to expand their industrial zones, in particular for refineries or fuel depots, including Lagos (Nigeria), Jakarta (Indonesia), Pointe-Noire (Congo), Haifa (Israel) and Ad-Dammam (Saudi Arabia). Additionally, there are 24

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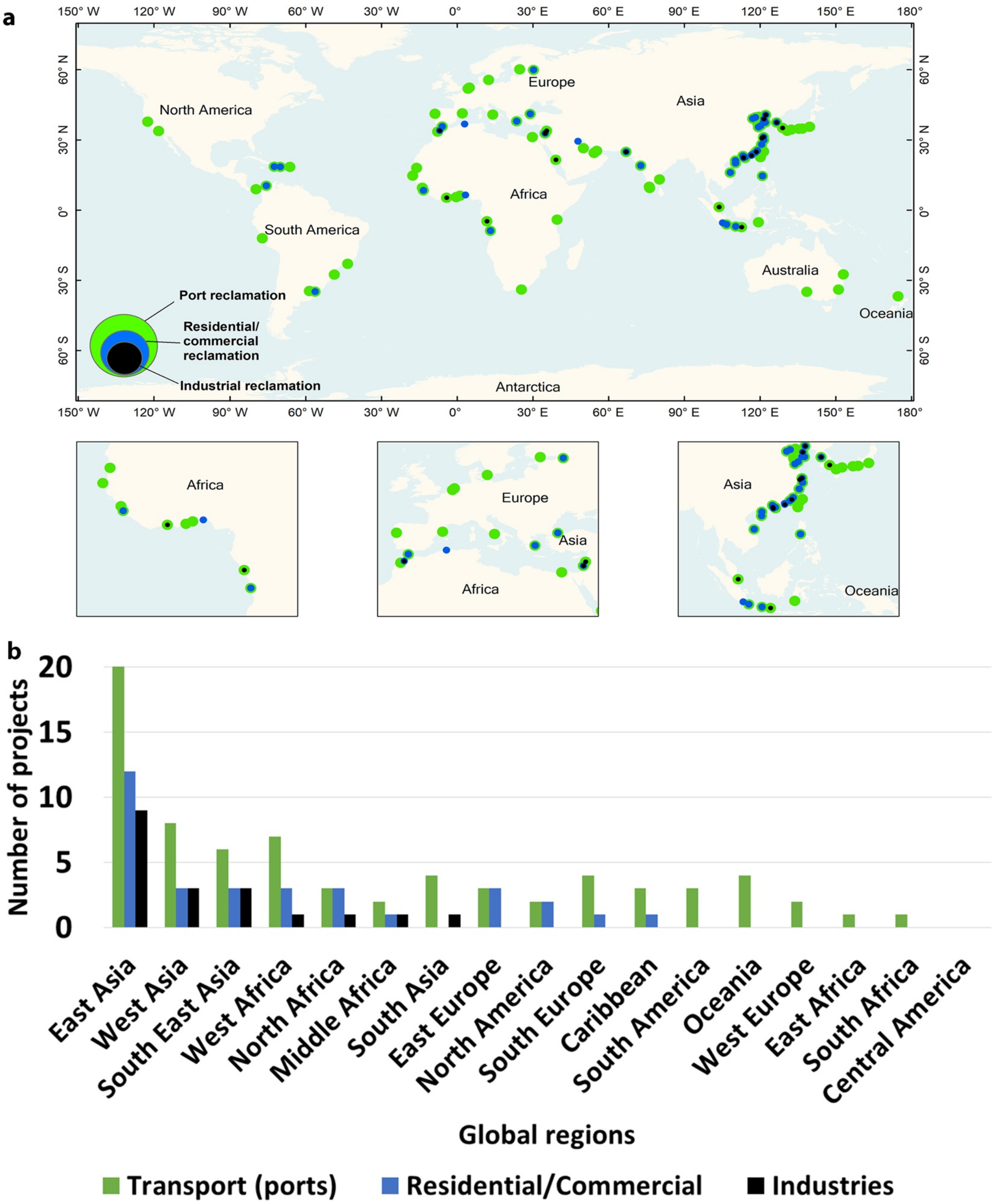

Figure 3. Spatial distribution of land use over reclaimed land at global scale.(a) Map of the most prominent land uses of reclamation projects are ports, residential/commercial and Industries. (b) Number of different land uses spread across different coastal cities over reclaimed land per region (2000–2020).

reclamation projects currently under construction, including cities such as Xiamen (in China), Jakarta, Jeddah (in Saudi A rabia), Haifa (in Israel), and Karachi (Pakistan).

