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Mapping Trajectories of Coastal Land Reclamation in Nine Deltaic Megacities using Google Earth Engine

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Abstract: Increasing demand for land resources at the coast has exerted immense pressure on vulnerable environments. Population and economic growth in coastal cities have combined to produce a scarcity of suitable space for development, the response to which has frequently been the reclamation of land from the sea, most prominently in China. Urbanization is a key driver of such changes and a detailed investigation of coastal land reclamation at the city scale is required. This study analyzed remote sensing imagery for the period 1990 to 2018 to explore the trajectories of coastal land reclamation in nine major urban agglomerations across the three largest deltas in China using the JRC Global Surface Water (Yearly Water Classification History, v1.1) (GSW) dataset on the Google Earth Engine platform. The results are considered in the context of major national policy reforms over the last three decades. The analysis reveals that total land reclaimed among nine selected cities had exceeded 2800 km^2 since 1984, 82% of which occurred after 2000, a year following the enactment of China's agricultural 'red line' policy. Shanghai exhibited the greatest overall area of land extension, followed by Ningbo and Tianjin, especially in the period following the privatization of property rights in 2004. In analyzing annual trends, we identified the developmental stages of a typical coastal reclamation project and how these vary between cities. Scrutiny of the results revealed voids in nighttime light satellite data (2014–2018) in some localities. Although these voids appeared to be characterized by construction, they were occupied by vacant buildings, and were therefore examples of so-called "ghost cities." In China, as elsewhere, continual land reclamation needs to be considered in relation to, inter alia, sea level rise and land subsidence that pose significant challenges to the vision of sustainable urban development in these three deltaic megacities.

Keywords: reclaimed land; coastal urbanization; global surface water dataset; nighttime light dataset; China; red line policy

1. Introduction

The low elevation coastal zone (LECZ) supports 40% of the world's population, and its limited land resource is subject to immense pressures that are exacerbated by sea level rise [1,2]. Recently, large scale coastal land reclamation has become an important manifestation of the human urban footprint [3]. Mega reclamation projects represent a significant threat to marine ecosystems and deserve much closer scrutiny. In addition, the United Nations' recent report "The Ocean and the Sustainable Development Goals under the 2030 Agenda for Sustainable Development" addresses the land reclamation of salt marshes, intertidal flats, and mangroves as a primary threat to the sustainability of coastal and marine ecosystems [4]. Recent examples of such mega structures at the coast include the Palm resorts of Dubai, international airports in Hong Kong, Macau, and Singapore, mega smart city projects such as 'Eko Atlantic' in Lagos, Nigeria, and Songdo smart city, South Korea. The scale of land reclamation taking place on the world's coasts today is unprecedented and a critical understanding of the spatial and temporal characteristics of these high impact practices is overdue. While reclaiming land is a global phenomenon, China's hunger for land [5–7] has resulted in it clearly outstripping other nations in land reclamation for development at the congested coastal frontier (Figure 1a,b). Understanding the policy context, along with information about the nature, magnitude and impacts of such projects, is clearly a requirement if the goal of sustainable coastal urbanization is to be achieved. The process is deeply rooted in understanding the major policy reforms that China implemented to maximize coastal benefits for its cities and, in turn, help to sustain its national economy.

In 2018, China celebrated 40 years of reform and development, during which rapid economic and population growth were accompanied by high rates of coastal urbanization and an accelerated demand for land. This demand resulted in noticeable land use transformation, initially characterized by a shift from agriculture to urban development [8,9]. However, for cities at the coast, land reclamation has become the dominant means by which they extend and develop their urban areas [6]. Since 1985, more than 6000 km^2 of land has been reclaimed in China, principally within and around its shining coastal cities; where coastal reclamation is especially concentrated in cities located in its three highly vulnerable deltaic ecosystems [10]. Notwithstanding the associated deleterious environmental and ecological impacts [5,6,11,12], coastal land reclamation has emerged in China as a key strategy to address three issues, i.e., urban land scarcity, the promotion of a so-called 'eco-civilization', and as an adaptive measure to combat sea level rise [7,13,14].

Until now, much of the studies on coastal land reclamation have been at a national scale [5,6]; however, this paper aims to analyze the changing spatial extent of coastal land reclamation in China at the individual city scale, and in relation to evolving urbanization and associated planning policies. In doing so, we address the following objectives for nine megacities located in the world's three largest urbanized deltas:

1. Using the GSW dataset to map the annual occurrence of coastal land reclamation, including change in total area, spatial distribution, and statistical trends from 1990 to 2018;
2. Using normalized difference indices (NDVI and NDBI), to identify the nature of seaward land extension through a consideration of how the process evolves, from the initial reclamation phase to the establishment of land use development.
3. To assess the relationship between the pattern of coastal land reclamation and annual GDP growth rate against the background of China's economic and policy reform;
4. To strengthen the analysis by validating results with ground-truth remotely sensed imagery to capture the most recent patterns of land use over reclaimed land.

Although China has a very high rate of urbanization (2.9 percent per year between 2000–2013), much of which is at the deltaic coast (Figure 1c), it houses less than 50% of the global per capita mean of arable land, resulting in potential food insecurity [15–17]. Therefore, land has become a zone of intense resource conflict between agriculture, urban construction, and ecology; the so-called 'land use trilemma' [7,13]. In response to this tension, the state government established what is known as the agricultural 'red line' policy [7], by which a total of 1.2 million km^2 of basic farmland was delimited nationally under the New Land Administrative Law of 1999, and this established a strict spatial limit for urban expansion [9,18].