Data extracted from OSM for a city-scale analysis of the top 17 cities in each region with the greatest areas of reclaimed land show that more than 20,000 ha have been reclaimed in these cities. Among these cities, more than 6,000 ha (25%) is being used for transport, mainly ports, followed by road and airport expansion. Additionally, 20% is used for industrial purposes closely associated with port administration (Figures 4a.1 and 4a.2). Coastal cities reclaiming land for residential/commercial purposes (e.g., the infamous Great Sea Wall of Jakarta) accounts for 9% (Figure 4a.3). Furthermore, "greening" of reclaimed land for recreational purposes in the form of parks, greenways and artificial wetland reserves, which together occupy 18% of the total across all cities (Figure 4a.4)

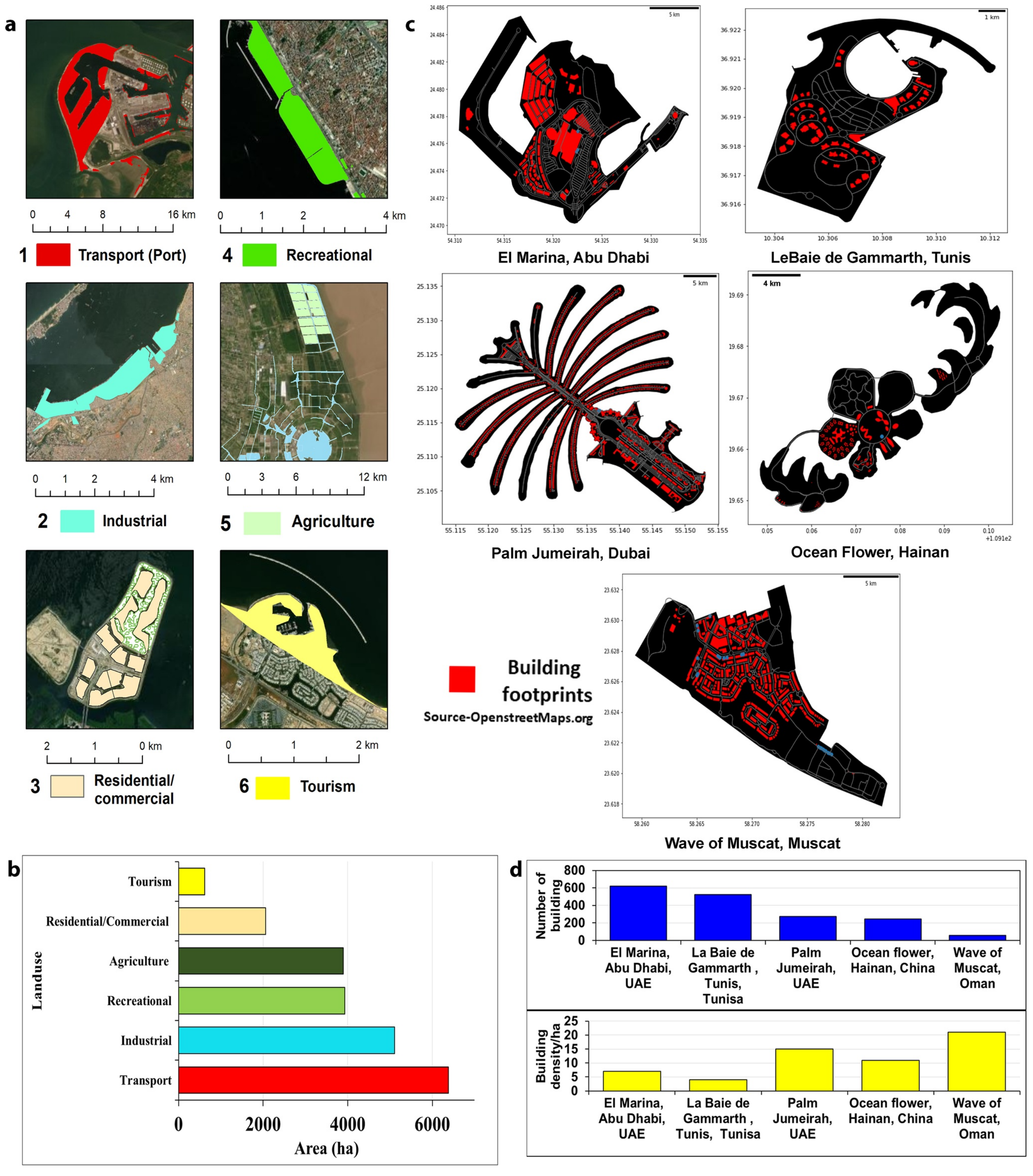

Figure 4. (a) Map illustrating 6 typical land uses over reclaimed land and building footprints over prestigious reclamation sites. (Source: OSM) (1) Rotterdam port—Netherlands (2) Industrial zone—Luanda Angola, (3) Residential zone-Jakarta Indonesia, (4) Park—stanbul, Turkey, (5) Aquaculture and Agricultural land—Shanghai, China, (6) Marina—Muscat, Oman (b) Graph showing land use area (in ha) tabulated for 17 largest reclamation sites from each. (c) Map of prestige reclamations superimposed with their recent building footprint. (d) Graph showing number of buildings and density/ha of five largest prestigious reclamation sites.

is a noteworthy land-use type. In Shanghai and Dubai, >3,800 ha of reclaimed land is now being used for recreation, serving additionally the functions of coastal restoration and protection, mainly in the form of artificial parks. Reclamation for agriculture and aquaculture, notably in Shanghai, is another prominent land use, accounting for more than 3,800 ha (17%) in all (Figure 4a.5). While reclaimed land allocated to tourism infrastructure and facilities is a relatively minor land use (2.82%, Figures 4a.6 and 4b), it includes some highly prestigious developments designed to gain reputation and competitive advantage in terms of investment (Paris, 2017), for example, the iconic Palm Jumeirah and The World in Dubai (UAE), the latter being one of the world's largest examples of reclamation (>5,000 ha) for prestige purposes. Other examples include Haikou, China (715 ha), Makassar, Indonesia (158 ha), Muscat, Oman (60 ha), Ad-Dammam, Saudi Arabia (56 ha), and Panama City (12 ha), where land reclaimed from the sea is occupied by luxurious hotels and amusement parks, elite residential establishments and exclusive commercial centers. Analysis of building footprints for the five largest sites reclaimed for high-profile prestige constructions reveals a total of 1,719 buildings covering more than 260 ha of land area (a = density, $D_B = 6.6$ buildings/ha) (Figures 4c and 4d. According to current OSM data, some 1,202 buildings collectively in the eco-city of Abu Dhabi, Tunis, and Muscat are used for high-end tourism resorts and residential complexes and occupy more than 220 ha ($D_B = 5$ buildings/ha). The Palm Jumeirah in Dubai comprises more than 250 luxurious villas/buildings on just 18 ha of land ($D_B = 13.9$/ha). Similarly, 240 buildings over the reclaimed Ocean Flower Island in Hainan, China cover more than 20 ha ($D_B = 12$/ha), although this project has been subject to considerable controversy environmental issues (Man, 2020).

4. Discussion

A remarkable geographical, quantitative, and qualitative shift in the pattern of coastal reclamation over the past two decades is apparent. Increasingly, cities across the world are engaging in reclamation as a means of expanding their city boundaries. Moreover, coastal reclamation is a multi-purpose intervention not simply limited to creating land for agriculture, port expansion or as a flood prevention measure as was historically the case. What is driving this global coastal reclamation fever? Several explanations may be advanced.

1. Unparalleled port development and expansion coincides with a period of increased globalization of production and consumption chains (Horner & Nadvi, 2018). Although construction of marine and airports on reclaimed land is not exclusively a recent phenomenon, expanding trade and transport has dramatically increased the volume of goods moved from port to port (Federico & Tena-Junguito, 2019) (also see Figure S10.1 in Supporting Information S1). Both air freight and containerized cargo (ocean shipping) have expanded rapidly in recent years, with volumes of the latter growing at an annual rate of 8.0 per cent between 1980 and 2018 (UNCTAD, 2019). In 2018, more than 785 million TEU (20-foot equivalent units) were handled by all ports worldwide (World Shipping Council, 2019). Our study shows that cities that are the largest exporters of containerized goods, such as Shanghai, have reclaimed very substantial amounts of land since 2000. The trend is particularly evident in China, which alone accounts for one-half of the global maritime trade growth since 2010 (UNCTAD, 2019). The rise of China since its "opening up" as the world's factory has prompted the port expansion in a number of its major coastal cities (Zhang, 2021). Shanghai, for example, ranks as number one in the top 50 global container ports World Shipping Council, 2019; Zhang, 2021; Zhou et al., 2020). Additionally, Tianjin, Shenzhen and Qingdao have collectively reclaimed more than 44,000 ha of land to meet the demand for space at their port jurisdictions. Other major ports include Singapore (3,735 ha reclaimed), which ranks second globally in terms of container trade volumes (UNCTAD, 2019), (Rotterdam (Netherlands), and Busan (South Korea). China's recent economic investment initiatives are directly associated with port development in many other countries (Li et al., 2021; UNCTAD, 2019; World Shipping Council, 2019; Zhang, 2021; Zhou et al., 2020) and a number of these new or expanded ports are constructed on reclaimed land, including in Luanda (Angola), Abidjan (Cote d'Ivoire). As noted by others, such investments have emerged as a key force behind the expansion of coastal cities in general, particularly in the African continent (Han & Webber, 2020). Since 2000, there has been a significant investment for key development projects in the African continent such as railways, ports, healthcare, etc.(Chen, 2016; Ehizuelen, 2017) Increased ocean trade in Africa is clearly prompting reclamation for port expansion, as in Luanda (Angola), Accra (Ghana), Port Elizabeth (South Africa), Nouakchott (Mauritania), Mombasa (Kenya), and Abidjan (Cote d'Ivoire) (Figure S10.2 in Supporting Information S1). Abidjan, for example, has received a massive financial boost (more than 2.5 billion USD) to its port infrastructure (including land reclamation) and is now one of the largest ports in West Africa in terms of throughput (Aid Data, 2017) (Figure S10.3 in Supporting Information S1).