With rising demand for suitable land, many tidal flats and coastal wetlands were drained and converted to agricultural, residential, commercial, or industrial land. These high levels of construction and urbanization, especially in the major deltaic regions of China (Figure 1d–f), have led to a massive loss of natural wetlands and their associated ecosystems, and needs effective policy integration [12,19–22]. With growing concerns regarding such degradation, the government has begun promoting 'eco-civilization' in major coastal cities [14]. Meanwhile, land extension as a 'by-product' of coastal protection is a common feature of recent coastal dynamics, especially in the world's coastal megacities [3]. China's coastal zone is predicted to face increased risks of flooding; Brown et al. (2018) [23] suggest that almost 100 million people in China (SSP3 scenario) face potentially catastrophic flooding and storm surges, largely consequent on future RSLR. While China and other countries may currently have the means to geo-engineer their coastlines to mitigate flood risk from rising sea levels, mostly by constructing sea-walls, escalating energy and material costs are likely to make such interventions less feasible in the future [2,10]. Land reclamation is now a dominant feature of China's coastal urbanization heightening exposure to risk and vulnerability [6,12]. Therefore, understanding the key policies behind seaward land expansion at the city scale is vital, as is a more detailed consideration of the pattern and process of land use changes over recently reclaimed land.

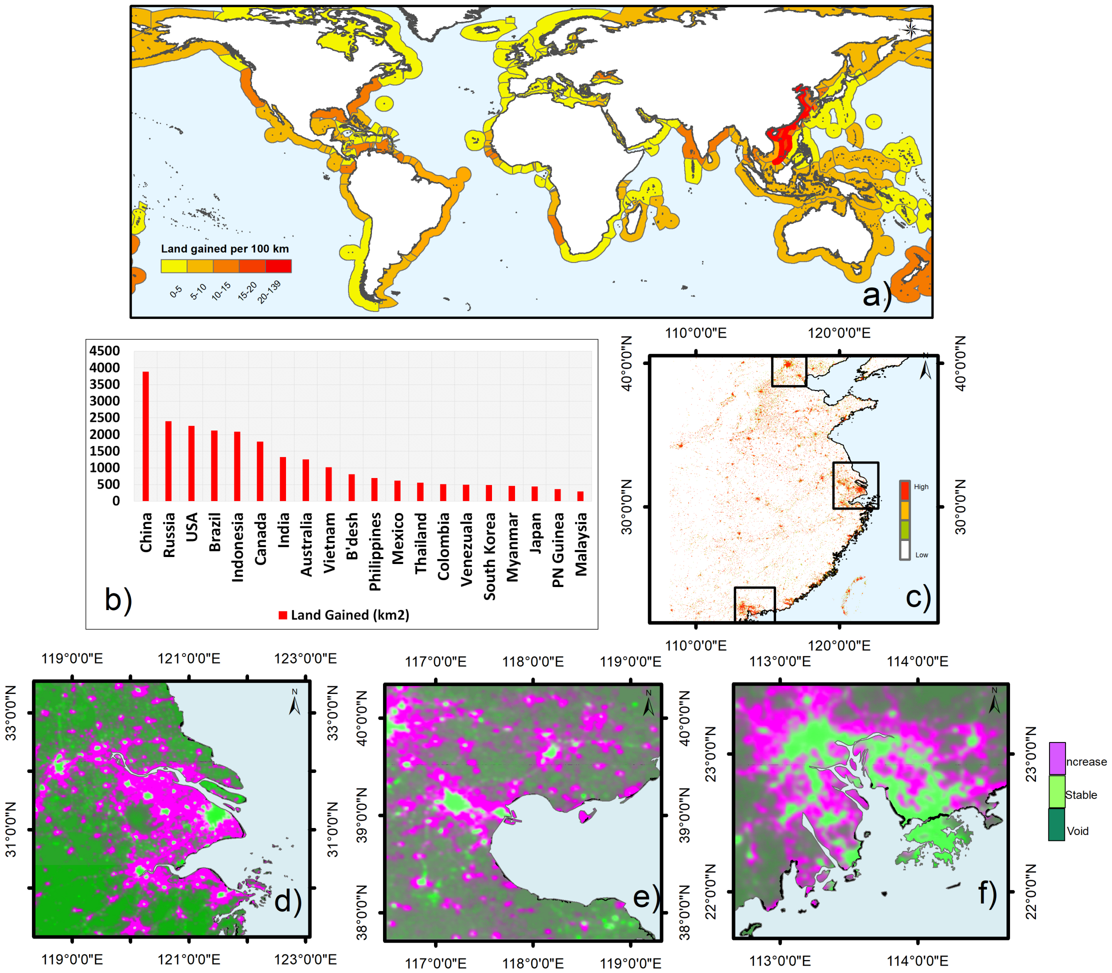

Figure 1. (**a**) Global map of land gain per 100 km of the coastline between 1984 and 2015 using GSW; (**b**) illustrates, for each country, the total area of land gain; note China clearly has the highest value. (**c**) Global human settlement layer (GHSL) Population grid (no. of people per cell) for coastal China (2015) (JRC, CIESIN, 2015), Nighttime light linear regression over time using DMSP OLS (Nighttime Lights Time Series Version 4, Defense Meteorological Program Operational Linescan System) showing urban expansion 1992–2014 as indicated by nighttime light data for deltaic megacities: (**d**) Yangtze, (**e**) Tianjin-Tangshan and (**f**) Pearl.

2. Materials and Methods

The AWEI (automatic water extraction index) and Ostu's thresholding method are used in the Google Earth Engine (GEE) platform to extract coastlines from the atmospherically corrected surface reflectance of the Landsat 5 TM sensor using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) [24–26]. Moreover, cloud, shadow, and water masks of the Landsat imagery used in this study were obtained from 'pixel_qa' band generated using the CFMASK algorithm [27]. An annual composite of 1990 was further processed to obtain a 20 km seaward buffer to include off-shore reclamation around islands (from the 1990 coastline) as the spatial extent in calculating the area of land reclaimed for nine cities in China. Each city boundary was obtained from the OpenStreetMaps website (https://www.openstreetmap.org/). The AWEI distinguishes between 'water' and 'non-water' pixels by taking the difference of spectral bands and using coefficients to enhance the spectral separation between the two distinct surfaces [28,29]. AWEInsh enables the eradication of non-water pixel areas and it was used here in areas with an urban background; where greater accuracy was achieved through the removal of shadow pixels not effectively eliminated by AWEInsh. AWEInsh was calculated as in Equation (1) [28]. (GEE code 1, see Appendix A)

$$\text{AWEInsh} = 4 \times (\text{Green} - \text{SWIR1}) - (0.25 \times \text{NIR} + 2.75 \times \text{SWIR2}) \quad (1)$$

The GSW water classification history v1.1 database [29], which describes the dynamics of water presence over the 29-year period (1990–2018) on a pixel basis, was used as the primary source of data to calculate the annual rate of land reclamation along the coastline of nine deltaic cities using GEE (Figure 2). In this study, we followed the interpretation of this dataset as explained by Mentaschi et al. (2018) [25], whereby each 30 m pixel was classified as (1) "land" in the absence of water pixels; or, in the case of within-year fluctuations between water and land and (2) "seasonal water." (GEE code 2 and 3, see Appendix A) For our study, we combined these two classification types to map and tabulate annual change in coastal land reclamation (Figure S1 and GEE code 4, see Appendix A). Furthermore, to delineate coastal land in calculating the reclamation area using GSW, the Advanced Land Observing Satellite (ALOS) DSM 30m was used as a masking layer in the GEE platform [30] (GEE code 4, see Appendix A). Additionally, the Landsat TM 5 and 8 OLI/TIRS images of the summer composite (July to September) of NDVI and the NDBI annual composite were employed in the GEE to map the stages of coastal land reclamation for the Dongjiang Bay Scenic Area in Tianjin. Mann–Kendall and Sen's slope estimator were applied using Matlab R2019a and ArcGIS 10.2, to tabulate and map statistical trends and assess the magnitude of change, respectively. Subsequently, stratified random ground GPS points were identified to enable visualization and linear regression over time of monthly average radiance composite images from 2014 to 2018, using average Day Night Band radiance values (avg_rad'-nanoWatts/cm^2/sr) of nighttime data from the Visible Infrared Imaging Radiometer Suite (VIIRS) in GEE code 5 (see Appendix A) editor API platform. Validation of the results was performed using field investigation in Tianjin and Shanghai, as well as through visual interpretation of high-resolution historical Google Earth Pro© imagery and Baidu© streel level maps.

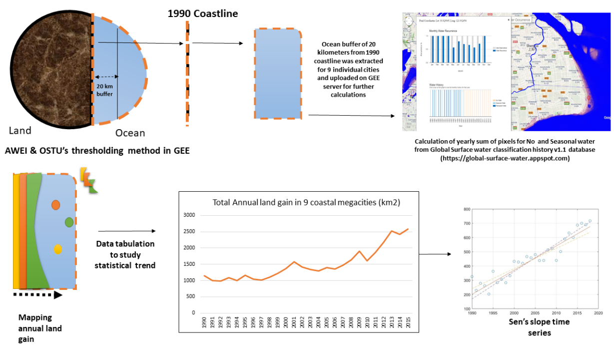

Figure 2. Flowchart illustrating the methods and steps followed in this study.

3. Results

Analysis of the GSW dataset facilitated the visualization and calculation of the spatial distribution of coastal land reclaimed in each year since 1990, for the nine individual cities (Figures 3 and 4a). According to Supplementary Materials, the total land reclaimed across the nine cities exceeded 2800 km^2 over the duration, of which 82% was gained post 2000 (Figure 4b and Figure S1). The most prominent overall increases occurred in Shanghai (Figure 3a) (1990: 325.54 km^2, 2018: 717 km^2), followed by Ningbo (1990: 267.31 km^2, 2018: 634.30 km^2) (Figure 3e), and Tangshan (1990: 195.73 km^2, 2018: 424 km^2) (Figure 3b). Zhong et al. (2019) [31] commented on the extent of Shanghai's urban expansion, but did not consider reclaimed land in their analysis, thereby underestimating the scale of change. Furthermore, Figure 5 shows statistical trends in the temporal pattern of reclamation for eight of the nine cities.