2. Coastal land reclamation for residential/commercial uses is strongly associated with growth in the volume and value of the real estate. Our findings suggest that one of the evolving major land uses on reclaimed land is for upscale living, shopping, leisure, and entertainment. The attractiveness of the coast has favored growth in waterfront urban and commercial developments and is closely associated with the increase in real estate values and, more broadly, the global real estate boom (Bisaro et al., 2020; Bisaro & Hinkel, 2018). Again, China, in particular, has experienced an explosion in its real estate market over the past two decades and investment in this sector ballooned from 6 billion RMB in 2001 to 11 billion RMB in 2017, an almost 20-fold increase(Cai et al., 2020). Recent studies have highlighted the role of the real estate market in driving land expansion (Chee et al., 2017; Petrişor et al., 2020). Importantly, such a trend is also apparent in the Global North. Denmark's Copenhagen, for example, plans to reclaim another 260 ha of land to build luxury residences.
3. Luxrious urban place-making for recreational purposes is emerging as an important driver of coastal land reclamation for the purposes of residential/commercial development. One of the most striking features of 21st-century coastal land reclamation is the construction of artificial islands. Increasingly, cities are deploying geoengineering to create uniquely shaped offshore parcels of land for luxury developments, examples of which include the Palm Jumeriah, Palm Jebel Ali, and the world map-shaped archipelago of The World in Dubai (UAE), the Qatar Pearl in Doha (Qatar), the fish and crescent-shaped islands of Durrat Al Bahrain (Bahrain), the Ocean Flower and Nanhai Pearl Islands in Hainan (China), CitraLand City in Makassar (Indonesia), and Ocean Reef Islands in Panama City (Panama). Luxury resorts and high-value private properties in these islands indicate that their construction is closely tied with real-estate growth and that this is driven by the quest for prestige. Reclamation is a highly cost-intensive and time-consuming civil engineering practice requiring substantial capital investment that may deliver short-term returns. Luxury has become the catalyst for this kind of urban transformation (Oppenheimer et al., 2019)· Reclaimed sites serve as new urban icons of elevated status, where attractive seascapes and striking architecture capitalize on the natural and cultural resources of the area. Such developments initially attract tourists and high-wealth individuals while raising the political and economic profile of the city, ultimately attracting longer-term investment (Koch, 2018; Koch & Valiyev, 2015). Coastal reclamation for prestige is often accompanied by the expansion of green spaces with the aim of improving environmental quality and further enhancing desirability. Parks, gardens and artificial lakes or wetlands are recreated in the name of restoring nature, a type of development that has been referred to as "green forcing" (Firth et al., 2020). Examples include Sino-Singapore Eco-city in Tianjin (in China) (Liu et al., 2019), Istanbul's (Turkey) coastal park (Kuşçu Şimşek & Arabacı, 2021), and exclusive housing in Panama City. Finally, It is now widely accepted that urban expansion at the coast is expected to grow globally (Firth, 2016; Bugnot et al., 2021). Moreover, in the context of current levels in regional SLR, it is important to take account of large scale reclamation at the coast. Additionally, risk over reclaimed land is higher primarily due to the phenomena of land subsidence (Sengupta et al., 2020), which needs further investigation in order to provide the relative impact of SLR (Floerl et al., 2021).