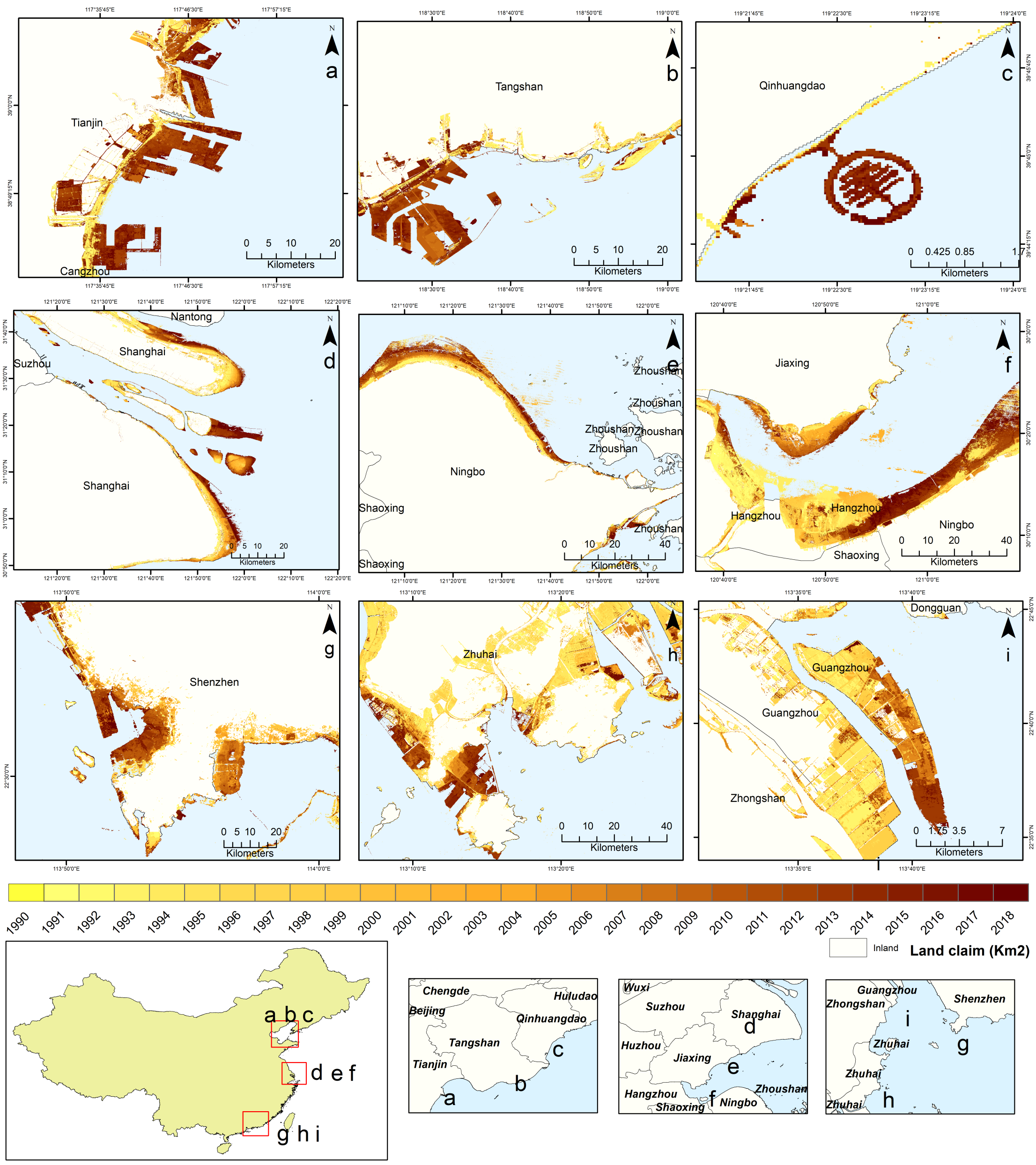

Figure 3. Annual progression in coastal land reclaimed for nine major coastal cities across three deltaic urban agglomerations, derived using the GSW dataset. (**a**) Tianjin, (**b**) Tangshan, (**c**) Qinhuangdao, (**d**) Shanghai, (**e**) Ningbo, (**f**) Jiaxing, (**g**) Shenzhen, (**h**) Zhuhai, (**i**) Guangzhou.

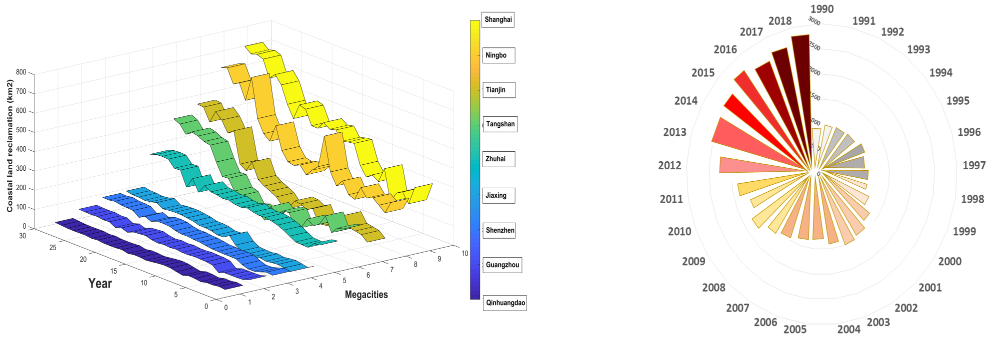

Figure 4. (**a**) Annual increase of coastal land reclamation in nine major coastal megacities in China. (**b**) Radar chart (1990–2018) illustrating the total annual gain in coastal land for the nine cities; note that land extensions are predominantly post-2000; darker colors = greater areas of land reclaimed annually.

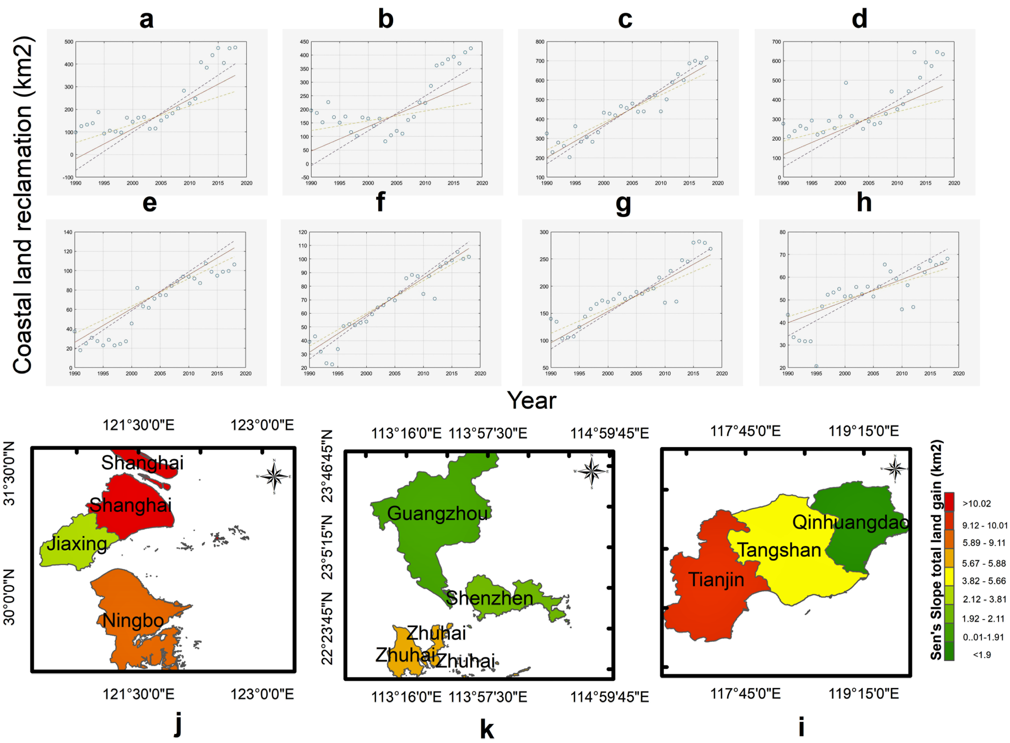

Figure 5. Sen's slope for temporal trends in coastal land reclamation for (**a**) Tianjin, (**b**) Tangshan, (**c**) Shanghai, (**d**) Ningbo, (**e**) Jiaxing, (**f**) Shenzhen, (**g**) Zhuhai, and (**h**) Guangzhou. All the cities exhibit a statistically significant increasing trend (Qinhuangdao is not shown as increase is not statistically significant). Maps show that, statistically, the maximum degree of change is in Shanghai, followed by Tianjin and Zhuhai (Sen's slope value). In terms of annual coastal land reclamation (**i**) Yangtze River delta-Ningbo = 9.10 km^2, Shanghai-15.53 km^2, Jiaxing = 3.81 km^2, (**j**) Pearl River delta-Shenzhen = 2.10 km^2, Zhuhai = 1.19 km^2, Guangzhou = 5.88 km^2, (**k**) Tianjin = 10.01 km^2, Tangshan = 5.66 km^2, Qinhuangdao = 0.12 km^2 (alpha = < 0.05).

The regression for Shanghai, Ningbo, and Shenzhen suggested that approximately the same additional amount of land had been reclaimed every year during the period 1990 to 2018. However, in other cities, in particular Tianjin and Tangshan, there were periods of rapid development associated with large-scale projects (e.g., Caofeidian Eco-city, see Reference [32]), resulting in greater residual values (Figure 5a–h). Additionally, cities generally exhibited a more regular linear regression after 2000. Spatial variability in the area of reclaimed land could be observed among the three urban agglomerations; where more than 1800 km^2 of land extension occurred around the cities of the Yangtze estuary, followed by Tianjin-Tangshan-Qinhuangdao (925 km^2), and the Pearl River agglomeration

(438 km^2) (Figure 3). Besides individual city planning policies, this variation was also because some cities, including Shenzhen, Zhuhai, and Guangzhou, had smaller administrative boundaries along the actual coastline. Statistical analysis revealed a strongly positive increasing trend in the total annual rate of coastal land reclamation over time (Figure 5j–i). Shanghai exhibited the maximum magnitude of increase (15.53 km^2/decade), followed by Tianjin (10.1 km^2/decade), and Ningbo (9.10 km^2/decade) at a 95% significance level. Assessment of coastal land reclamation using the GSW dataset in GEE allowed for detailed interpretation of the dynamics of the construction process. According to the Supplementary Materials, Fluctuations could be explained where reclamation of 'land' was followed by construction of water bodies, such as off-shore artificial lakes or reservoirs, and in some cases, these were again replaced by land use changes in the construction plan [7] (Figure S1).