5. Conclusion

Our analysis provides a large-scale overview of an important and ongoing global phenomenon characteristic of many major coastal cities using advanced algorithms and cloud computing analytics, although a more refined analysis would benefit from higher resolution data. Optical images cannot capture coastal areas with very high precision (Toure et al., 2019) and rapid mapping of reclamation at the coastal frontier requires SAR (Synthetic Aperture Radar) imagery for more accurate quantification of its spatial extent (Ottinger & Kuenzer, 2020). In addition, distinguishing between expansion due to natural processes and human construction remains challenging and medium-scale resolution images (30 m) may fail to accurately distinguish areas of land that are reclaimed through geoengineering interventions. Developments in remote sensing technology and higher resolution images will in future allow mapping such changes and increase the reliability of future measurements. Data upgrades in OSM should facilitate a more efficient evaluation of land uses over reclaimed land. Moreover, recent reports have documented coastal reclamation in small scale cities with populations of less than 1 million, including Doha (Qatar), Colombo (in Sri Lanka), Manama (in Bahrain) and Mundra (in India), which were not included in this study.

Despite these limitations, this paper demonstrates that a substantial number of the world's major coastal cities have engaged in reclamation over the past two decades, adding more than a quarter of a million hectares of land to the global coast. We demonstrate that 21st-century coastal reclamation is now a global phenomenon involving

106 out of 135 major coastal cities and that the primary land uses on reclaimed land are ports, port-related industries, and residential/commercial functions. Cities in East Asia and the Middle East have been especially active in extending their coastlines via reclamation which is a multi-purpose undertaking driven by increased global trade, real-estate growth, and the desire for reputation. There is a clear need to go beyond the simple narrative of population growth to explain urbanization at the coast. As for prestigious place-making, we see that more cities are promoting and advocating coastal reclamation for ecological restoration (Posthoorn et al., 2019) such as Chongming island in China (Chen et al., 2018) and Marker Wadden Island in the Netherlands (Xiong & De Visser, 2018). Numerous "eco-cities" such as Caofeidian eco-city in Tangshan (China) (Choi & Sengupta, 2014) La Baie de Gammarth in Tunis (Tunisia), Songdo Eco-city in Incheon (South Korea) (Eireiner, 2021) and El Marina in Abu Dhabi (UAE) also rely on reclamation as part of their land planning. Such controversial aspects of coastal reclamation demand further investigation into whether they indeed fulfill the environmental goals they claim to achieve. Moreover, coastal cities are increasingly vulnerable to SLR and coastal flooding (Almar et al., 2021; Tellman et al., 2021; Vitousek et al., 2017) and this paper demonstrate that reclamation further increases this risk. In anticipating that the impact of SLR will vary from one city to another, it is clear that further research is required to reveal the vulnerability of reclaimed coasts to SLR and quantify the impact of reclamation globally (S12). Nevertheless, results of our analysis can inform policymakers as to more effective coastal land use planning toward meeting Sustainable Development Goals (SDGs) in the era of SLR.

Data Availability Statement

Supplementary data on Coastal land reclamation for 135 cities can be found in the online version shared via Zenondo, and is available here https://doi.org/10.5281/zenodo.7528236. The Deltares Aqua Monitor provides information on global surface water change and can be accessed from https://github.com/Deltares/aqua-monitor. Functions to apply cloud mask to Landsat different collections were obtained from https://github.com/fitoprincipe/geetools-code-editor/blob/master/cloud_masks. MERIT DEM used to perform zonal statistics of elevation available in the GEE dataset catalogue (https://developers.google.com/earth-engine/datasets/catalog/MERIT_DEM_v1_0_3). Population data were obtained from the United Nations Department of Economic and Social Affairs Population Dynamics; The World's cities in 2018; data booklet (https://digitallibrary.un.org/record/3799524?ln=en). Administrative boundaries of individual cities were extracted from OSM. Data sources and statistical concepts for estimating the urban population can be downloaded from the UN file WUP2018-DataSource-Urban-Population.xls (https://population.un.org/wup/Download/). SLR data were downloaded from the supplementary material of the special report on the ocean and cryosphere in a changing climate (https://www.ipcc.ch/srocc/chapter/chapter-4-sea-level-rise-and-implications-for-low-lying-islands-coasts-and-communities/#article-supplementary-material). Data on Chinese investment into African ports expansion was downloaded from AID data website (https://www.aiddata.org/data/geocoded-chinese-global-official-finance-dataset). Additionally, GIS shapefiles (polygons) of reclaimed land between 2000 and 2020, land use shapefiles and building footprints created in this study are available from the corresponding author upon reasonable request. Furthermore, an interactive web-based UI is developed to explore and learn about recent reclamation for 20 major cities globally (https://dhritirajsen.users.earthengine.app/view/reclamationsplit). All GEE and Python codes used in this study are available for the peer review process on the GitHub page (https://github.com/dhritirajsen/Mapping_Coastal_land_reclamation).

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