4. Discussion

4.1. The Evolving Policy Context

Figure 6a summarizes the annual trend of coastal land reclamation in relation to the implementation of key major policy reforms [33]. Following the incorporation of guaranteed private property rights into the Chinese constitution in 2004, the nature of the relationship between annual GDP growth and land reclamation appeared to shift. At this time the trend lines diverge, and the two parameters appear to become decoupled (Figure 6a). The annual growth in GDP slows after 2005, although the area of reclaimed land continues to rise, following the implementation of Marine Functional Zoning (MFZ; 2010–2020) [34] and the Ecological Red Line policy (ERP) (2015) [14].

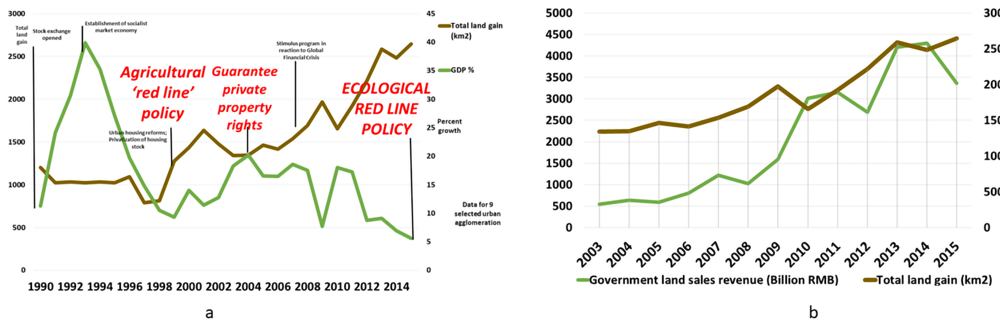

Figure 6. (**a**) Total annual land reclaimed across all nine cities plotted against annual growth in GDP; the graph also indicates China's major phases of policy reform over the period. (**b**) National land sales revenue (billion RMB) (Source-Ministry of land and Resources (2004–2016) plotted against total annual land reclaimed for nine megacities.)

The strong positive relationship between land sales revenue, urban sprawl, and China's economic growth rate is illustrated in Figure 6b [8,35]. The area of reclaimed land for the nine cities continued to rise between 2003 and 2010 as the annual revenue from government land sales increased. However, despite the decline in land sales during the past few years, the annual rate of land reclamation has continued to grow. The decoupling of land reclamation from GDP and land sales suggests that factors other than economic growth are at play, such as increasing housing rent values, the declining contribution of labor to GDP in response to the shift from agriculture to industry, and the fact that households are allocating more to savings than previously [15,36]. Indeed, local governments' outstanding debt now exceeds 18,400 billion RMB [37]. However, in the context of the recently implemented ERP, the rate of coastal land reclamation remains high.

Figure 7 highlights the stages of rapid development for a typical major coastal land reclamation project, the Dongjiang scenic area, an artificial beach in Tianjin (GEE code 6, see Appendix A). Construction of dykes was completed within two years of the plan being initiated and, by 2010, 35 km^2 of land was reclaimed. Patterns in vegetation and built-up land highlight the evolution of a systematic post-reclamation land use configuration. Higher values of built-up land in 2010 characterize the initial phase of land use development, although this diffuses over time and the NDBI levels eventually decline, probably due to urban green landscaping after land construction [16]. Note that, as construction on the reclaimed land develops, the NDVI and NDBI also change in areas adjacent to the reclamation site.

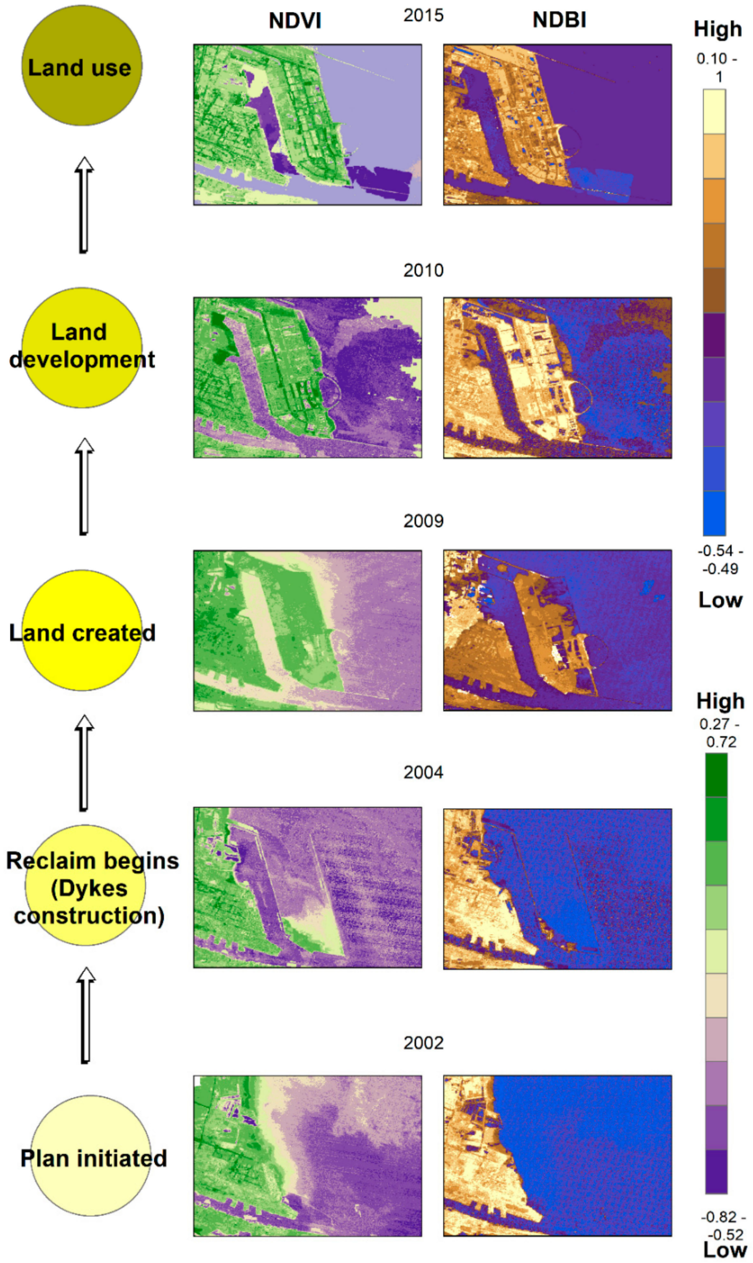

Figure 7. A model of the five phases of land reclamation illustrated by the changes in NDVI & NDBI values in the Dongjiang Bay Scenic Area (artificial beach), Tianjin.

4.2. Recent Patterns of Land Use on Reclaimed Land

In considering what land uses characterize the reclaimed land, it is notable that, after 2000, most reclaimed land has been used for urban development, ports, and manufacturing [38]. However, a more nuanced picture of the changing land uses over time may be obtained using monthly average night time radiance based on advanced infrared imaging technology [39]. Nighttime light data enables the interpretation of earth surface characteristics that are not well captured by daytime imagery, and both the nature and intensity of the human footprint may be more reliably assessed using this data source [40]. Furthermore, to extract more accurate land use information on reclaimed land, we established several GPS-fixed ground observation points and used these points in combination with VIIRS nighttime data to investigate the 2014–2018 trend in urban land use intensity in the nine cities under consideration. Figure 8 reveals that there has been a gradual increase in nighttime radiance for GPS points (Figure 8e,g,h,i) corresponding to high resolution ground and street-level images acquired through Baidu Inc. These reveal the urban intensity for three of these sites (Figure 8(1i,2ii,3iii)).

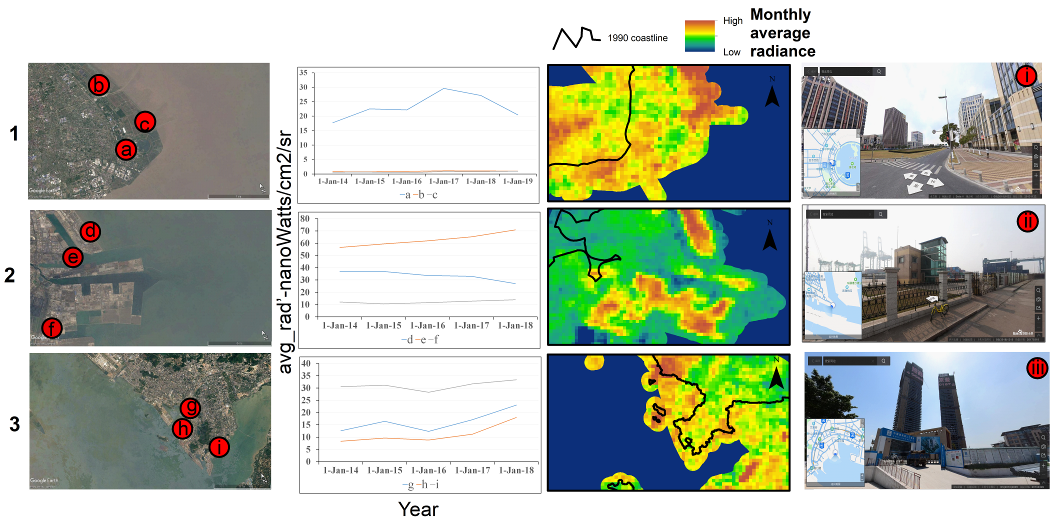

Figure 8. Maps showing the combination of ground-truthed GPS points (**a**–**i**) and mean monthly radiance composite imagery based on night time data from the VIIRS and Baidu street maps (i, ii, iii) which showcases change in nighttime light data over four years (2014–2018) over reclaimed land (**1**) Shanghai, (**2**) Tianjin, (**3**) Shenzhen. (Street view images-© Baidu Inc.)

Recently reclaimed land is typically associated with the development of major ports (e.g., the Bohai and Shenzhen Bay regions). Notably, some localities in Tianjin are characterized by prominent voids in nighttime radiance (Figure 8(2d) and Figure 8(2f)). This suggests that, while reclaimed land in Shanghai and Shenzhen was developed immediately, there was delayed development in Tianjin, probably due to financial constraints and mixed land use planning. [37] Comparisons with ground-truth images suggest that, although some of these voids are indeed characterized by construction, the buildings remain unoccupied, and are therefore examples of the so-called "ghost cities" [41]. Meanwhile, local governments are investing more capital and engaging in 'prestige construction' to maximize land revenue profits [36]. Ground observation points (b), (c), and (d) also exhibit decreased levels of night time radiance; where in these cases, the land use change involves the establishment of plantations, artificial wetlands, or wetland parks [20].

This study reveals that maximum seaward land extension has occurred in the megacities of the major coastal deltas. Even with the implementation of ERP and MFZ, which aim to preserve a quarter of China's land [14,41] and plan effective marine resource utilization [34], preserving coastal land for ecological and agricultural land uses in the era of excessive urbanization remains a major challenge [4,7]. For instance, authorities in the Yangtze River delta region, which is home to 150 million people, have planned to set aside 28,995 km^2 of land for conservation [42]. However, recent studies have highlighted ongoing serious land degradation at the coast, especially due to large scale geoengineering activities. [4,11] Furthermore, with a growing population, rising sea levels, and the frequent occurrence of extreme weather events, it becomes extremely important to critically evaluate the role of reclaimed land at the coast. A more detailed understanding of the process of coastal land reclamation at the individual city scale, as demonstrated in this paper, offers important insights. In addition, we show that analysis of advanced remote sensing imagery, such as the nighttime light dataset and Baidu© street view (Figure 8), enables details of the human footprint over congested reclaimed land at the coast to be revealed. The combination of three key datasets provides for rapid visualization and calculation of the extent of coastal land reclamation, and this could be further used to analyze, as well as monitor, reclaimed land at high spatial and temporal resolution. The method is potentially applicable to the assessment and monitoring of the extent of coastal land reclamation at a global scale using the GEE.

5. Conclusions

This study was undertaken to evaluate coastal land reclamation as a key instrument in China's evolving planning policies, especially with respect to urbanization. Such large-scale reclamation at city scale highlights its impact over an interconnected land–ocean continuum, which also has global implications with respect to recent climate change. To account for and highlight coastal modifications at the city scale, we used a global dataset on surface water (JRC-GSW v1.1) to map the annual gain in coastal land for nine megacities across the three largest deltas in China. The results of this investigation illustrated the very rapid expansion of reclamation post-2000, following the implementation of the agricultural red line policy. While much reclaimed land has been developed for ports, industry, and housing, in some localities (Shanghai in particular), the construction of artificial wetland parks and 'eco-cities' indicates a move toward 'restoration governance' [7,43,44]. Such constructions also raise questions regarding equal accessibility and mobility in cities with the emergence of privatization in 'eco-urbanism' [45].

In addition, this study also charted coastal land reclamation in relation to China's major policy reforms and it showed how reclaimed land has played a key role in revenue generation. The introduction of guaranteed private property rights has also had an important effect in promoting construction of, and over, reclaimed land [7,33]. High resolution nighttime light images and ground observations revealed unique patterns of urbanization over recently reclaimed land (2014–2018); where much of the land developed for housing had a low radiance value, whereas ports were accompanied by considerably higher values. China's modern vision of ecological conservation through the ERP (2015–2021) [14], as well as MFZ (2010–2020) [34] needs to take reclaimed land into account and how these newly built surfaces can contribute to its 'eco-civilization'. In order to assess the impact of RSLR and plan for future coastal flooding, future research needs to account for changes in coastal elevation that result from the combined effects of seaward land extension and coastal land subsidence. Considering the current state of knowledge on economic development, rapid urbanization, sea level rise, land subsidence, climate change, and the increased frequency and magnitude of extreme events in coastal deltaic regions of China [46,47], a detailed evaluation is overdue on how building new land systems at the coast affects the levels of risk for people living or working in such localities is overdue. Google Earth Engine is a powerful long-term analytical tool to this end.

Supplementary Materials: The following are available online at http://www.mdpi.com/2072-4292/11/22/2621/s1, Figure S1: Annual figures of coastal land reclaimed (km^2) and rates of change for the nine cities (1990–2018); Color gradations indicate annual rate of change for individual cities. Fluctuations can be explained where reclamation of 'land' is followed by construction of water bodies, such as artificial lakes or reservoirs, in some cases these are again replaced by vivid land use changes in the construction plan. [7].

Author Contributions: D.S. and X.Z. processed the satellite GSW images; R.C., M.E.M. and Y.R.C. contributed to the description and discussion of the policy and its relation to coastal land reclamation; A.B. contributed to the statistical analysis and cartographic design; D.S. and M.E.M. led the writing of the paper; all authors analyzed the results and contributed to the final version of paper.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Google Earth Engine API codes:

1. Shoreline extraction using AWEI and OSTU thresholding method https://code.earthengine.google.com/2e49958c2bf39f0ea1d70a9b79a01cf8
2. GSW export image 'No water' class https://code.earthengine.google.com/e9e865be3af42abca872f5262fb2f34d
3. GSW export image 'seasonal water' class https://code.earthengine.google.com/7aedc1a8e1af3b8b091bd51e822a3632
4. GSW calculate annual change in 'No water' and 'seasonal' bands https://code.earthengine.google.com/074f6f73ccf5d6943cde94321a73f0d3
5. Linear Regression over time for Night time light data https://code.earthengine.google.com/803ba5530538f84abe3812b8fb4f71f9
6. Export NDVI and NDBI images https://code.earthengine.google.com/0e90dd6d76db4ea7fbfac819bee46eab

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